



# **Vers l'éco-conception de technologies émergentes : prise en compte du changement d'échelle dans l'analyse de cycle de vie**

Lucas Riondet

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## THÈSE

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École doctorale : I-MEP2 - Ingénierie - Matériaux, Mécanique, Environnement, Energétique, Procédés, Production

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### Vers l'éco-conception de technologies émergentes : prise en compte du changement d'échelle dans l'analyse de cycle de vie

Toward the eco-design of emerging technologies: how to integrate upscaling in life cycle assessment?

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*La symbiose entre science et innovation technico-industrielle a désormais basculé  
dans un rapport de capture pure et simple.*

**Isabelle Stengers**

## Résumé

Les sciences environnementales ont établi la non-soutenabilité des activités humaines dans les sociétés modernes. Ce constat est notamment formalisé par le cadre des limites planétaires. Il implique de transformer nos sociétés industrialisées en engageant de nécessaires transitions écologiques.

L'aphorisme « changement d'échelle de technologie émergente » est employé en ingénierie pour représenter les enjeux de développement et d'industrialisation de technologies pour la transition écologique. Les énergies renouvelables ou les véhicules électriques en sont des illustrations concrètes. En revanche il n'existe pas de définition explicite caractérisant le « changement d'échelle » en science de la conception, ni d'analyse des liens entre le phénomène de « changement d'échelle de technologie » et les ambitions de soutenabilité environnementale. La thèse vise donc à répondre à la question « *Comment aider les concepteurs à prendre en compte le changement d'échelle de technologies émergentes dans une approche de soutenabilité et d'intégration en conception ?* ».

La méthode pour y répondre a consisté à réaliser dans un premier temps une revue de la littérature pour identifier les invariants qui caractérisent le changement d'échelle en ingénierie, incluant l'ingénierie environnementale. Après cette première étape de caractérisation, une attention particulière a été portée sur les pratiques d'Analyse de Cycle de Vie (ACV), en développement ou opérationnelles, potentiellement adaptées pour traiter les spécificités du changement d'échelle du point de vue environnemental. Enfin, une approche par cas d'étude a été utilisée pour déterminer les points d'intérêts et les difficultés d'intégration dans un processus d'éco-conception de technologie émergente dans le secteur de l'énergie. Les systèmes photovoltaïques sont développés comme illustration fil rouge dans cette thèse.

En termes de résultats, l'étude des invariants du phénomène de changement d'échelle de technologie émergente a permis de démontrer qu'il se compose de plusieurs facettes caractérisées en cinq archétypes : maturer (*scaling-up*), massifier (*mass-producing*), déployer (*deploying, reaching a level*), intégrer (*integrating into a complex system*) et limiter environnementalement (*down-limiting*). Cette approche par archétype révèle que le changement d'échelle n'est pas construit sur une vision d'analyse d'impacts environnementaux. Il découle en grande partie de pratiques de conception et de logiques industrielles qui ne visent pas directement la soutenabilité. En revanche, des recommandations pour les concepteurs portant sur le choix de modes d'ACV (prospectif, conséquentiel, régionalisé, absolu) adapté ont été proposées pour chacun des



archétypes. Pour leur mise en œuvre, une méthode intégrée d'analyse environnementale du changement d'échelle agrégeant les cinq archétypes a été développée et illustrée. Ce processus, nommé EAU pour *Environmental Assessment for Upscaling*, s'adresse à une équipe de conception faisant collaborer un ingénieur expert technique et un ingénieur « cycle de vie », garant des principes d'éco-conception. D'autres expertises peuvent y être ajoutées. Enfin, des travaux d'approfondissement sur les archétypes 3 (*deploying*) et 5 (*down-limiting*) ont servi de supports pour l'opérationnalisation en conception des archétypes en explicitant de bonnes pratiques pour une équipe de conception.

En conclusion, cette thèse présente des apports conceptuels, méthodologiques et opérationnels supportant l'intégration en conception d'aspects environnementaux associés au phénomène de changement d'échelle de technologies émergentes. Elle ouvre en perspective de nouvelles pratiques de conception reposant sur une vision socio-technique du cycle de vie dans une forte pluridisciplinarité, incluant par exemple, des approches par scénarii prospectifs ancrés dans une perspective de soutenabilité environnementale absolue.

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---

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# 1

## Introduction : cadre général de la thèse

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## 1.1 Introduction

### 1.1.1 La non-soutenabilité des sociétés modernes

Au cours des dernières décennies, les sciences naturelles abordant les interactions entre le système terrestre et les activités humaines ont dressé un bilan alarmant : La dégradation de la biosphère et le changement climatique sont deux phénomènes cruciaux qui soulignent la nature critique de ces interactions. La *Plateforme Intergouvernementale Scientifique et Politique sur la Biodiversité et les Services Écosystémiques* (IPBES) et le *Groupe d'Experts International sur l'Évolution du Climat* (GIEC) publient régulièrement des rapports, destinés aux citoyens et aux décideurs, qui synthétise les dernières études scientifiques sur l'érosion de la biodiversité et le changement climatique. L'IPBES indique par exemple qu'en 2019, près de 85% de la surface des zones humides a disparu, 75% de la surface de la Terre a subi des altérations majeures et 66% des mers subissent des effets cumulatifs de plus en plus graves [1]. Par ailleurs, le GIEC a établi en 2023 que le réchauffement climatique observé entre 1850 et 2019 est de plus 1,06 degré Celsius (avec une marge d'incertitude comprise entre 0,8 et 1,3 degré Celsius), entraînant des changements des conditions météorologiques et des extrêmes climatiques dans de vastes régions, affectant et menaçant les écosystèmes et populations humaines [2]. Ces réalités et leur gravité, bien qu'incontestables, sont difficiles à appréhender pour des non-experts. L'ampleur des interactions des phénomènes en jeu, à différentes échelles spatiales et temporelles, requièrent les expertises conjointes de nombreuses disciplines scientifiques (e.g. écologie, climatologie, géologie, sociologie, paléontologie), formant la *science du système Terre* [3]. Cette science permet de caractériser la soutenabilité des activités humaines dans leur ensemble. Ici le terme de soutenabilité est à comprendre au sens de « ne pas compromettre la capacité des futures générations à subvenir à leurs besoins en répondant aux besoins du présent » [4], [5].

En revanche, du point de vue d'autres disciplines scientifiques, et pour ce qui nous intéresse, de la science de la conception, l'analyse de la soutenabilité est encore trop superficiellement traitée. Plusieurs illustrations seront détaillées dans la suite de la thèse. L'appropriation directe par des concepteurs des questions de société dont fait partie la soutenabilité est comme nous le verrons difficile. Des équipes de recherche inter-disciplinaires, en parallèle du GIEC et de l'IPBES, ont en revanche travaillé à rendre lisible et explicite les relations entre l'Humain et le Vivant pour la société civile, incluant évidemment les concepteurs.

Le *Stockholm Resilience Centre* créé en 2007 s'inscrit pleinement dans cette démarche

en proposant, entre autre, le cadre des *limites planétaires*. On peut comprendre ce cadre comme un outil de synthèse scientifique : Publié en 2009 et actualisé 4 fois depuis (en 2015 [6], 2020 [7], 2022 [8], et 2023 [9]), les limites planétaires présentent la Terre comme un système régi par les interactions entre neuf phénomènes biophysiques (Cf **Figure 1.1**).

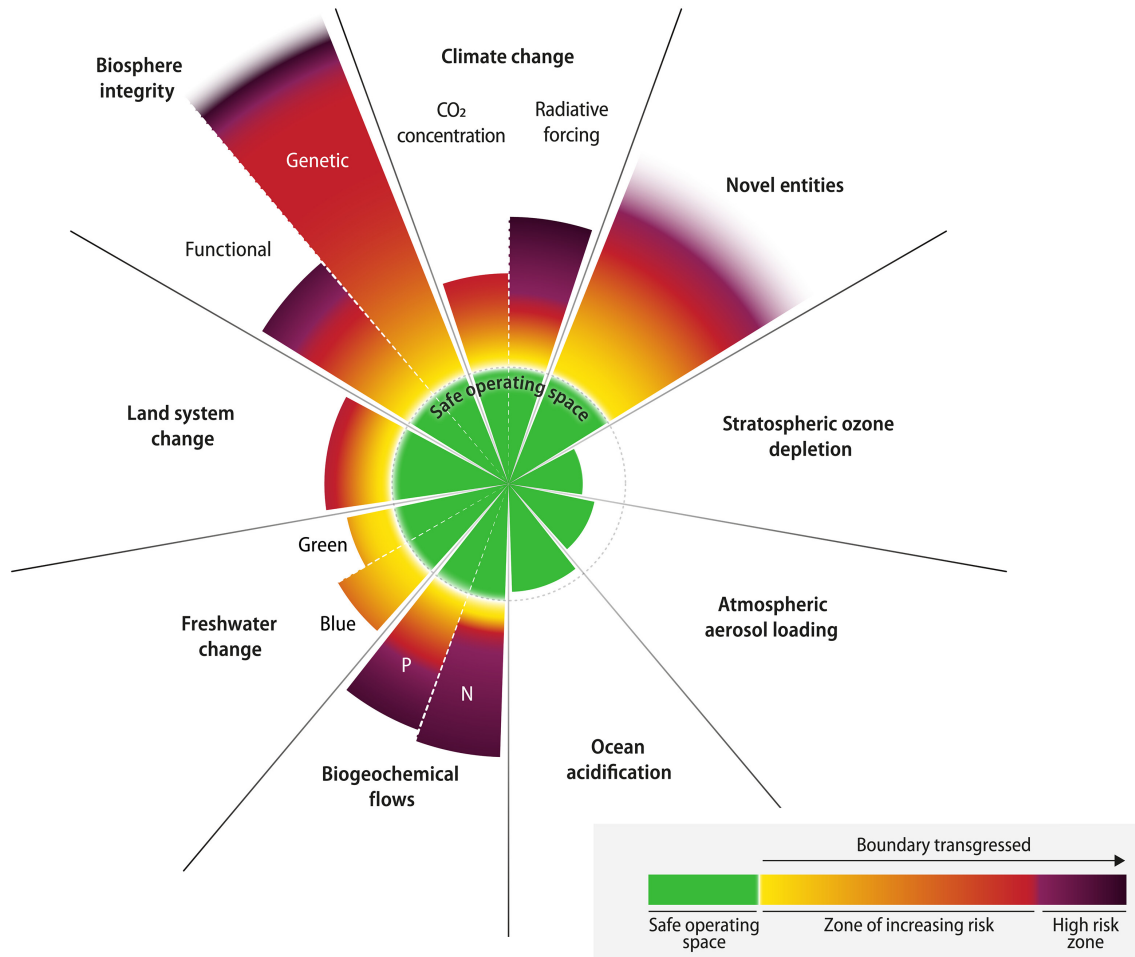


**FIGURE 1.1** – Cadre des limites planétaires et dépassement établis par Richardson et al. (2023) [9].

On retrouve notamment le changement climatique (*climate change*) et l'intégrité de la biosphère (*biosphere integrity*) parmi les neuf limites identifiées. La nouveauté de cette approche est qu'elle exprime des limites socio-environnementales définissant une *zone de fonctionnement sûre* (« *safe operating space* » en anglais) à l'échelle planétaire. Sur la **Figure 1.1**, cet espace est représenté par le cercle central en vert. Le cadre des limites planétaires décrit la stabilité du système « Terre » vis-à-vis des pressions générées par les activités humaines à différentes échelles. Des phénomènes à l'échelle planétaire (e.g. changement climatique, la dégradation de la couche d'ozone) sont ainsi

mis en relation avec des phénomènes régionaux (e.g. modification des usages de sols, érosion de la biodiversité) et locaux (e.g. utilisation d'eau douce). Cette mise en relation est permise par un travail d'agrégation de plusieurs modèles bio-physiques issues de la science du système Terre. Chaque limite est ainsi caractérisée par une ou plusieurs variables de contrôle et une valeur seuil  $y$  est associée à partir de modélisations pour éviter de passer des *points de bascule* environnementaux [10]. Par exemple, le changement climatique est caractérisé en mesurant la concentration en  $\text{CO}_2$  dans l'atmosphère ( *$\text{CO}_2$  concentration*) et le forçage radiatif et leurs seuils respectives sont de 350 parties par million (ppm) et 1 Watt par mètre carré ( $\text{W}/\text{m}^2$ ). Les limites planétaires positionnent par conséquent les sociétés humaines en fonction de capacités estimées par simulations de résilience du système Terre, c.-à-d. de capacité de l'environnement à résister aux pollutions (*Carrying Capacity* en anglais).

Ce positionnement est dît « absolu », en ce qu'il ne dépend pas d'une référence arbitraire ou d'une vision optimiste (ou pessimiste) des promoteurs du modèle. Formulé autrement, le cadre des limites planétaires est utilisé pour quantifier la soutenabilité environnementale de l'humanité à l'échelle planétaire. En ce sens, le fait que six de ces neuf limites ont été franchies en 2023 (Cf zones rouges et violettes sur la **Figure 1.1**) démontre la non-soutenabilité des sociétés modernes [9].

Pour résumer, l'intérêt du cadre des limites planétaires est qu'il synthétise les connaissances scientifiques actuelles en neuf dimensions environnementales qui « font système » entre elles et avec les sociétés humaines. La vision **multicritères** et  **systémique** véhiculée par ce cadre scientifique est une composante structurante de l'analyse de la soutenabilité. A contrario, le dépassement des limites planétaires documente l'impasse du développement tel que nous le connaissons, sans pour autant nous indiquer de chemins possibles pour en sortir. Cela nécessite des stratégies complémentaires appuyées par des leviers d'action et déclinées à toutes les échelles (e.g. internationale, nationale, sectorielle).

### 1.1.2 Soutenabilité et transition(s) écologique(s)

Le cadre des limites planétaires, ont rappelé Steffen et al. (2015) en conclusion de leur article, n'a pas été conçu pour être décliné régionalement à l'échelle des pays par exemple [6]. Malgré cela, ce cadre s'impose progressivement en tant qu'outil de référence de la (non)soutenabilité environnementale.

## Diffusion d'indicateurs de soutenabilité à différents niveaux

A l'échelle des sociétés, gouvernements [11], institutions politiques [12] et citoyens semblent se saisir des limites planétaires à travers de nombreux médiums (livres [13], [14], articles de journaux [15]-[18], supports de cours [19], [20] et de vulgarisation [21], [22]). Cet intérêt, qu'il soit superficiel ou porté par une réflexion sur la soutenabilité, s'accompagne de nouveaux travaux de recherche de différentes communautés scientifiques pour transformer cet outil d'alerte et de communication en outil de pilotage vers la soutenabilité.

Folke et al. (2016) propose par exemple une restructuration des Objectifs de Développement Durable (ODD) des Nations Unies via le prisme des limites planétaires [23]. Cette démarche aboutit à positionner l'économie au service du monde social, lui-même intégré dans la biosphère. Il s'agit d'un paradigme cohérent avec le cadre des limites planétaires. Différents paradigmes définissent la relation entre environnement, monde social et économie, chacune impliquant une philosophie et une définition de la soutenabilité [24]. Dans cette thèse, nous souscrivons autant que possible à celui des limites planétaires et de la soutenabilité absolue.

Kate Raworth, en tant qu'économiste, a participé à intégrer une lecture sociale des limites planétaires en proposant la « théorie du donut » [25]. Une économie soutenable serait définie selon elle comme l'ensemble des activités permettant la réalisation de besoins sociaux minimaux (accès à l'eau, la nourriture, l'éducation, la santé, etc.) sans dépasser les limites planétaires. La transposition de ce paradigme à l'échelle de l'entreprise [26], [27] ou de communauté, et le caractère universel des besoins identifiés [28] sont des axes de recherche débattus. En revanche, ces travaux soutiennent l'idée que de nouveaux projets de société sont nécessaires et possibles pour rester dans les limites planétaires tout en répondant aux besoins écologiques et sociaux qui s'entremêlent. Par exemple, au premier ordre, chaque limite planétaire peut être associée à un secteur industriel spécifique. L'implication majeure du secteur de l'énergie dans le changement climatique est le cas le plus médiatisé : 39% des émissions de gaz à effets de serre en 2021 sont attribuées à la production d'énergie [29]. Cette comptabilisation fait du secteur de l'énergie le plus contributeur au changement climatique. Par ailleurs l'agro-industrie est principalement mise en cause par rapport à la dérégulation des flux du phosphore [30], de même pour le secteur du packaging vis à vis de la pollution plastique incluse dans la limite « novel entities » [31]. Le secteur du froid/climatisation a été le principal contributeur à la dégradation de la couche d'ozone et les réglementations des années 1990 sur les fluides frigorigènes ont contribué à maintenir cette limite dans la zone de

fonctionnement sûr [32], [33]. Cette approche manque d'une vision systémique mais a le mérite d'interpeller l'industrie sur les questions de soutenabilité environnementale.

## Transitions écologiques et scénarios

Il apparaît clairement que de vastes transformations des modes de vie, incluant les systèmes de production qui les sous-tendent sont nécessaires « pour guider le développement humain sur une planète changeante » [6]. Selon leur degré de subversion des sociétés actuelles, de nouveaux projets de société ont plus ou moins infusés depuis les années 1970 à aujourd'hui. Sans être exhaustif, ils sont conceptualisés par les termes *développement durable* [34], *redirection* et *bifurcation écologique* [35], *décroissance*, *a-croissance*, ou *post-croissance* [36], ou enfin *transition(s)* [37].

En ingénierie comme nous le verrons dans les sections suivantes, le cadre de réflexion le plus répandu aujourd'hui est celui des transitions écologiques. Selon Geels et al. (2017), les transitions sont des transformations « orientées », en ce qu'elles impliquent des décisions prises pour atteindre un état futur, soutenable et souhaité de la société [38]. En d'autres termes, les transitions sont des moyens planifiés pour atteindre un objectif politique de soutenabilité.

Il existe une grande diversité de feuilles de route visant à implémenter des indicateurs de soutenabilité : sans être exhaustif, on peut d'abord penser aux rapports scientifiques du GIEC et de l'IPBES à des échelles planétaires et régionales. Les états et institutions politiques se dotent également de stratégies de transition pour leurs territoires respectifs : de la stratégie nationale bas carbone [39] déclinant les accords de Paris [40], aux ODD des Nations Unies [41] en passant par le Green New Deal Étasuniens [42] ou le Green Deal Européen [43]. Ces grandes stratégies nationales ou sub-nationales s'articulent avec des travaux de scénarisation portés par des organismes ou collectifs spécialisés : on peut mentionner les scénarios de l'*Agence Internationale de l'Energie* (IEA en anglais) [44] ou de l'*Agence Internationale pour les Energies Renouvelables* (IRENA en anglais) [45]. Au niveau français, l'ADEME (renommée il y a quelques années « Agence de la transition écologique ») participe au développement de scénarios sur le futur de la société française à l'horizon 2050 [46]. En collaboration ou non avec ces institutions, on trouve également des entreprises nationales comme RTE [47] ou des entreprises de conseil comme *Carbone4* [48], *Sciences Based Target* [49], *The Natural Step* [50] ou encore *Deloitte* [51] se positionnant sur des scénarios de transitions. Enfin, des organisations non-gouvernementales comme le *Shift project* [52], l'association *NégaWatt* [53], ou *Oxfam* [54] fournissent également des scénarios et

supports pour la transition écologique.

Cette liste non-exhaustive de feuilles de route présente des approches et objectifs variés (pluri-indicateurs ou non, appuyés sur des scénarios ou non, horizon temporel et zone géographique variables) qui ont peu de chance d'être cohérentes les unes avec les autres.

Dès lors, le constat de non-soutenabilité des sociétés est traduit en actions à mener pour « atteindre la soutenabilité » déclinées aux échelles internationales, nationales puis sectorielles. Ces actions s'inscrivent dans une perspective de transition vers un idéal à atteindre, et un rapport au temps planifié pour y parvenir. La place attendue des concepteurs de technologies dans ces feuilles de route dépendent par conséquent de l'idéal visé. La sensibilisation aux enjeux environnementaux dans la société étant focalisée sur les changements climatiques [9] et les questions énergétiques, nous proposons donc de discuter dans la section suivante du glissement de *transition écologique* à *transition énergétique* (et technologique) en science de la conception.

### 1.1.3 Transition technologique et changement d'échelle de technologies

Lorsque des scénarios de futures transitions sont formulés, leur potentielle faisabilité est étudiée du point de vue industriel aux regard des implications en termes d'énergie et de matières premières consommées.

#### Transitions et Énergie

Un point important est que pour une partie des scénarios cités, les impératifs de transition se traduisent pour l'industrie et l'ingénierie par des objectifs de développement de technologie. On retrouve cette idée derrière différentes appellations, par exemple « Green technologies » pour les Nations Unies [55] ou « innovations radicales » et « technologies émergentes et futures » pour la Commission Européenne [56], [57]. Cela découle d'une vision relativement « top-down », chargeant les concepteurs de technologie de la responsabilité environnementale des *solutions de rupture* à développer pour lutter (principalement) contre le changement climatique. L'aphorisme « *changement d'échelle de technologie émergente* » est employé dans ce contexte pour décrire le phénomène attendu pour répondre aux enjeux de société. Ce concept, bien que non-défini uniformément, se comprend ici comme l'application à niveau d'ingénierie d'une stratégie sectorielle ou sinon mondiale.



En d'autres termes, atteindre la soutenabilité serait rendu possible *par le développement de nouvelles technologies*. Plusieurs organismes affiliés au développement de technologies utilisent implicitement ou explicitement cette hypothèse (e.g. l'IRENA, l'IEA ou encore la commission européenne). L'IEA en donne une illustration frappante avec la **Figure 1.2**. Il s'agit du tracé au cours du temps des émissions de CO<sub>2</sub> évitées suivant le *Scénario de Développement Durable* (SDS en anglais) publié en 2020 visant la neutralité carbone mondiale en 2070 [44]. Ce scénario se décline sur plusieurs secteurs industriels (mobilité, logement, énergie).

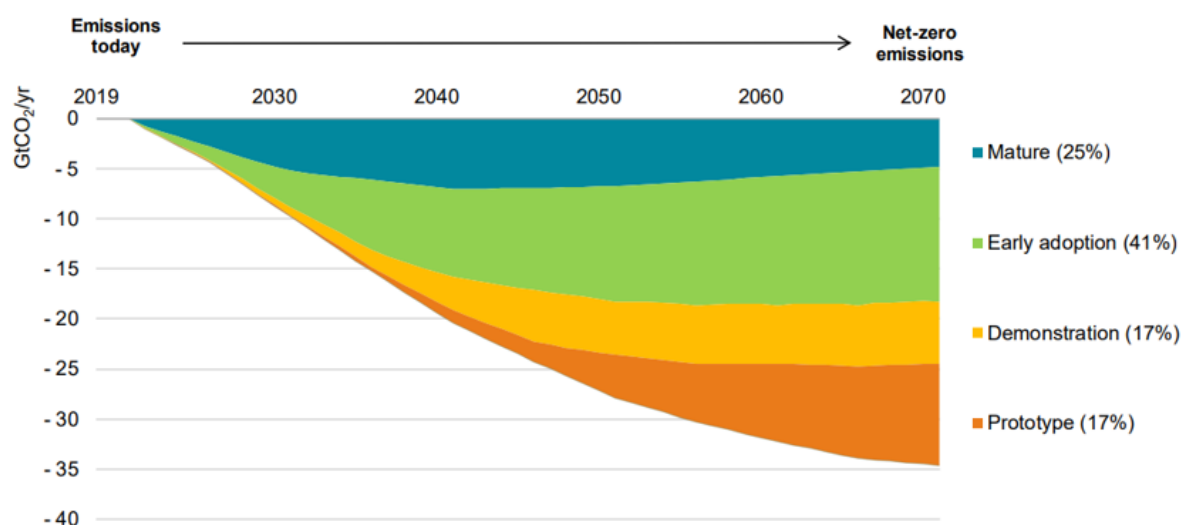


**FIGURE 1.2** – Émissions de gaz à effets de serre évitées au cours du temps suivant le scénario de développement durable (SDS) de l'IEA pour une neutralité carbone mondiale atteinte en 2070 avec une probabilité de 66% de rester sous les 1.8 °C de réchauffement climatique. [44].

Les représentations de ce type sont dites « prospectives » au sens où elles tracent un champ des possibles pour un horizon temporel donné [58]. Les travaux de prospective s'appuient sur des données et des hypothèses de modélisation, par exemple, portant sur les performances techniques d'une technologie, son industrialisation et son traitement en fin de vie, son déploiement dans la société, ses potentiels usages, etc. Cette liste non-exhaustive peut faire émerger une forme de paradoxe : dans le cas d'une technologie émergente, au sens d'un prototype, peu de données sont disponibles. Pourtant on constate sur la **Figure 1.2** que des technologies n'existant actuellement pas à l'échelle industrielle (*prototypes* en orange et *démonstrateurs* en jaune) constituent plus de la moitié des technologies permettant la diminution des émissions de gaz à effets de serre à l'échelle mondiale et à l'horizon 2070. De tels scénarios de prospective reposent donc sur un grand nombre d'hypothèses non-testées, parfois non-formulées, sur le déploiement inédit de technologies. Autrement dit, proposer des scénarios de transition

énergétique, et donc faire de la prospective, impose de s'interroger sur la faisabilité du changement d'échelle d'une technologie non-mature industriellement. La plausibilité de ce type de scénarios incombe alors à l'industrie et en premier lieu à la recherche et développement (R&D) sur les technologies à faire émerger. Ce positionnement place la recherche et l'ingénierie dans un rôle de pourvoyeur et de garant de la faisabilité des scénarios d'un point de vue socio-technique. Cette faisabilité est ainsi souvent étudiée à la lumière de la science de la conception, sans pour autant parvenir à couvrir l'ensemble des sujets de prospective (e.g. capacité industrielle de production, traitement en fin de vie, effets socio-structurels). Les concepteurs, pour traiter la soutenabilité des technologies qu'ils développent, ont ainsi besoin d'intégrer de nouvelles approches prospectives dans leurs pratiques. Ils peuvent pour cela s'appuyer sur des scénarios pré-existants (e.g. scénarios RTE), bien que la plupart restent focalisés sur une approche « carbone » (Cf **Figure 1.2**).

### Transitions et Matières premières

Un second axe mis en avant dans les scénarios de développement de technologies est l'estimation des matières premières nécessaires pour les réaliser. Le phénomène de criticité des matières premières, dépassant la seule question de disponibilité des ressources, est en partie lié à la faisabilité des transitions énergétiques. La criticité des métaux, puis par extension des matières premières, a été définie pour la première fois dans les années 2010. Graedel et al. (2012) en propose une définition de la criticité s'appuyant sur trois dimensions ; elle intègre 1) le risque d'approvisionnement de la ressource, 2) la vulnérabilité socio-économique vis à vis d'une restriction d'accès à la ressource pour l'entité pour laquelle la criticité est évaluée (société, pays ou entreprise), et 3) les implications environnementales de l'utilisation de la ressource étudiée. Les auteurs présentent cette troisième composante comme un indicateur « pour les concepteurs, les décideurs politiques et les agences non-gouvernementales des potentiels impacts environnementaux associés à l'utilisation d'un métal en particulier » [59]. Ce concept a donc été pensé pour la prise de décision et structuré par des dimensions économiques, sociales et environnementales.

En parallèle, Klinglmair et al. (2014) caractérise la criticité comme relative à une entité [60]. Autrement dit, les matières premières jugées critiques peuvent ne pas être les mêmes pour une entreprise, une région ou un pays entier. De nombreuses méthodes et indicateurs ont été développés depuis pour prendre en compte cette spécificité (e.g. Yale [59], ESSENZ [61], EC-RMC [62], GeopolRisk [63]) et s'adapter à l'échelle des



prises de décision. Ces méthodes reprennent pour certaines les trois axes de Graedel et al. [59], et d'autres se limitent à une analyse de risque économique. Cette orientation dépend de l'entité pour laquelle on analyse la criticité et de sa vision politique sur les ressources matérielles. Le choix de méthode de criticité est donc fortement lié à l'idéal de soutenabilité à atteindre par l'entité (e.g. état, entreprise) sur lequel est construit sa stratégie de transition.

La criticité est régulièrement étudiée dans des scénarios de transition s'appuyant sur des développements technologiques sans précédents comme ceux de l'IEA ou de l'IRENA. La **Figure 1.3** illustre la criticité relative au déploiement de technologie pour la transition énergétique dans un scénario de la commission européenne [64]. Pour cet exemple, la composante de risque d'approvisionnement est mise en avant pour 24 matières premières (colonne de gauche) et redistribuée ensuite pour neufs groupe de technologies (colonne du milieu). Enfin, trois secteurs d'activité sont représentés (l'énergie, la mobilité et l'armée) comme nécessitant en priorité une ou plusieurs des technologies.

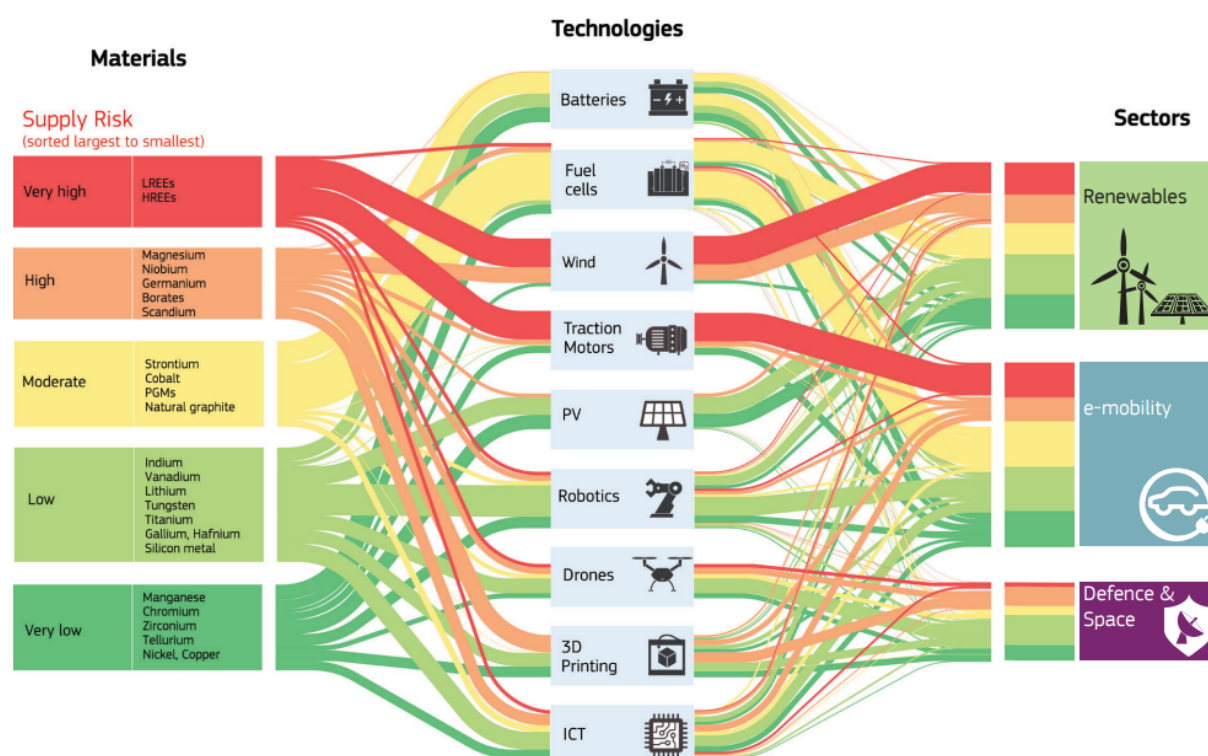


**FIGURE 1.3** – Analyse de la criticité de 25 matières premières par le risque d'approvisionnement (*Supply Risk*) pour la transition énergétique du point de vue de la commission européenne [64]. La technologie est placée au centre de l'analyse.

On comprend dans le contexte des transitions énergétiques, que les réflexions sur la criticité ont un rôle de confrontation des scénarios aux réalités industrielles. Les matières

premières apparaissent comme un facteur limitant la faisabilité techno-économique du déploiement d'une ou d'un groupe de technologies. Ces réflexions attestent donc d'un besoin pour les concepteurs d'anticiper les aspects cumulés en terme de matière première du déploiement de leurs objets d'étude (i.e. technologies).

En synthèse, les transitions écologiques soulèvent plusieurs points en lien avec la conception de technologies :

- On recense une grande diversité de scénarios de transition, adossée à des compétences d'analyse prospective peu développées en science de la conception. Cela suppose par exemple d'intégrer en amont des réalités socio-économiques et environnementales dépassant le périmètre d'étude habituel d'un produit et de sa chaîne de valeur.
- L'activité de conception de technologie pour un certain nombre de scénarios est placée au centre pour traiter des enjeux de soutenabilité. Cela résulte d'une approche *technology push*.
- Les concepteurs ne sont cependant pas directement nourris d'une vision de la soutenabilité. Le lien entre technologie et soutenabilité est réalisé par les scénarios (vision descendante ou *top-down* en anglais) en donnant des projections sur des indicateurs techniques (e.g. gain d'efficacité, stabilisation et maturation de nouvelles technologies). Les besoins technologiques peuvent être identifiés pour plusieurs secteurs stratégiques en parallèle.
- Enfin, dans le passage entre les résultats des sciences du système Terre et la mise en oeuvre de transitions résulte une perte de vision systémique et multicritères. La perte de vision systémique est identifiable lorsque les objectifs sont déclinés à l'échelle sectorielle sans expliciter leurs raisons environnementales et en invisibilisant parfois les interactions inter-sectorielles. De plus, un certain nombre de scénarios sont construits sur une optimisation mono-indicateur ( $\text{CO}_2$  *equivalent*) pour un secteur industriel donné, en tenant compte des aspects matériels de façon réduite, le plus souvent sous la forme d'une analyse de risque pour la sécurisation des approvisionnements. Cette approche est alors perçue par les concepteurs comme une approche soutenable.

### 1.1.4 Critiques de la transition énergétique et du technosolutionnisme

L'idée selon laquelle la transformation de la société doit s'appuyer sur de forts développements technologiques est largement critiquée dans les communautés scientifiques : en sciences historiques, épistémologie, et en science de la conception.

#### Critiques par les sciences historiques

En développant des scénarios de transition énergétique se déroulant sur plusieurs décennies, l'ingénierie se rapproche des champs de recherche des sciences historiques. L'historien des sciences Jean-Baptiste Fressoz s'est attaché à questionner l'historicité du concept de *transition énergétique*. Selon lui, le concept de transition, pourtant au coeur de nombreux dispositifs de lutte contre le changement climatique, n'aurait pas de consistance scientifique. Il reposerait sur la substituabilité des technologies ainsi que sur une vision faussée de la dynamique des systèmes de production socio-techniques. La substituabilité, c'est à dire le fait qu'une technologie remplace une autre technologie pour un même usage n'a jamais été observée [65]. En effet, l'approvisionnement en énergie des industries du XIXème et XXème siècles n'est pas passé d'une source d'énergie à une autre (biomasse puis charbon, puis gaz et pétrole). A la place, l'industrie se serait complexifiée en combinant les différentes sources d'énergie disponibles, aboutissant à un système complexe nécessitant toujours plus d'énergie et de matière pour fonctionner. Utiliser le terme de « transition énergétique » d'après ce travail consiste en réalité à « diminuer l'intensité carbone de l'économie », sans poser la question de la taille de l'économie et les pressions qui en résultent sur l'environnement [66].

François Jarrige, également historien, agrège les questionnements autour des fondements de l'idée que le progrès est conditionné par le progrès technique [35], [67]. Il invite ses lecteurs à remettre en question la place de la technologie dans nos sociétés en retraçant les alternatives aux développements techniques comme fin en soit. Il démontre qu'une vision *technology push* est incompatible avec la soutenabilité car intrinsèquement liée à la réification/marchandisation du vivant.

Ces deux auteurs (Fressoz et Jarrige) synthétisent les apports de nombreux auteurs démontrant que défendre une transition technologique profite à une vision technosolutionniste des enjeux environnementaux ne reposant sur aucune réalité industrielle ou historique.

## Critiques de la science de la conception

José Halloy, physicien, complète la critique du techno-solutionnisme en abordant la soutenabilité industrielle par le biais du lien entre flux d'énergie et matières premières [68]. Il propose le concept de « technologie zombie » pour désigner des technologies en cours de développement ou de diffusion dans la société qui ne seraient plus en adéquation avec les besoins et contraintes présentes et futures (notamment en termes de soutenabilité). Le développement de ces technologies zombies serait ainsi poussé par des impératifs obsolètes et/ou dépassés [69]. Fortement inspiré par le biomimétisme, José Halloy promeut en opposition le concept de « technologie vivante ». Ce type de technologie est caractérisé par une utilisation de flux d'énergie (c.-à-d. puissance) aux mêmes ordres de grandeur que ceux observés dans la biosphère (en dessous du kiloWatt). La plupart des technologies et procédés actuels dépassent cet ordre de grandeur. N'étant pas affilié à une communauté de conception, il interagit cependant avec le domaine des *low-techs* et prône un changement de rapports aux techniques pour transformer l'industrie et la société.

Face à la responsabilité de la soutenabilité des sociétés toute entière, les leviers de conception « classique », principalement portés par une *vision produit* ne suffisent pas : pour le mettre en évidence, Ceschin et Gaziulusoy (2016) [70] développent une vision socio-technique des pratiques de conception. Ces auteurs retracent une évolution des approches de conception de 1990 à 2015 traitant les trois dimensions de la soutenabilité : environnementale, économique et socio-éthique. On retrouve par exemple les premiers écrits fondateurs du *Green Design*, de l'éco-conception et du biomimétisme dans les années 1990, les approches cycle de vie (« du berceau à la tombe » du produit, *cradle-to-grave* en anglais), et conception systémique (produit-service) dans les années 2000. A partir des années 2010, Ceschin et Gaziulusoy identifient le développement de la conception pour les transitions soutenables (*design for sustainability transitions* en anglais). Dans ces travaux, les différentes approches de conception sont positionnées les unes par rapport aux autres sur deux axes d'étude : l'échelle systémique du problème de conception (axe des ordonnées) et le type d'approche développée pour y répondre (axes des abscisses). Ces deux échelles s'appuient sur cinq niveaux de système, répartis entre le niveau du matériau (le plus bas) à celui du système socio-technique (le plus haut). La **Figure 1.4** présente une version actualisée de ce cadre publiée en 2019 [71]. Les cinq niveaux de système sont représentés par des cadres imbriqués les uns dans les autres. Les auteurs ont complété cette structure avec un sixième niveau qui correspond à l'échelle des phénomènes bio-physiques présentés dans l'introduction

(*socio-technical system level* en anglais). L'intérêt de cette représentation sur deux axes est double : présenter une revue des approches de conception liées à la soutenabilité, et montrer le besoin d'étendre le domaine de compétence des concepteurs en terme d'échelle et de discipline scientifique.

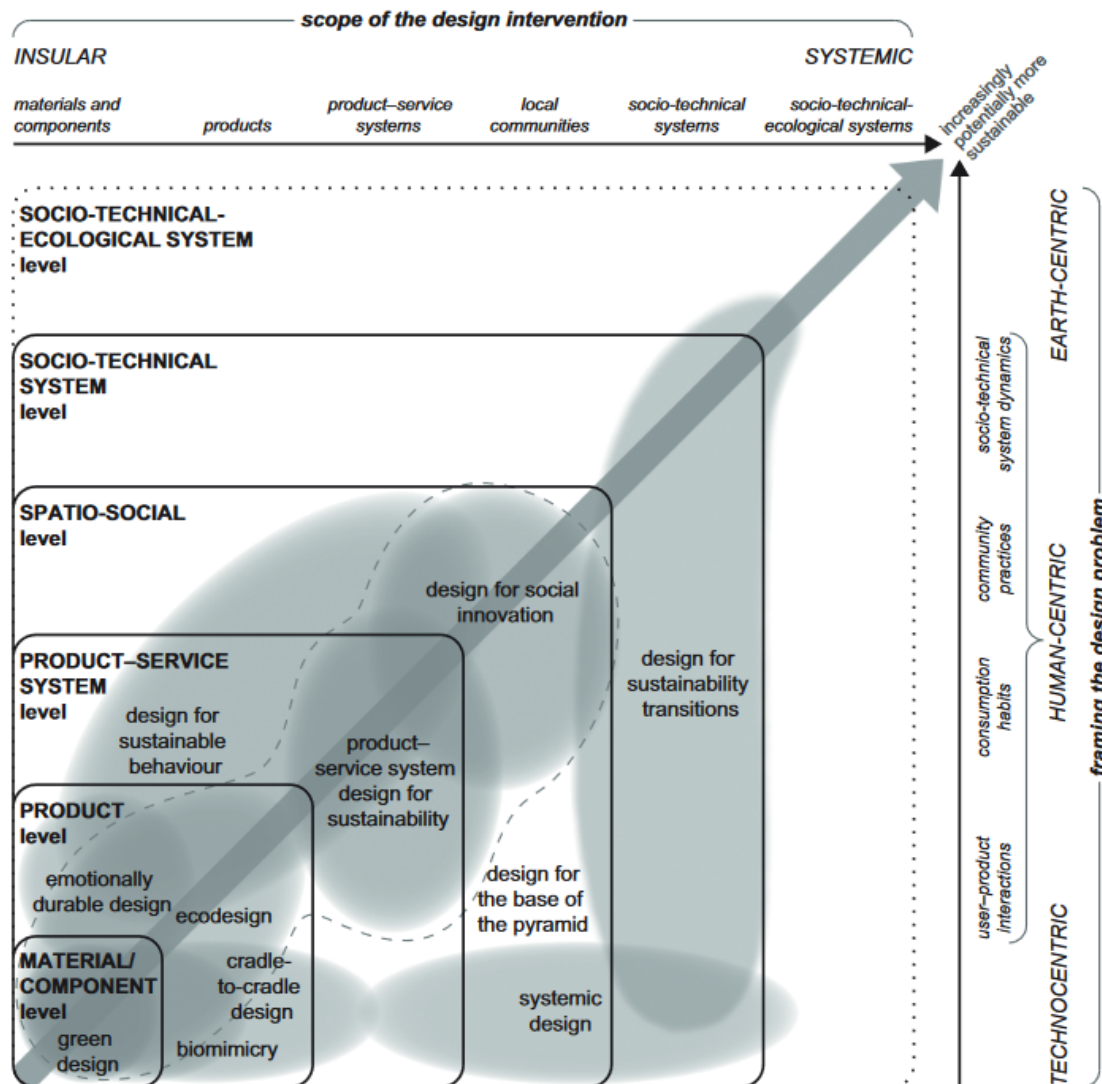


**FIGURE 1.4** – Cadre socio-technique pour une conception systémique et positionnement des approches de conception pour la soutenabilité, présenté par Ceschin et Gaziulusoy en 2019 [71].

De façon rétrospective, cette cartographie met en lumière la focalisation des approches de conceptions classiques (1990 à 2000) et d'ingénierie cycle de vie (*Life Cycle Engineering* en anglais) (2000 à 2010) sur une échelle produit et composant. L'éco-conception y est par exemple positionnée à l'échelle du produit, à coté d'une vision cycle de vie. Dans cette représentation, ces approches sont techno-centrées, ce qui sous-entend que les

interactions humain-technologie étaient historiquement faiblement prisent en compte. A noté que les contours de ces approches ne sont pas figés dans le temps : ils dépendent principalement des pratiques des acteurs qui s'en revendiquent. Autrement dit, l'éco-conception peut par exemple pour certains acteurs se limiter à un choix de matériaux et pour d'autres déjà intégrer des problématiques socio-techniques ou même tendre vers l'intégration en conception d'une vision centrée sur le système Terre (*Earth-centric* en anglais). Le but de cette représentation est donc moins de positionner « dans l'absolu » les approches de conception, mais plutôt de discuter leurs zones d'influence relatives.

Le second intérêt de la **Figure 1.4** est de situer un manque à combler vers une vision systémique et socio-technique de la conception pour la soutenabilité. Les auteurs insistent sur le fait qu'une vision systémique est nécessaire, mais que si elle porte uniquement sur les aspects techniques cela reste insuffisant pour traiter les problématiques liées à une transition vers la soutenabilité à l'échelle de la société. A l'inverse, Ceschin et Gaziulusoy montrent la nécessité d'une science de la conception pour les transitions soutenables qui permettrait de traiter l'échelle d'un système socio-technique. Les auteurs proposent le terme de « conception pour les transitions soutenables », *Design for Sustainability Transitions* (DfST) en anglais. Les fondements d'une telle approche s'appuient sur les développements de nombreux auteurs présentés en **Figure 1.5**.

| Contributions                                                                                       | Theoretical Foundations                                                                                                                                                                                                                                                |
|-----------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Gaziulusoy [19]; Gaziulusoy, Boyle and McDowall, [23]; Gaziulusoy and Brezet [28]                   | Sustainability science; complex adaptive systems; system innovations and socio-technical transitions theories; futures studies (scenarios); product development; business strategy                                                                                     |
| Joore [20]; Joore and Brezet [32]                                                                   | Industrial design; systems engineering; sustainable product development; system innovations and socio-technical transitions theories                                                                                                                                   |
| Ceschin [22,24,25]                                                                                  | Product-service systems; strategic design; system innovations and transitions theories; strategic niche management                                                                                                                                                     |
| Kossoff [21]; Kossoff, Tonkinwise and Irwin [34]; Irwin [29,30]; Irwin, Tonkinwise and Kossoff [31] | Chaos and complexity theory; Goethean science; holism; needs theory; everyday life discourse; indigenous knowledge; post-normal science; social psychology; social practice theory; alternative economies; socio-technical system innovations and transitions theories |
| Heiskanen et al. [26]; Hyysalo, Johnson and Juntunen [37]                                           | User innovation in transitions                                                                                                                                                                                                                                         |

**FIGURE 1.5** – Principaux contributeurs et concepts associés à la conception pour la soutenabilité des transitions, capture d'écran extraite de Ceschin et Gaziulusoy (2019) [71].

En synthèse, la critique du concept de « transition énergétique » avancée notamment par Jean-Baptiste Frescoz [65] et la cartographie des approches de soutenabilité en conception de Ceschin et Gaziulusoy [71] montre :

- une nécessité de questionner les concepts par la confrontation aux réalités phy-



siques et pratiques des acteurs concernés.

- que de nombreuses approches socio-techniques et systémiques sont en développement (Cf. DfST) et de nouvelles approches manquent pour traiter la soutenabilité en conception en lien avec l'échelle du système écologique (*socio-technical ecological system* en anglais).

## 1.2 Besoins en conception intégrée pour le changement d'échelle de technologies

Afin de répondre aux enjeux de société actuels et futurs, il est souhaitable de pouvoir identifier ce qui fait la soutenabilité d'une technologie durant sa phase de conception, c.-à-d. avant sa phase d'industrialisation. Cela permettrait d'éviter alors d'utiliser du temps et des moyens pour une technologie qui s'avèrerait non-soutenable. Dekoninck et al., (2016) démontre que le manque de connaissances de l'équipe de conception est un des freins pour la mise en œuvre de l'éco-conception [72]. Pour beaucoup de concepteurs, intégrer, même au niveau du composant, une analyse des aspects sociaux et environnementaux reste difficile. Il y aurait ainsi une forme de scission entre les experts de la soutenabilité (e.g. les auteurs cités en **Figure 1.5**) et les concepteurs. En ce sens, Hofmann et al. (2018) [73] reconnaît que les ingénieurs et concepteurs en sciences des matériaux sont peu investis sur les problématiques politiques et environnementales associées à leur objet d'étude.

Par ailleurs, les moyens mis en œuvre en ingénierie pour analyser la soutenabilité sont souvent problématiques du fait de leur superficialité ou d'un choix inapproprié de méthode.

Pour illustrer cette superficialité, les scénarios de déploiement de technologie d'énergie renouvelable [44], ou même de développement de nouveaux procédés [74] intègrent majoritairement la soutenabilité comme une variable aux cotés de variables techniques, possiblement optimisable, et ce souvent de façon mono-indicateur ( $\text{CO}_2$  *equivalent*). Cela contrevient à l'idée de soutenabilité puisqu'elle suppose plusieurs dimensions non-équivalentes (Cf. limites planétaires) et implique donc une approche multicritères. De plus, la littérature en éco-conception documente la difficulté de choix de méthode [72], [75]-[77]. Les concepteurs doivent pouvoir identifier les analyses et indicateurs pertinents pour étudier la soutenabilité de leurs solutions. Cela inclut les analyses environnementales, mais aussi des métriques reflétant des aspects socio-techniques (e.g. criticité des matières premières). Par conséquent, les difficultés de choix de

méthode de conception sont exacerbées dans le cas du changement d'échelle du fait de son manque de définition en tant que phénomène et de ses implications en termes de soutenabilité. Ces éléments dressent pour les concepteurs un besoin d'analyses sociales, politiques et environnementales de leur objet d'étude accompagnés de méthodes et d'indicateurs appropriés.

Pour résumer, ce chapitre a mis en évidence la non-soutenabilité des sociétés modernes. La conception de technologie est mise en avant pour supporter des transitions écologiques. Il est demandé aux concepteurs, en s'inscrivant dans des scénarios de transitions, de favoriser le « changement d'échelle de technologies émergentes ». Les concepteurs, pour le traiter, se doivent d'adopter des approches 1) de soutenabilité environnementale multicritères, 2) prospectives, 3) systémiques et 4) socio-techniques. Cependant les critères de choix de méthode et l'expertise nécessaire pour adresser ces quatre caractéristiques peuvent manquer aux concepteurs de technologies émergentes.



## 1.3 Plan du manuscrit

Le chapitre présent a introduit les besoins en conception intégrée pour le changement d'échelle de technologie émergente. La thèse comporte 10 chapitres.

Le **chapitre 2** présente les deux hypothèses de travail de la thèse, c.-à-d. le fondement de notre approche de recherche.

Le **chapitre 3** formalise la question de recherche ainsi que les trois verrous adressés dans cette thèse. Ce chapitre présente également les trois propositions développées pour répondre à la question de recherche.

Le **chapitre 4** présente et justifie les choix des méthodologies de recherche utilisées pour construire les propositions afin de répondre à la question de recherche principale.

Le **chapitre 5** synthétise les apports scientifiques étayant les trois propositions de la thèse. La thèse étant une *thèse par articles*, cinq articles de journaux et trois articles de conférences ont été rédigés et/ou soumis pour communiquer nos apports. Les chapitres 4 (méthodes) et 5 (résultats) dressent des liens avec les articles approfondissant les éléments de méthodologie ou les résultats de recherche.

Les **chapitres 6, 7 et 8** constituent le coeur du manuscrit en regroupant les huit articles en fonction des trois formes de contributions : conceptuels, méthodologiques et opérationnels.

Le **chapitre 9** introduit une discussion critique sur l'ensemble des travaux et dresse les perspectives de recherche selon deux axes : 1) les usages potentiels des archétypes de changement d'échelle en science de la conception, et 2) les pratiques de l'ACV en conception pour la soutenabilité environnementale.

Enfin, le **chapitre 10** synthétise et conclut sur la thèse.

# 2

## Positionnement et hypothèses de travail

### Sommaire

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La thèse comme introduit dans le précédent chapitre, contribue à l'intégration en conception de la soutenabilité environnementale. Elle vise à développer une pratique de la conception pour un changement d'échelle soutenable de technologies émergentes. Afin d'adresser cet objectif et d'orienter notre travail de recherche, nous nous appuyons sur deux hypothèses de travail qui sont présentées dans le présent chapitre : 1) L'ACV est considérée comme un vecteur d'intégration en conception de la soutenabilité environnementale, 2) le questionnement des concepts associés aux changement d'échelle de technologie émergente peut permettre de formaliser les phénomènes à prendre en compte dans l'ACV. Ces hypothèses permettent d'identifier trois verrous principaux qui seront affinés aux chapitre 3.

## 2.1 Conception intégrée, ACV et soutenabilité environnementale

Nos travaux s'attachent à identifier les moyens d'intégrer l'analyse de la soutenabilité environnementale, c.-à-d. les aspects environnementaux de la soutenabilité, en conception. Dans un soucis de lisibilité, les termes *soutenabilité environnementale* peuvent parfois être substitué par *soutenabilité*.

### 2.1.1 Conception intégrée et éco-conception

La conception intégrée est définie par l'intervention d'acteurs et d'expertises dans le processus de conception d'un système (e.g. un produit, service). Ce processus a pour finalité d'améliorer un ou plusieurs aspects du produit fini (eg. coût, qualité, délai) [78]. Dans cette thèse, nous nous focalisons sur l'intégration en conception de la soutenabilité environnementale. Nous faisons le choix de rapprocher ce type d'intégration en conception avec l'éco-conception. Dans cette thèse, l'éco-conception est définie comme une pratique de conception intégrant les enjeux environnementaux tout au long du cycle de vie d'un système technologique dès les phases amont du processus de conception [79]. A noter que la thèse se positionne également sur la criticité des matières premières qui n'est pas considérée comme un indicateur environnemental. En revanche, cette métrique couvre des phénomènes à l'échelle du système socio-technique (Cf **Figure 1.4**). Cela rejoint la proposition de Ceschin et Gaziulusoy de considérer des échelles dépassant celle du seul produit dans le champ d'étude des concepteurs pour viser la soutenabilité. De plus, la criticité des matières premières, a

été historiquement assimilée en conception par le biais d'indicateurs sur la déplétion des ressources minières [80].

Dans ce cadre, nous nous appuyons sur le paradigme « d'équipe de conception » proposé par Brambila-Macias et Sakao (2021) s'appuyant sur la collaboration entre plusieurs profils d'experts [81]. L'équipe de conception, illustrée en **Figure 2.1**, est ainsi formée, a minima, d'un ou plusieurs experts techniques (bleu) et d'un ou plusieurs experts garant des principes d'éco-conception (vert). Les auteurs ont démontrés que cette organisation est plus efficace qu'un technicien se chargeant directement de l'éco-conception. La littérature en éco-conception de technologie en laboratoire présente cette composition d'équipe comme un cadre minimal [82]. Nous considérons ainsi que d'autres rôles peuvent être définis et d'autres expertises intégrées, comme par exemple l'ajout d'un profil de décideur attaché à la stratégie d'entreprise [83].

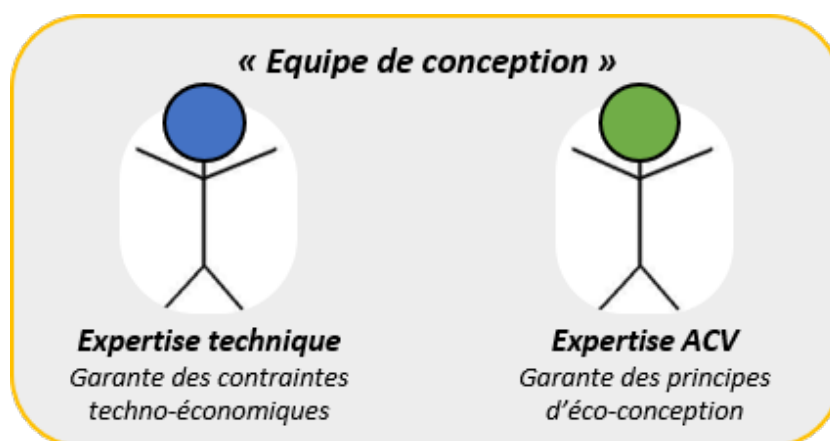


**FIGURE 2.1** – Cadre de conception intégrée minimal : une expertise technique et une expertise en analyse environnementale

Dans nos travaux, nous avons également privilégié la définition d'un « concepteur » comme un acteur du processus de conception détenant principalement une expertise technique. Le concepteur est donc assimilé à l'expert technique dans la plupart de nos écrits, en cohérence avec la littérature en ingénierie.

## 2.1.2 Eco-conception et Analyse de Cycle de Vie

L'éco-conception doit s'appuyer sur une « vision cycle de vie » selon la norme [79]. Décrite il y a 10 ans comme une méthode fastidieuse et complexe à mettre en oeuvre [77], [84], l'ACV est progressivement devenue un moyen privilégié d'appliquer cette vision cycle de vie [81].

De nombreux travaux ont été réalisés pour simplifier et/ou étudier l'accessibilité de l'ACV en conception [76], [81], [85]. Les quatre étapes de la norme [86] et leur liens d'interaction confortent l'expert cycle de vie (ou ACViste) dans une démarche réflexive (Cf **Figure 2.2**). Cette démarche est semblable à la vision classique d'un processus d'éco-conception souvent présenté comme une démarche incrémentale.

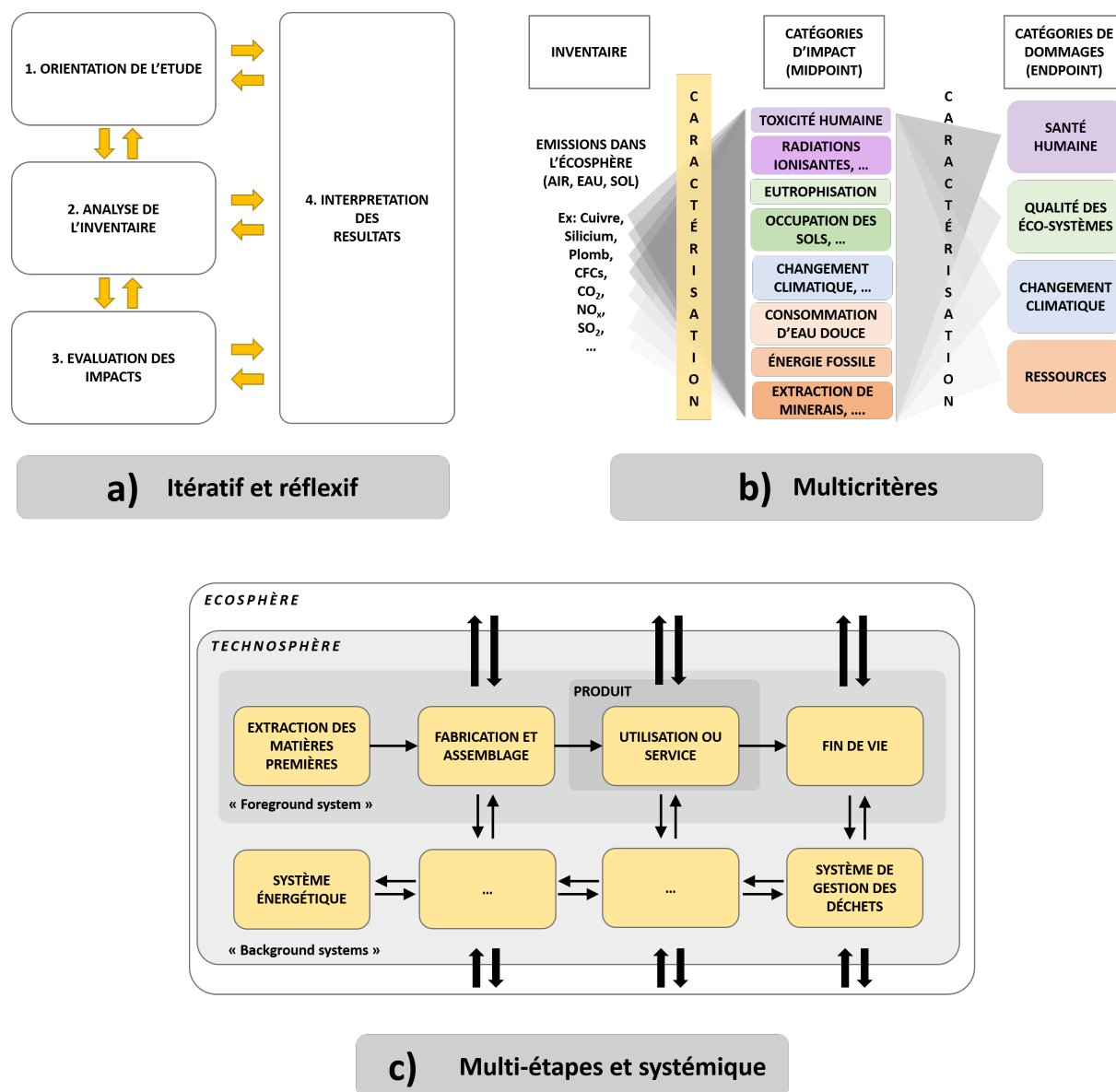


**FIGURE 2.2** – Représentations « classiques » de l'ACV : (a) les 4 étapes selon la norme ISO 14040 : 2006 [86], (b) la conversion de l'inventaire en impacts environnementaux ; et (c) les trois systèmes imbriqués de l'inventaire : le produit, le *foreground system* et les *background systems*. Adaptés de Kara et al. (2023) [87], Jolliet et al. (2003) [88] et Charbuillet (2023) [89]

Dans ce contexte, nous avons choisi d'investir la pratique de l'ACV comme un cheval de

Troie [90] afin de promouvoir une approche satisfaisant les quatre caractéristiques suivantes :

- itérative, pour s'intégrer dans une démarche réflexive,
- multicritères, pour être représentative des enjeux environnementaux,
- multi-étapes, pour être représentative des activités industrielles,
- systémique, pour considérer les liens entre produit, système industriel (voir socio-technique) et environnement.

Nous insistons sur le fait que l'aspect systémique désigne le plus souvent une approche centrée sur le « *foreground system* », c.-à-d. le système de produit sur lequel le concepteur peut agir directement, en intégrant des éléments des « *background systems* » définissant les systèmes industriels et chaînes de valeurs qui soutiennent le *foreground system* et sur lesquels le concepteur n'a pas de levier direct. La partie c) de la **Figure 2.2**) illustre une modélisation de l'inventaire de cycle de vie d'un produit comprenant un exemple pour les deux types de systèmes : le type de matière première utilisée, qui dépend du choix du concepteur, et les caractéristiques de l'énergie électrique utilisée qui dépendent du système énergétique local et donc hors du champ d'action du concepteur. Ces deux éléments sont donc catégorisés comme faisant respectivement partie du *foreground* et *background system*. En revanche il est aussi possible d'élargir la définition de systémique à une vision socio-technique promue par Ceschin et Gaziulusoy [91]. De même, l'aspect multicritères est traditionnellement associé au fait de prendre un regroupement pré-établi d'indicateurs (e.g. ReCiPe2016 midpoint [92], 18 indicateurs). En ce sens, nous désignerons par ACV une méthode mue par les quatre caractéristiques précédemment citées. Elles sont couvertes en combinant les trois représentations usuelles de l'ACV illustrées en **Figure 2.2**.

### 2.1.3 Nouvelles approches d'ACV pour la soutenabilité environnementale : AESA et ACV prospective

Pendant la première phase d'analyse de la littérature, deux formes d'ACV ont retenu notre attention : l'approche de *soutenabilité environnementale absolue* et l'ACV *prospective*.

D'une part, la proposition de l'*Absolute Environmental Sustainability Assessment* (AESA), associée aux cadre des *limites planétaires*, semblait suggérer la possibilité de caractériser la soutenabilité environnementale d'un produit de façon rationnelle et objective en s'appuyant sur des modèles scientifiques. Pigosso et al. [77] identifiait en

2015 dans une revue de la littérature en éco-conception le challenge que serait l'intégration en conception des limites planétaires. D'autre part, un groupe de chercheurs en ACV autour de l'ETH de Zûrich (Bernard Steubing, Christopher Mutel et Stephanie Hellweg, Romain Sachi) promouvait l'idée dès 2015 qu'il devenait possible de simuler des impacts environnementaux d'un produit qui n'existerait pas encore, sur la base d'inventaires scénarisés [93], [94].

Ces deux approches, AESA et ACV prospective, sont relativement récentes au regard de l'histoire de l'ACV. Elles sont apparues après 2015, et comme nous le verrons dans la thèse, sont par conséquent encore à éprouver sur certains aspects méthodologiques et opérationnels. Nous avons cependant fait le choix de nous appuyer dessus pour investir de nouveaux leviers d'éco-conception de produits ou du moins de challenger les pratiques « classiques » appuyées sur l'ACV au regard des défis posés par la prise en compte du changement d'échelle.

En synthèse, nous formulons l'hypothèse que l'ACV est une méthode d'analyse de la soutenabilité environnementale (multicritères, systémique). De plus, nous comptons sur l'ACV (multicritères, itérative/réflexive) en tant que vecteur d'intégration de la soutenabilité environnementale dans la conception de technologies émergentes.

## 2.2 De la nécessité de travailler les concepts pour une meilleure intégration en conception

La deuxième hypothèse de travail de la thèse est qu'il est nécessaire de se donner une définition des concepts mobilisés dans le cadre de la thèse. Cette orientation permet d'une part de se reposer sur des travaux de recherche amont et de circonscrire le champ de recherche par des caractéristiques claires (e.g. groupe d'auteurs travaillant sur le sujet, disciplines scientifiques mobilisées). D'autre part, cette hypothèse de travail permet d'identifier les concepts qui n'ont pas de définition explicite et les dissocier des autres, mieux structurés. En l'occurrence, un concept mal défini, limite son étude rigoureuse par les communautés de conception. Pour un concepteur travaillant sur un concept sans définition homogène, les méthodologies permettant l'étude ou l'anticipation du phénomène associé à ce concept sont difficilement identifiables. Cela peut sembler trivial, mais comme nous le verrons, les concepts de *changement d'échelle* et de *technologie émergente* sont mal définis dans la littérature scientifique.

En première lecture, et malgré leur présence récurrente dans les communications scientifiques, les termes « changement d'échelle » et « technologie émergente » ne

semblent pas faire référence à un phénomène unique. Par exemple, dans le secteur de l'énergie électrique, la conception et l'étude des composants électroniques, des systèmes embarqués, des réseaux électriques de transport ou de distribution présentent autant d'objets faisant appel à la notion d'*échelle* (spatiale, temporelle, de productivité et/ou d'efficacité, etc). De même pour la qualification de l'*émergence* d'une technologie qui peut évoquer la nouveauté en soi d'un système technique, au même titre que des questions sur un impératif à faire émerger des technologies particulières.

Ainsi, le changement d'échelle renvoie à des pratiques de conception de technologie, et embrasse des aspects de maturité technologique, d'industrialisation, de déploiement dans la société (socio-technique), de *prospective* et parfois de soutenabilité.

En anglais, le terme de « changement d'échelle » présente plusieurs traductions possibles en lien avec l'échelle (*scale*). La **Figure 2.3** présente un aperçu d'une première étude de la littérature scientifique avec des mots clefs tels que *upscaling*, *scaling-up*, *scaling*, *deployment*.

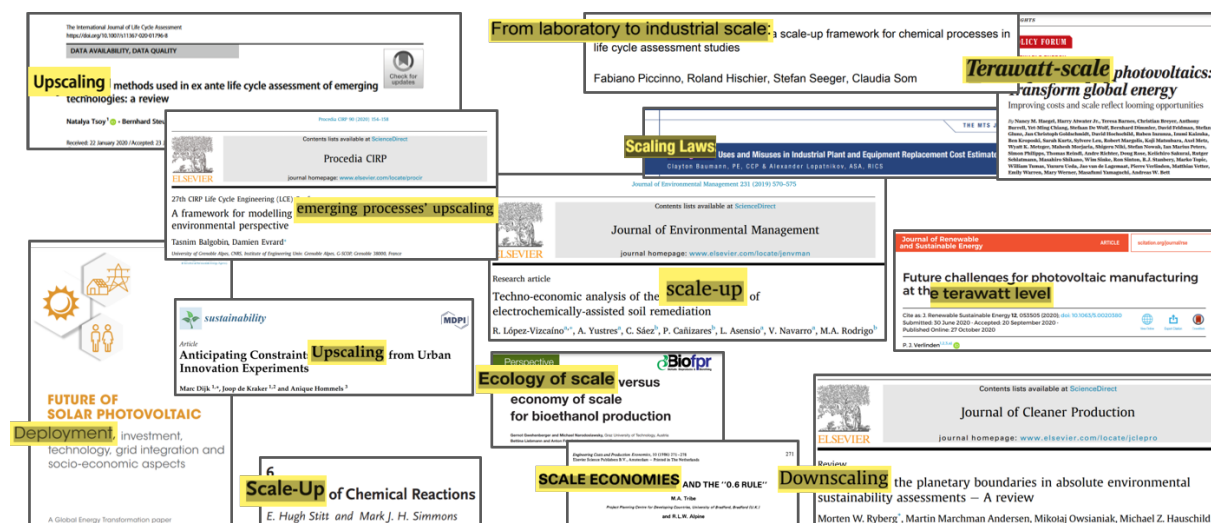


**FIGURE 2.3** – Visualisation d'une sélection de références bibliographiques identifiées au début de la thèse faisant référence au changement d'échelle.

Cette figure sert d'illustration pour montrer que : 1) plusieurs types de littérature et de domaines scientifiques se réfèrent au changement d'échelle ou à des termes associés : ce sont des documents académiques mais également des rapports d'entreprises ou d'institutions nationales ou internationales. 2) Ce qui est entendu par « changement d'échelle » est rarement défini. 3) Les domaines et phénomènes couverts (mal délimités et décrits partiellement) étant vastes, les approches et méthodes pour traiter le changement d'échelle sont variées. Elles ne traitent pas systématiquement de l'analyse de la soutenabilité environnementale des technologies.



Ces premiers éléments font l'effet de *buzz-words* ou de *mots-valises* utilisés pour désigner des préoccupations d'organismes, d'entreprises et de laboratoires de recherche à priori réelles sans pour autant permettre d'identifier s'il s'agit de nouvelles thématiques ou d'une réactualisation de travaux et d'expertises établies sous un terme « novateur » ou « à la mode » tels que *systémique*, *durable*, *circulaire* ou encore *résilient*.

Notre hypothèse de travail est donc de considérer qu'il est pertinent, pour traiter la soutenabilité en conception, de questionner, au préalable, le sens et la spécificité que les sciences industrielles et de la conception donnent à l'aphorisme *changement d'échelle de technologie émergente* puis d'identifier les méthodes d'analyse sous-jacentes.

### 2.3 Hypothèse générale de travail

Il apparaît donc clairement que la formule « changement d'échelle de technologie émergente » peut véhiculer différents sens selon le profil de l'interlocuteur (e.g. chercheur, ingénieur, planificateur) et son secteur d'ingénierie (e.g. énergie, chimie, bâtiment). Nous considérons nécessaire, pour appréhender les phénomènes associés au changement d'échelle de technologie, d'adopter une vision trans-sectorielle en science de la conception, c.-à-d. appuyée sur une expertise en ingénierie généraliste (génie mécanique, électrique et électrotechnique, génie des procédés, etc). En parallèle, dans un contexte d'intégration en conception, les apports attendus se positionnent à l'interface entre cette vision trans-sectorielle et la vision concepteur (*design thinking* en anglais). Autrement dit, la thèse s'inscrit dans la recherche d'un équilibre entre une spécialisation sur des phénomènes socio-techniques et l'identification d'éléments minimaux mais suffisants pour en traiter la complexité en conception. Cette orientation est portée par les deux équipes de recherche associées à la thèse : l'équipe *COncception SYStémique : Humain, Environnement, Technologies* (COSYS) du laboratoire **G-SCOP** de Grenoble et l'équipe *Ingénierie Mécanique et Conception* (IMC) de l'**institut Arts et Métiers** de Chambéry rattaché à l'**Institut de mécanique et d'ingénierie** (I2M) de Bordeaux. Ces deux équipes ont profité aux travaux de recherche sur le changement d'échelle en interrogeant régulièrement sur le « quoi intégrer », « dans quel objectif » et « comment ». Le besoin de réduire l'écart entre les approches actuelles (souvent mono-indicateur, peu-systémique et/ou peu anticipative) et les développements d'analyses environnementales « avancées » a donc été interrogé à la lumière de l'expertise et des pratiques en conception intégrée et en éco-conception. Cela a conditionné une démarche d'aller et retour entre des approches expertes, et une pratique de la conception adossée à des

lignes directrices et à des paramètres nécessaires et minimaux à prendre en compte. Nous synthétisons le positionnement et les hypothèses de travail de la thèse par la formulation suivante :

**« L'Analyse de Cycle de Vie (ACV) peut être un vecteur d'intégration en conception pour analyser la soutenabilité environnementale du changement d'échelle d'une technologie émergente ».**

Pour finir, cette thèse est en partie un travail de recherche exploratoire car elle vise à dresser les contours du changement d'échelle en conception. Le titre « **vers** l'éco-conception de technologie émergente » indique que les travaux n'ont pas l'ambition d'épuiser définitivement le sujet mais plutôt d'ouvrir le champ interdisciplinaire de l'éco-conception de technologies émergentes. Ces discussions scientifiques initiées pourraient ainsi donner lieu à de nouveaux projets de recherche comme discuté dans le **chapitre 9**.

Pour résumer, ce chapitre a permis de détailler le cadre de travail de la thèse. Ainsi, les travaux de la thèse se positionnent dans la conception intégrée pour la soutenabilité et s'appuient sur deux hypothèses : 1) L'ACV est considérée comme un vecteur d'intégration de la soutenabilité environnementale en conception, 2) le questionnement des concepts associés au changement d'échelle de technologie émergente peut permettre de formaliser les phénomènes à prendre en compte dans l'ACV. Ces deux hypothèses étant liées, elles ont été regroupées en une seule hypothèse de travail. Ce positionnement permet d'adresser l'hypothèse à tester suivante « il est possible via une méthode fondée sur l'ACV d'aider les concepteurs à intégrer en conception la soutenabilité du changement d'échelle d'une technologie émergente ». Le chapitre suivant formalise la question de recherche et les axes de recherche pour tester cette hypothèse.

# 3

## Questions de recherche, verrous et propositions

### Sommaire

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Ce chapitre a pour but de formaliser les questions de recherche et verrous associés, et les axes de travail de la thèse pour y répondre. La thèse étant une thèse par articles, les axes de recherche sont adossés à trois articles de conférences et cinq articles de journaux. Le présent chapitre ainsi que les **chapitres 4, Méthodes de recherche** et **5, Synthèse des apports de la thèse** présentent par conséquent une vue d'ensemble des travaux de recherche et redirigent vers la ou les publications sur des points précis. En complément, l'**Annexe A.1** synthétise la stratégie de communication scientifique des apports de la thèse à la date du 10 Octobre 2024.

### 3.1 Formalisation des axes de recherche

L'hypothèse investie dans cette thèse est qu'il est possible d'aider les concepteurs à intégrer la soutenabilité en conception du changement d'échelle d'une technologie émergente. La Question de Recherche (QR) qui en découle et qui structure l'ensemble des travaux de recherche est :

**QR : « Comment aider les concepteurs à prendre en compte le changement d'échelle de technologies émergentes dans une approche de soutenabilité environnementale ? ».**

Afin de répondre à cette question de recherche, nous avons identifié trois formes de contributions : conceptuel, méthodologique et opérationnel. Les deux premières formes traitent des aspects théoriques de la question de recherche, c.-à-d. les difficultés de définition et d'étude d'un phénomène donné. Le troisième constitue des éléments de blocage empêchant la mise en pratique des résultats de thèse dans un contexte de conception intégrée. A partir du contexte présenté en **chapitre 1** et **2**, et des états de l'art détaillés dans les publications nous proposons dans ce chapitre d'explicitier les trois verrous de recherche adressés dans la thèse. Une ou plusieurs questions de recherche découlent de ces verrous. Chacun des trois verrous est couvert par une *proposition* dont la méthodologie est détaillée dans le **chapitre 4**. Ainsi la thèse est structurée par trois axes de recherche, définis par un verrou, des questions de recherche et une proposition pour y répondre.

Les axes de recherche conceptuel, méthodologique et opérationnel de la thèse répondant ensemble à la question de recherche principale sont ainsi respectivement formalisés dans les **sections 3.1.1, 3.1.2 et 3.1.3**.

### 3.1.1 Verrou 1 : Le *changement d'échelle* et *technologie émergente* sont des termes polysémiques en ingénierie

Ainsi, l'analyse préliminaire de la littérature nous a permis de constater qu'il n'y a pas de convergence vers une définition homogène du ou des phénomènes de *changement d'échelle* en science de la conception. Ce constat est détaillé dans l'**Article de conférence 1** publié en 2022 (Cf. **chapitre 6, section 6.1**). De plus, ce qu'est une « *technologie émergente* » est également discuté en ingénierie et en planification industrielle. L'état de l'art couvrant ce sujet est présenté dans l'**Article 1** (Cf. **chapitre 6, section 6.2**). Ces deux concepts présentent à première vue différentes connotations plus ou moins assimilées à une pratique de conception.

La polysémie du changement d'échelle de technologie dans les communautés de concepteurs rend ainsi difficile l'identification des leviers de conception sur les aspects environnementaux. Ce verrou est considéré comme conceptuel puisqu'il fait référence à une problématique de caractérisation de concept et des phénomènes qui y sont associés. Nous l'avons nommé « verrou 1 » et rattaché à la question de recherche suivante :

**QR1.1 : « comment caractériser le changement d'échelle de technologies émergentes dans les communautés de conception ? ».**

Pour répondre à cette question et lever le verrou 1, nous avons proposé d'établir un **cadre de caractérisation du changement d'échelle en science de la conception**. Ce cadre de caractérisation s'appuie sur l'identification d'éléments communs à différentes communautés de conception utilisant des termes dérivées du changement d'échelle afin d'en extraire une généricité.

Cette approche, nommée « approche par invariant » dans nos travaux, est adossée à une méthodologie de revue de la littérature détaillée dans l'**Article 1** (6.2) et justifiée dans le **chapitre Méthodes de recherche, section 4.1.1**). La proposition 1 consiste ainsi en un cadre de caractérisation qui permet la collecte, l'explicitation et la production de définitions du *changement d'échelle* pour la science de la conception. En parallèle, les définitions de *technologie émergente* sont collectées par revue de la littérature et étudiées en relation avec celles du changement d'échelle.

La proposition conceptuelle permettant de lever le verrou 1 s'appuie donc sur deux apports : 1) un cadre théorique permettant la caractérisation de cinq définitions du changement d'échelle, aussi appelés « archétypes », 2) la caractérisation de l'articulation entre les concepts de « changement d'échelle » et de « technologie émergente ». Comme nous le verrons par la suite, les cinq archétypes de changement d'échelle

occupent une place centrale dans la thèse en permettant de regrouper un grand nombre d'analyses derrière des termes bien identifiés.

### 3.1.2 Verrou 2 : La multiplicité des méthodes disponibles pour analyser la soutenabilité environnementale d'un changement d'échelle rend difficile les choix pertinents des concepteurs vis-à-vis de leur objet et objectif d'étude

Les équipes de conception, dans une démarche d'éco-conception, peinent à identifier les approches et méthodes d'analyses et d'indicateurs adaptés [75], [81]. Nous avons pu démontrer dans le prolongement de la levée du verrou 1, que cette problématique se vérifie pour l'étude, par des concepteurs, du changement d'échelle de technologie. En effet, l'**Article 1** (6.2) traite aussi la question de recherche : **QR2.0 : « Quelles sont les pratiques, méthodes et recommandations pour analyser le changement d'échelle d'une technologie émergente dans une perspective d'intégration en conception ? »**. Un travail de revue de la littérature en ingénierie et en conception a permis de recenser un grand nombre de méthodes techno-économiques (TEA en anglais) pour analyser ou anticiper le changement d'échelle. Un travail similaire de veille pour les approches d'ACV a mis en évidence une faible porosité entre les approches classiques de conception pour le changement d'échelle et les approches d'analyse environnementale quantitative. Concrètement, peu d'approches d'ACV sont directement associées à l'étude d'une technologie en amont du processus de conception : van der Giesen et al. (2020) présentent une revue des caractéristiques de cette approche d'ACV [95]. Ils regroupent notamment les modes d'ACV *ex-ante* [82], [96], *anticipatory* [97] et *prospective* [98], [99] comme étant différents termes se référant à la même pratique. Ce sont en effet les premières approches à émerger pour des recherches avec les mots clefs « LCA » et « emerging technology ». En revanche, plusieurs autres modes d'ACV ne sont pas référencés comme faisant partie de cette littérature mais semblent partager des caractéristiques avec les TEA pour le changement d'échelle. Par exemple, l'ACV territorialisée [100] et de transition [101] n'émergent pas avec des recherches par mots clefs associés au changement d'échelle. Pourtant ces approches adoptent des visions systémiques et sectorielles compatibles avec l'analyse de la soutenabilité d'un changement d'échelle. De même, l'AESA comme nouvelle approche d'analyse de la soutenabilité (Cf **section 2.1.3**) est également assez peu associée aux définitions du changement d'échelle identifiées en science de la conception. Par extension, les modes

d'ACV *consequentielle, simplifiée, paramétrée, dynamique, regionalisée* et *spatialisée* sont également des approches mal connues des concepteurs et donc peu identifiées comme pertinentes dans leur recherche de méthodes d'analyse. L'état de l'art sur 15 modes d'ACV compatibles avec l'analyse du changement d'échelle est détaillé dans la première partie de l'**Article 2** (7.1), selon leurs objet et objectif d'étude.

Ces éléments étayent ce que nous avons identifié comme un deuxième verrou : une problématique d'identification de méthode adaptée pour les concepteurs par rapport à leur objet et objectif d'étude. Par conséquent, en accord avec nos hypothèses de travail, nous avons proposé d'orienter le choix de méthode de conception soutenable par un cadre et une méthode de prise en compte du changement d'échelle intégrée dans une approche ACV. Cette proposition conduit à traduire le verrou 2 par deux sous-questions de recherche QR2.1 et QR2.2. Dans un premier temps, le verrou 2 est associé à la sous-question de recherche suivante :

**QR2.1 : « comment l'ACV permet d'analyser ou anticiper le changement d'échelle d'un point de vue environnemental ? »**

Les archétypes de changement d'échelle constituent une grille de lecture de la littérature : ils permettent de rapprocher les méthodes en science de la conception et celles en analyse environnementale sur la base des mêmes critères d'objet et d'objectif d'étude. Ainsi, la question QR2.1 a été traitée en développant un cadre, par archétype, de recommandations pour les équipes de conception afin d'analyser avec un ou plusieurs modes d'ACV le changement d'échelle d'une technologie. Ce cadre formalise les besoins méthodologiques, recommandations et modes d'ACV pertinents pour analyser environnementalement un archétype de changement d'échelle parmi les cinq identifiés. Un choix de méthode est dit *pertinent* lorsqu'il conduit à une analyse minimale sans faire de transfert d'impact, et/ou sans négliger de partie significative du système dont on souhaite analyser les implications environnementales. Les travaux associés à cet apport, nommé « apport 3 », sont détaillés dans l'**Article 2** (Cf. **chapitre 7, section 7.1**). L'apport 3 est ainsi considéré comme un apport méthodologique car 1) il synthétise les méthodes existantes et pertinentes, 2) il aide au choix de méthode sur la base de recommandations. Cependant, le cadre d'ACV par archétype s'adresse en premier lieu à des praticiens de l'ACV (ACVistes). En cela, l'apport 3 n'est pas explicitement et exclusivement inscrit dans une perspective d'intégration en conception. Le verrou 2 n'est donc pas complètement levé par le développement du cadre d'ACV par archétype. Une seconde question de recherche a été formulée en ce sens afin que son traitement permette la levée du verrou 2 :

**QR2.2 : « Comment conduire une ACV avec une approche par archétype dans un contexte d'éco-conception ? »**

Le contexte d'éco-conception fait référence ici à l'hypothèse de travail qu'une équipe de conception est un lieu d'interactions entre des expertises techniques et une expertise en ACV. L'apport 3 ne garantissant pas ces interactions, nous proposons de développer une méthodologie spécifique. La méthodologie *Environmental Assessment for Upscaling* (EAU) a donc pour objectif de concaténer le cadre d'ACV pour une équipe de conception. Elle offre, en fonction des objectifs d'étude de l'équipe, une structure permettant l'intégration de la soutenabilité environnementale dans un projet de conception. Cela se traduit par une modélisation minimale à respecter pour prendre en compte le changement d'échelle. De plus, le processus EAU propose une coordination des expertises entre expert technique, expert ACV et manager de l'entreprise pour la collecte de données et la formulation d'hypothèse de modélisation. Les travaux associés à cet apport, nommé « apport 4 », sont détaillés dans l'**Article 3** (Cf. **chapitre 7, section 7.2**). Fort de l'apport 4, et moyennant les contraintes de modélisation, il devient possible pour l'équipe de conception de prendre en compte le changement d'échelle d'une technologie émergente avec une approche d'ACV dans sa phase de conception.

La proposition méthodologique permettant de lever le verrou 2 s'appuie donc sur deux apports : 1) un cadre d'ACV par archétype de changement d'échelle présentant des recommandations et permettant l'alignement entre les méthodologies d'ACV avec des aspects du changement d'échelle de technologie, 2) une méthodologie spécifiques (EAU) pour aider les équipes de conception à intégrer ces modes de prise en compte du changement d'échelle dans une structure agrégée.

**3.1.3 Verrou 3 : Une expertise spécifique est nécessaire pour permettre aux concepteurs d'appliquer des méthodes d'analyse du changement d'échelle.**

Dans ce troisième axe de recherche, nous nous sommes intéressés à l'opérationnalisation des concepts et méthodes développés dans la thèse dans les communautés de conception. Un travail supplémentaire est donc nécessaire pour répondre aux besoins en intégration identifiés au chapitre 1. Ces éléments supportent l'idée que certains aspects du changement d'échelle ne sont habituellement pas traités par les équipes de conception. Ce manquement est exprimé plus largement en éco-conception par Brambila-Macias et al. (2021). Les auteurs relèvent que la littérature académique en



éco-conception est focalisée sur les méthodologies et moins sur les connaissances, l'utilisation et la performance (c.-à-d. l'effectivité) [81].

En complément des besoins en conception intégrée synthétisés au chapitre 1, quatre expertises spécifiques relevant de nos travaux ont été identifiées comme critiques pour les concepteurs :

- Les archétypes de changement d'échelle sont un élément structurant de notre travail de recherche. En tant que nouveaux concepts, il est important de les rendre accessibles pour les différentes communautés de conception et secteurs d'ingénierie.
- La mise en pratique du processus EAU, sous la forme combinée d'une ACV prospective et d'AESA, peut sembler hors de portée d'une équipe de conception.
- La criticité des matières premières est un indicateur d'un phénomène couvert par l'archétype 3 (*reaching a level*). En revanche, les méthodologies d'analyse de la criticité sont cantonnées à une utilisation par des experts, et assez peu intégrées dans le processus de conception de matériaux ou de technologie [73].
- L'AESA est, comme l'analyse de la criticité, une approche qui semble réservée à des spécialistes. En effet, les auteurs ayant développé l'AESA ne s'adressent pas spécifiquement à des concepteurs de technologies. A notre connaissance au début de la thèse, il n'existait, par exemple, qu'une seule référence structurante sur l'AESA présentant une « vision produit » [102].

Nous proposons par conséquent, pour faciliter l'opérationnalisation de ces quatre expertises, de **guider les pratiques des concepteurs par des recommandations et supports dédiés**.

Chacune des quatre expertises est rattachée à un apport scientifique numéroté de 5 à 8. Ces quatre apports s'appuient sur une méthodologie de cas d'étude et d'explicitation des bonnes pratiques. L'apport 5 regroupe les illustrations, le formalisme et les outils développés dans l'ensemble des travaux pour faciliter l'adoption des archétypes par les concepteurs. L'apport 6 consiste en deux cas d'étude dans le secteur du photovoltaïque préparant et illustrant le processus EAU. Enfin, les apports 7 et 8 présentent des cas d'étude de recommandations pratiques pour le concepteur, développées à partir de l'encadrement de deux stages de recherche de six mois (Cf **chapitre 4, section 4.3.3**). L'apport 7 adresse les deux questions « *Comment la méthode d'analyse de la criticité de la commission européenne (EC RMC) est-elle adoptée dans la littérature scientifique ? et dans quelles mesure la méthode actuelle répond aux besoins des décideurs (e.g. concepteurs, chercheurs) pour estimer la criticité ?* ». Cet apport constitue une

analyse de l'adoption de la méthode européenne d'analyse de la criticité des matières premières (EC-RMC) dans les communautés de chercheurs. Il développe un cadre pour non-spécialistes d'identification de l'alignement entre leurs objectifs d'analyse et celui de la méthode EC-RMC. Enfin, l'apport 8 répond à la question « *Comment sensibiliser les concepteurs de produits aux principes de partage ?* » en proposant une méthode pas à pas appliquée à un cas d'illustration dans le secteur de l'électronique de puissance. Des recommandations pour non-spécialistes sont également faites. Ces deux derniers apports sont considérés comme des résultats de recherche d'approfondissement sur les archétypes 3 et 5.

En synthèse, la proposition opérationnelle permettant de lever le verrou 3 s'appuie donc sur quatre apports : 1) des supports ludiques pour présenter les archétypes et utiliser le cadre d'ACV dans un contexte de conception, 2) une application du processus EAU sur un cas d'étude choisi (photovoltaïque), 3) une grille d'analyse pour l'application de méthode d'analyse de la criticité en conception, 4) des recommandations appuyées par un cas d'étude étape par étape sur un système électronique.

## 3.2 Articulation des axes de recherche

### 3.2.1 Interactions entre verrous de recherche

Les trois verrous identifiés formalisent trois axes de recherche. La catégorisation proposée (conceptuel, méthodologique ou opérationnel) permet de distinguer différentes formes d'apports scientifiques pour lever les verrous de recherche. Ils portent à la fois 1) sur le positionnement en tant que concepteur vis à vis du changement d'échelle d'une technologie émergente, 2) sur les pratiques courantes de conception associées, 3) sur l'intégration de nouvelles pratiques de conception pour la soutenabilité environnementale.

Comme présenté dans les **chapitres 1 et 2**, ces trois verrous s'articulent entre eux : Sans définition explicite, pas de méthodes clairement identifiées. La levée du verrou 1 est donc nécessaire pour lever le verrou 2. De même, sans avoir préalablement identifié les méthodes pertinentes, il n'est pas possible de considérer les aspects que les équipes de conception ne traitent pas et/ou devraient traiter.

Les interactions entre verrous de recherche ont abouti à des axes de recherche interdépendants. Les apports scientifiques pour lever les deux premiers verrous (conceptuel et méthodologique) s'alimentent en cascade, de la levée du verrou 1 vers le verrou 3. En revanche la levée du verrou 3 (opérationnel) constitue un axe transverse de recherche.

Les contributions associées ont influencé les apports des autres axes de recherche.

### 3.2.2 Synthèse illustrée des travaux de recherche

la **Figure 3.1** synthétise la formalisation des axes de recherche : elle organise les travaux réalisés pour répondre à la problématique de la thèse autour des trois verrous identifiés (encadrés gris). Chaque verrou a mené à un ou plusieurs travaux regroupés en une *proposition* (encadré bleu) soutenue par une méthodologie de recherche (encadré blanc). Ces éléments sont détaillés dans le **chapitre 4, Méthodes de recherche**. Comme mentionné dans les sections précédentes, les apports de la thèse participent à lever les trois verrous numérotés de 1 à 8 (encadrés en jaune) et sont détaillés au **chapitre 5, Synthèse des apports de la thèse**.

Le lien entre les verrous 1, 2 et 3 n'est pas représenté sur cette figure. Cependant son sens de lecture (de haut en bas) sous-entend que les apports permettant de lever un verrou contribuent à mieux étayer le verrou suivant, et servent de base pour les apports suivants. Par exemple, le *cadre des cinq archétypes* (apport 1) et la *caractérisation des interactions entre concepts* (apport 2) ont permis d'identifier le verrou 2 et de constituer la base du *cadre d'ACV par archétype* (apport 3). La relation entre les apports 3 et 4 est représentée par la flèche qui les relie. Ce point sera détaillé dans le **chapitre 5**. A noter que cette logique ne respecte pas entièrement l'ordre chronologique de réalisation et de publications des travaux de recherche. Le développement de la méthodologie EAU (Apport 4) et sa mise en pratique (Apport 6) ont par exemple été réalisés en parallèle. Nous reviendrons également sur ce point dans le **chapitre 5**.

Nous recommandons d'utiliser la **Figure 3.1** comme guide de lecture de la thèse. Une copie est disponible en **Annexe A.3**.

Pour résumer, ce chapitre a formulé la question de recherche de la thèse et formalisé les trois axes de recherche développés pour y répondre. Chaque axe se structure autour d'un verrou en science de la conception : un verrou conceptuel (verrou 1), méthodologique (verrou 2) et opérationnel (verrou 3). Ces verrous interagissent les uns avec les autres et imposent des propositions de recherche interdépendantes pour couvrir les manques. La thèse dénombre ainsi huit apports scientifiques pour lever les trois verrous et répondre à la question de recherche de la thèse. Le chapitre suivant détaille les méthodologies de recherche mises en oeuvre dans les trois axes de recherche.

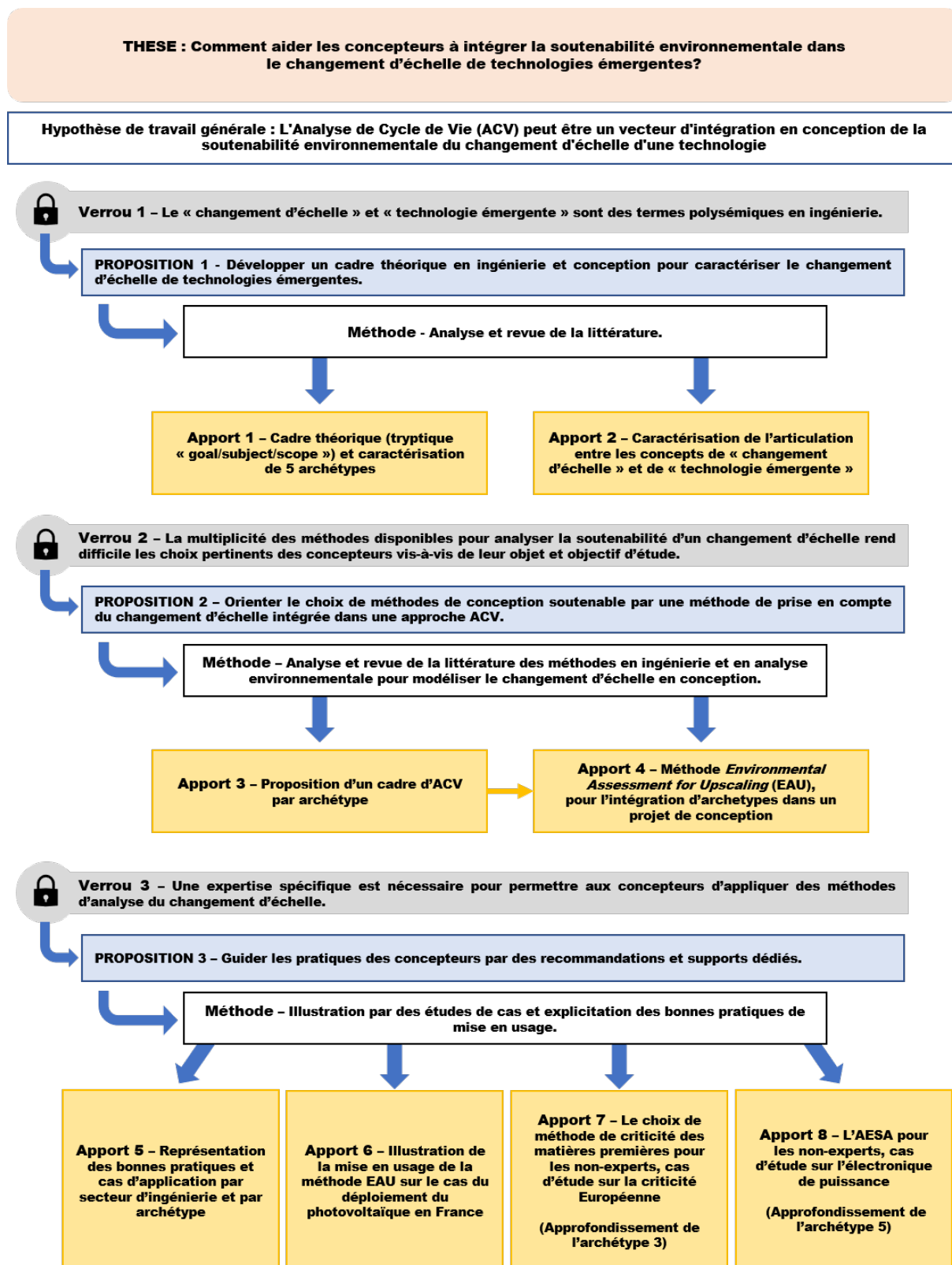


**FIGURE 3.1** – Structure de la thèse détaillée par verrous, propositions, méthodes et apports scientifiques.

# 4

## Méthodes de recherche

### Sommaire

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La démarche générale de la thèse repose, comme introduit dans le **chapitre 3**, sur les trois modalités suivantes : caractériser et conceptualiser, analyser et intégrer, et enfin opérationnaliser. Il s'agit donc d'une démarche explorative, pour la définition des concepts, et prescriptive pour l'analyse à en avoir en conception. La thèse étant une *thèse par articles*, chaque méthodologie supportant un apport scientifique a été formalisée dans une publication scientifique référencée (articles de conférences internationales et revues).

Ce chapitre a ainsi pour objectif de donner une vision d'ensemble des travaux de thèse et de préciser des éléments méthodologiques communs à plusieurs articles ou au contraire non-abordés dans un article en particulier.

Il contextualise les choix de méthode de recherche et renvoie, selon l'axe de recherche traité (conceptuel, méthodologique et opérationnel), vers les manuscrits d'articles disponibles respectivement dans les **chapitres 6,7 et 8**.

Ce chapitre est par conséquent composé de trois sections, chacune développant la méthodologie supportant un axe de recherche de la thèse.

## **4.1 Démarche pour traiter la polysémie des concepts : approche par invariants et archétypes**

Afin de lever le verrou qu'est la polysémie des concepts de changement d'échelle et de technologie émergente en ingénierie (Cf verrou 1), nous proposons de développer un cadre théorique en science de la conception (Cf proposition 1). La proposition 1 s'appuie sur une méthodologie de revue de la littérature par invariant et association sémantique, un travail de veille sur les méthodes de changement d'échelle en science de la conception et une analyse des mots clefs pour construire un corpus de publications.

### **4.1.1 Revue de la littérature systématique**

Dans nos travaux, les termes *upscaling* et *scaling-up* ont été choisis pour traduire en anglais le terme de « changement d'échelle » et *emerging technologies* pour traduire « technologies émergentes ». Une première difficulté pour traiter la littérature sur le *changement d'échelle* est que le phénomène associé est aussi référencé par d'autres mots clefs que *upscaling* ou *scaling-up*.

La **Figure 4.1** illustre les étapes d'application d'une approche de revue systématique avec le mot clef *upscaling* dans la base de données scientifiques *Web of Science*. Ce

traitement a également été appliqué aux autres mots clefs identifié sur la **Figure 2.3**. La partie gauche de la figure fixe le critère principal de sélection qu'est l'identification du mot clef dans le titre des articles. Ensuite, on peut lire verticalement les étapes successives de sélection pour réduire le nombre de références : 1) le type de publication doit être une revue de la littérature, 2) la publication associée à un secteur d'ingénierie (e.g. Électronique ou Chimie) et 3) les articles hors-sujet sont exclus après lecture du résumé ou du texte entier. Pour chaque étape de sélection est affiché le nombre d'articles et rapports scientifiques retenus, de 1754 articles à 6 articles finalement retenus.

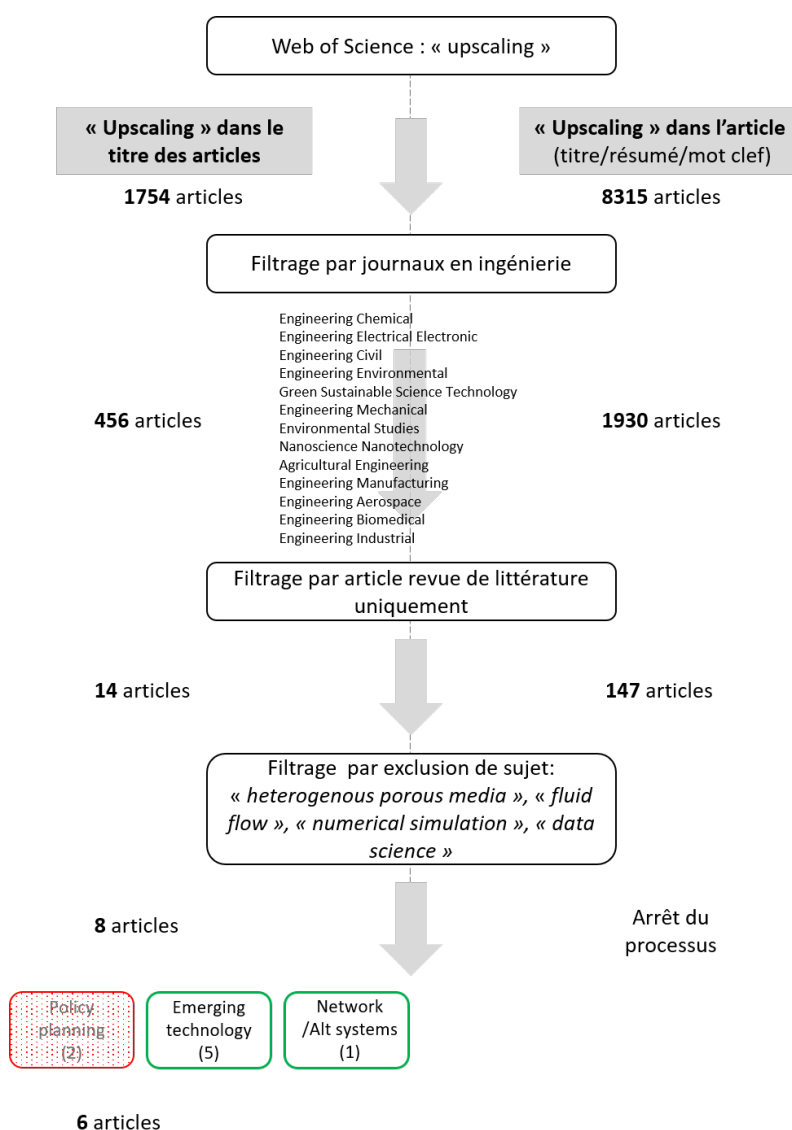


**FIGURE 4.1** – Méthodologie de revue de la littérature systématique ; sélection pour obtenir des articles de revue en ingénierie : à gauche avec le terme « upscaling » uniquement dans le titre, à droite dans leur titre, résumé ou en tant que mot clef.



Sur les six publications retenues, cinq présentent un lien avec les technologies émergentes. Une seule publication explicite une vision socio-technique et systémique. Deux articles ont finalement été mis de côté car issus d'une revue en planification politique (*policy planning* en anglais) et non en ingénierie ou science de la conception. La partie droite de la **Figure 4.1** utilise les trois mêmes étapes de sélection mais élargie la contrainte de présence du mot clef de recherche dans le titre, le résumé et les mots clefs. Cela a pour conséquence de multiplier par cinq le nombre d'articles dans le corpus d'articles identifiés, et par dix le nombre d'articles retenus.

L'inconvénient de cette méthode c'est qu'elle ne permet pas de contextualiser le terme recherché et donc de savoir quel est le sens qui lui est donné avant de lire l'article. Cela implique de devoir lire une grande quantité d'articles qui peuvent s'avérer non-pertinents thématiquement. De plus, une grande quantité de publications sélectionnés ne garantit pas nécessairement la couverture du sujet. Des publications, par exemple de différents champs d'ingénierie, qui traiteraient le phénomène associé au terme de recherche (e.g. *upscaling*) mais avec un vocabulaire différent ne seraient pas retenues dans ce processus. Autrement dit, le ratio publications pertinentes sur quantité de publications retenues est désavantageux en terme de temps de recherche. Combiner les termes de recherche (e.g. « *upscaling* » OR « *scaling-up* » AND « *emerging technology* ») pour couvrir plus de publications accentue cette problématique. Le processus a donc été interrompu (Cf. partie droite de la **Figure 4.1**).

En résumé, ce travail préparatoire de revue systématique a mis en évidence les difficultés associées à la revue par mots clefs polysémiques dispersés, au sens d'une littérature non-homogène : sans définition explicite ou consensuelle, la nécessité de contextualiser les mots clefs identifiés impose un temps investi considérable pour un ratio « informations pertinentes/taille du corpus étudié » limité. Il a donc été nécessaire de compléter cette méthode de revue de la littérature avec une approche sémantique, permettant de cibler le sens des termes utilisés.

### 4.1.2 Revue de la littérature par association sémantique

Nous avons ainsi développé à partir du travail préparatoire une approche par « invariants », c.-à-d. par l'identification d'éléments communs à plusieurs situations permettant de constituer une définition homogène d'un phénomène. Cette approche s'appuie sur l'hypothèse de travail suivante : le changement d'échelle est un phénomène caractérisable au travers des méthodes d'analyse qui y font référence. Pour simplifier, le phénomène de changement d'échelle est assimilé à une « fonction de transformation »

d'un état A à un état B. En s'appuyant sur les éléments à définir dans les analyses techno-économiques et environnementales, nous avons alors proposé trois invariants de caractérisation pour le changement d'échelle de technologie émergente.

- Objectif d'étude (*Goal* en anglais)
- Sujet de l'étude (*Subject* en anglais)
- Champ et focus d'étude (*Scope* en anglais). Soit ce sur quoi l'analyse se concentre, pour quel périmètre d'étude et depuis quel point de vue et discipline.

Les trois invariants sont définis en profondeur dans l'**Article de Conférence 1** et l'**Article 1** (Cf **chapitre 6**). Ce triptyque forme une grille d'analyse pour qualifier le sens que portent les auteurs d'une publication aux termes de *changement d'échelle*.

Ensuite, un processus d'association sémantique a été développé pour accroître la taille du corpus, appuyé par un travail de veille par mot clef de plus en plus étendu, dérivant autour du corpus initial : partant de termes relevant du champ lexical de l'échelle (*scaling*, *scale-up*, *scaling-up*, *upscaling*, *upscale*, de nouvelles références ont été ajoutées, soit par affiliation (bibliographie des articles déjà identifiés), soit par recherches ciblées par de nouveaux mots clefs comme « déploiement de technologie », « massification » ou *downscaling*. La méthode de revue par association sémantique a permis de constituer un corpus d'articles, de supports et de rapports scientifiques de 270 références entre l'année 2022 et 2023. Cette méthode est décrite dans l'**Article 1** (Cf **chapitre 6, section 6.2**). La combinaison du triptyque d'invariant pour guider la constitution du corpus a abouti à la caractérisation de cinq définitions, aussi nommées « archétypes ». Chaque archétype est caractérisé par un unique *Goal*, *Subject*, et *Scope*, au sens du périmètre et du focus d'étude.

### Caractérisation des archétypes par identification de besoins méthodologiques

L'invariant *Scope* a été approfondi par une analyse des méthodes techno-économiques de changement d'échelle, regroupant à la fois les méthodes d'analyse techniques (principe physique et/ou chimique) et les méthodes d'ingénierie intégrant des contraintes économiques. A partir de ce types de méthodes utilisés dans les dix secteurs d'ingénierie identifiées, des « besoins méthodologiques » (*methodological requirements*) ont été formulées. Cela sous-tend l'idée que le changement d'échelle est avant tout défini par une expertise technique. Ces besoins méthodologiques visent ainsi à compléter la définition du changement d'échelle du point de vue de la pratique de conception.

La catégorisation en archétype permet ainsi de décrire les phénomènes impliqués par le changement d'échelle de technologie, et l'identification de « besoins méthodologiques »

de cibler les méthodes d'analyse associées à la science de la conception. Ces éléments constituent l'« Apport 1 » (Cf **Figure 3.1**).

### 4.1.3 Analyse bibliométrique des mots clefs

Pendant le processus de revue de littérature, nous avons également procédé à un travail de clustering des mots clefs associés au changement d'échelle de technologie émergente. Cela a été fait dans le but de caractériser les interactions entre archétypes et d'équilibrer les recherches documentaires. A l'aide du logiciel de bibliométrie *VOSviewer*, la co-occurrence des mots clefs de recherche a été étudiée : le logiciel représente les mots clefs des articles sélectionnés sur un plan selon une métrique de proximité. Des liens sont ensuite tracés entre les termes co-occurents pour un même article. Il est possible d'ajuster le seuil de co-occurrence afin de ne représenter que les mots les plus récurrents. Enfin, des clusters sont identifiés automatiquement en seuillant le nombre de lien de co-occurrence entre un groupe de mots. Cela permet de regrouper les termes qui sont utilisés de façon récurrente et dans le même contexte.

Cette méthode a été utilisée pour donner du sens au corpus en construction. Il a permis de reconstruire un regroupements des mots clefs incarnant un ou plusieurs archétypes et de produire une image des relations entre les concepts *technologies émergentes* et *changement d'échelle* tels qu'ils sont utilisés dans la littérature en ingénierie. Ces résultats d'analyse sont nommés « Apport 2 » de la thèse. En ce sens, c'est un détournement de l'outil *VOSviewer*, habituellement utilisé pour de l'analyse automatique et systématique de la littérature.

En synthèse, afin caractériser le changement d'échelle de technologies émergentes, cinq archétypes ont été constitués puis caractérisés. Chaque archétype représente une facette du changement d'échelle de technologie et est incarné par 1) des mots clefs et 2) des méthodes d'analyse principalement techno-économiques. Une méthode de revue de la littérature a donc été mise en oeuvre : elle a été appuyée par un processus itératif d'associations sémantiques, une analyse des co-occurrences de mots clefs dans les publications identifiées et un travail d'approfondissement sur les besoins méthodologiques pour étudier les archétypes. Ces trois analyses ont permis de former un corpus de 270 publications et ont convergées vers la caractérisation de cinq archétypes de changement d'échelle (Apport 1) et de leur relation avec le concept de *technologie émergente* (Apport 2).

## 4.2 Démarche pour orienter le choix de méthodes d'analyse de la soutenabilité en conception

Dans cette section, nous présenterons les méthodes mises en oeuvre pour faciliter le choix d'une équipe de conception de méthodes d'analyse de soutenabilité appropriées pour ses objectifs de changement d'échelle de technologie (Cf verrou 2). Nous proposons pour cela une méthode de prise en compte du changement d'échelle intégrée dans une approche d'ACV (Cf proposition 2). Cette méthode, nommée *Environmental Assessment for Upscaling* (EAU) a nécessité la mise en oeuvre de plusieurs méthodes de recherche au préalable : les prochains paragraphes détaillent les méthodes de recherche développées pour 1) réaliser l'état de l'art des différentes modes d'ACV susceptibles d'analyser environnementalement des aspects du changement d'échelle (Cf section 4.2.1), 2) associer chaque archétype à un ou plusieurs modes d'ACV (Cf section 4.2.2), et 3) développer une structure permettant de combiner les modes d'ACV en fonction des besoins d'analyse, c.-à-d. le processus EAU (Cf section 4.2.3).

### 4.2.1 Etat de l'art en ACV

Ainsi, réaliser un état de l'art des modes d'ACV a été la première étape pour construire la proposition 2. Cet état de l'art s'est appuyé sur deux approches complémentaires : une méthode de revue de la littérature et un travail de revue des modes d'ACV par des formations et entrevues avec des experts en ACV.

La description de la revue de littérature est faite dans l'**Article 2** (Cf **chapitre 7, section 7.1**). Elle a fait émerger des publications proposant des états de l'art partiels de différents pans de recherche en ACV [96], [100], [101], [103], [104]. Le terme « mode » pour désigner une approche ou une pratique d'ACV est d'ailleurs repris de la revue de littérature « Digesting the alphabet soup of LCA » de Guinée et al. (2018) [103].

En complément, plusieurs formations généralistes (GI et formation continue, UVED) et trois formations doctorales ont été suivies pour acquérir des connaissances sur les modes d'ACV *prospectif* » et *conséquentiel* et couvrir des éléments d'expertise liés à l'ACV comme l'analyse d'incertitude par exemple : « Prospective Life Cycle Assessment and scenario modeling » de l'*université de Leiden* (2022), « Consequential Life Cycle Assessment » (2022) de *Gingko21* et *International Life Cycle Academy* et « Ecodesign of complex systems » du *réseau Eco-SD* (2021). Ces trois formations, incluant des débats avec les organisateurs, ont permis de mieux caractériser les modes d'ACV en fonction des besoins en analyse environnementale du changement d'échelle de technologie.

En parallèle, confortés dans une démarche de transfert de connaissance d'experts, nous avons contacté différents experts en ACV sur les modes conséquentiel (Bo Weidema, Denise Almeida), territorialisé (Audrey Tanguy), paramétrée (Paula Perez-Lopez) et d'AESA (Morten Ryberg et Mickael Hauschild, Teddy Serado). Ces échanges entre 2021 et 2024 ont permis de compléter la caractérisation des pratiques de chacun des modes d'ACV, en identifiant par exemple les principales difficultés d'application et les ressources disponibles associées.

Pour conclure, la revue de littérature, couplée aux formations et entrevues avec des experts a abouti à la caractérisation de 15 modes d'ACV en termes d'objectif d'analyse, sujet et périmètre d'étude, type de modélisation, contraintes pratiques et publications structurantes. Cet état de l'art est présenté en introduction de l'**Article 2** présenté en **section 7.1**.

#### 4.2.2 Construction d'un cadre d'ACV par archétype

Cette section porte sur la réalisation de recommandations des modes d'ACV pour analyser les aspects environnementaux d'un ou plusieurs archétypes. Nous avons appelé cela « cadre d'ACV par archétype » et est l'apport 3 de la thèse. Ce guide privilégie la stratégie d'orienter les équipes de conception vers des approches d'ACV compatibles avec leurs objectifs même si certaines n'ont pas été éprouvées dans un contexte de conception.

A partir des besoins méthodologiques identifiés pour chaque archétype et la caractérisation des modes d'ACV, notamment par objectif d'analyse, modélisation et périmètre d'étude, il a alors été possible d'appairer chaque archétype avec un ou plusieurs modes d'ACV. Certaines assignations ont été faites en accord avec la littérature existante : l'archétype 5 (*down-limiting*) est par exemple explicitement associé à l'ACV absolue et l'archétype 1 (*scaling-up*) à l'ACV ex-ante ou prospective. Pour les autres cas, si un mode d'ACV et un archétype partage le même objet d'étude (e.g. une technologie, un groupe de technologie, un secteur industriel) ou s'appuie sur un type de modélisation (e.g. systémique à grande échelle, causal, socio-technique, scénarisé) qui répond aux besoins méthodologiques de l'archétype, alors nous avons considéré une affinité entre eux. Le travail de mise en relation des archétypes avec l'ACV, complété par des recommandations sur les spécificités d'application des différents modes, constitue le cadre d'ACV par archétype, aussi nommé Apport 3 de la thèse. Cet apport est également présenté dans l'**Article 2** en **section 7.1**.

### 4.2.3 Développement d'une méthode agrégée de prise en compte des archétypes en ACV

Le processus EAU a été développé pour compléter le cadre d'ACV par archétype et permettre une prise en compte de plusieurs archétypes en ACV et en conception. Cette méthode a été construite sur un processus d'identification des points clefs pour les équipes de conception afin de prendre en compte les aspects environnementaux des cinq archétypes de changement d'échelle.

#### Cahier des charges du processus EAU

Nous nous sommes appuyés sur les quatre étapes de la norme ISO 14040 : 2006 pour formaliser la méthode en prenant pour exemple la littérature en ACV comme outil d'aide à la décision, notamment Kjaer et al. (2018) [83] et Langkau2023 [105]. Six critères ont été définis pour fixer le cahier des charges du processus EAU :

1. multicritères, multi-étapes et systémique,
2. anticipative et dont le résultat doit être représentatif du changement d'échelle,
3. adapté pour les équipes de conception,
4. doit s'appuyer sur des paramètres techniques,
5. générique, c.-à-d. indépendant du secteur d'ingénierie,
6. et évolutive.

La description détaillée de ces critères est faite dans la partie méthode de l'**Article 3** présenté dans le **chapitre 7, en section 7.2**. Ces six critères ont émergés de nos propres travaux (Cf hypothèse de travail au chapitre 2) ou s'appuient sur la littérature scientifique en conception intégrée. Le critère de représentativité du changement d'échelle (critère 2) a constitué la principale difficulté car cela implique de combiner toutes les approches d'analyse identifiées pour couvrir les cinq archétypes. L'expertise et les ressources pour un tel travail étant possiblement hors de portée des équipes de conception, nous avons donc cherché à identifier une « modélisation minimale pour les équipes de conception ». Ce travail d'identification, en plus de la littérature et des travaux précédents, s'appuie sur une approche par cas d'étude.

#### Approche par cas d'étude dans le secteur de l'énergie

Un cas d'étude a ainsi été mis en oeuvre pour plusieurs raisons.

- D’abord pour prendre le rôle d’un expert ACV dans une équipe de conception et identifier les ressources (e.g. logiciel, bases de données) et pratiques (e.g. modélisation du système, nombre de simulations) nécessaires à la tenue d’une analyse environnementale de changement d’échelle. Une partie de la collecte de données a été réalisée par le biais de l’encadrement de stage étudiants de trois semaines en 2022 (Marin Guibert et Gaëtan Martin) et 2023 (Thibault Roudier) à l’Institut Arts et Métiers de Chambéry et co-encadré avec Véronique Perrot-Bernardet (encadrante de thèse). Un travail d’analyse de données a aussi été réalisé par le biais de l’encadrement de stage de recherche de Leticia Labadi (Cf **section 4.3.3**).
- Le cas d’étude a également eu pour but de nous rapprocher d’un profil de concepteurs et/ou experts techniques et de fixer des contraintes liées au processus de conception d’un produit. Notre choix de système d’étude s’est porté sur les systèmes photovoltaïque. Nous avons ainsi eu des contacts ponctuels ou réguliers avec des experts du photovoltaïque de l’*Institut Photovoltaïque d’Île de France* (IPVF) (Daniel Suchet, Lu Quercin), du *CEA* (Nouha Gazbour, Antoine Perelman) et de l’*OIE Mines Paris* (Paula Perez-Lopez, Mathilde Marchand), des experts du réseau électrique *RTE* (Guillaume Busato, Colombe Peyrusse), et un expert en modélisation des flux de matières dans la société de l’*ISTerre* (Olivier Vidal). De plus, j’ai assisté à plusieurs séminaires proches d’une vision concepteur de technologie dans le secteur de l’énergie pour identifier les performances et métriques mises en avant par les concepteurs (CDP IDEX PowerAlps 2023 [106], Lancement PERP TASE 2023 [107], Carnot Energie Days 2021 et 2022 [108], Sustainable Energies Forum 2022).
- Enfin, le cas d’étude a aussi visé à tester un ordonnancement des étapes clefs de la méthode en développement pour itérer vers une version de plus en plus complète. Trois versions du processus EAU ont ainsi été générées.
- Plus généralement, et selon le choix de l’objet d’étude, le cas d’étude peut servir de preuve de concept ou démontrer la diversité de situations possibles. L’objet d’étude doit pour cela illustrer le phénomène à tester. Pour notre cas, nous souhaitons d’abord développer une preuve de concept. Il a donc fallu choisir une technologie émergente, en cours de développement industriel, dont le changement d’échelle est modélisable techniquement et environnementalement. Le cas d’étude nous a permis de proposer et tester une forme *minimale* de modélisation, que nous avons ensuite essayé de rendre la plus générique possible et intégrée dans le processus EAU.

Ces éléments montrent qu’une approche par cas d’étude couvre le critère que la méthode soit adaptée aux équipes de conception (critère 3) et basées sur des paramètres techniques (critère 4). Selon la méthode de validation empirique, les critères de généralité et d’évolutivité pourraient être atteints en multipliant les cas d’étude de différentes natures. Dans cette thèse, un seul cas d’étude a pu être établi sur deux technologies de panneaux photovoltaïques (silicium monocristallin et tandem silicium-perovskite). Ces systèmes ont été choisis parce qu’ils répondent à plusieurs définitions de l’ « émergence » en tant que technologie (nouvelle ou immature) ou faisant partie des énergies renouvelables (industries émergentes) et à fort développement en recherche. C’est également un système technique intégré à un système socio-technique (réseau électrique) et donc adapté à une vision systémique. Le photovoltaïque met ainsi en évidence des caractéristiques de chacun des archétypes de changement d’échelle. Enfin, le photovoltaïque est étudié par plusieurs corps de métiers et institutions ce qui permet d’illustrer les phénomènes de changement d’échelle en s’appuyant sur une littérature et des modèles abondants, sinon disponibles. Nous nous sommes donc servi du photovoltaïque comme fil conducteur avec la conviction que ce cas d’étude permet un travail de transposition à d’autres systèmes techniques (e.g. batterie, éolienne, électronique de puissance) et d’autres secteurs d’ingénierie (e.g. numérique, mobilité, alimentation, bâtiment).

Pour conclure, la démarche pour orienter les choix de méthodes en conception pour la soutenabilité a été construite sur l’idée de mettre l’accent sur les points de vigilance qui diffèrent d’une approche « classique » de l’ACV (i.e. attributionnelle retrospective) et de renvoyer les utilisateurs vers les méthodes les plus pertinentes lorsqu’elles existent. Le cadre d’ACV par archétype (apport 3) et le processus EAU (apport 4) répondent à cette exigence. La méthode de recherche employée combine 1) la revue de la littérature scientifique, 2) des périodes de formations et d’entrevue avec des experts, et 3) une approche empirique pour extraire des recommandations à destination des équipes de conception. Dans une optique d’intégration en conception, les recommandations se fondent sur une approche normée (ISO 14040 : 2006 et IEC 62430 : 2019).

### 4.3 Démarche pour expliciter des bonnes pratiques pour les concepteurs

En parallèle des axes de conceptualisation (**section 4.1**) et de développement méthodologique (**section 4.2**), nous avons abordé le sujet de l’opérationnalisation des apports de la thèse. Plus précisément, dans le paradigme d’équipe de conception dans



lequel nous nous plaçons (Cf **chapitre 2, section 2.1.1**) certains profils de concepteurs manquent d'éléments de contexte pour pouvoir utiliser les apports de la thèse (verrou 3). Nous avons par conséquent proposé des recommandations et supports spécifiques pour guider les pratiques des concepteurs (proposition 3). Cette proposition se traduit par quatre contributions visant l'opérationnalisation en conception du cadre d'ACV par archétype et des archétypes (apport 5), de le processus EAU (apport 6), de la criticité des matières premières (apport 7) et de l'AESA (apport 8). Les **sections 4.3.1, 4.3.2, et 4.3.3** détaillent ainsi les méthodes de recherche pour aboutir respectivement aux apport 5, 6, 7 et 8.

### 4.3.1 Développements de supports dédiés à l'opérationnalisation des apports de thèse

#### Développement de représentations et outils visuels

Pour faciliter l'adoption des archétypes de changement d'échelle, nous avons suivi une approche didactique, c.-à-d. portant sur la manière de transmettre les connaissances. Cette approche est présente dans l'ensemble de la thèse mais se manifeste pour deux exemples focalisés sur la production d'outils visuels :

Un travail de **représentation symbolique** pour les archétypes de changement d'échelle afin de les dissocier d'un cas particulier (champ d'ingénierie) et isoler un phénomène générique. Construit dès la première année de la thèse dans l'**Article de conférence 1** (6.1) et affiné ensuite dans l'**Article 1** (6.2), ces symboles ont permis d'explicitier la généricité du phénomène de changement d'échelle et de se départir des termes utilisés dans différents secteurs d'ingénierie.

En complément, lors de la définition des archétypes et des types d'approches d'analyse, nous avons pris le parti de donner des exemples de différents champs d'ingénierie, sur différents types de technologie. En contrepartie, et pour faciliter l'accès aux ressources identifiées durant la revue de littérature selon sa discipline (ou secteur d'ingénierie) nous avons proposé un **outil de représentation bibliographique** pour rendre accessible la diversité de la littérature sur le changement d'échelle.

Ces deux exemples illustrent une démarche didactique visant à expliciter que le changement d'échelle, à travers ses archétypes, est un phénomène qui s'applique dans tous les secteurs de l'ingénierie.

### 4.3.2 La communication scientifique pour l'opérationnalisation

Un aspect important de la thèse a été de confronter les travaux de recherche auprès de plusieurs groupes de chercheurs par le biais de présentations, séminaires ou conférences. Ces événements ont été des occasions de revues par les pairs mais aussi de dissémination scientifique pour l'opérationnalisation des apports de la thèse.

Ce processus s'est déroulé auprès de plusieurs communautés :

- Les deux équipes de recherche accueillant la thèse, soit l'équipe de recherche *COSYS* du G-SCOP et *IMC* de l'I2M de Bordeaux et l'institut Arts et Métiers de Chambéry,
- Des communautés proches du développement de technologies dans le secteur de l'énergie (Carnot Energie, CDP IDEX PowerAlps et le laboratoire G2ELab),
- Des communautés plus généralistes en conception rattachées à des conférences francophones (Réseau Eco-SD (2024)) et internationales (CIRP Design (2022), CIRP LCE (2023, 2024)).

Enfin, les activités d'enseignement en parallèle de la thèse ont participé à introduire la prise en compte du changement d'échelle en ACV auprès d'un public étudiant entre 2022 et 2024. Cela s'applique particulièrement dans l'UE « Advanced LCA » en M2 et « éco-conception de produits et services » en M1 à l'école d'ingénieur **GI** et également à l'institut Arts et Métiers de Chambéry dans le parcours *Manager du Changement et de l'Innovation Durable* (MCID) sous l'UE « Analyse de Cycle de Vie ».

Une partie du cas d'étude développé pour construire le processus EAU a été formalisé en deux articles de conférence, l'**Article de conférence 2** et **Article de conférence 3** (Cf. **chapitre 8, section 8.1** et **8.2**). Ces articles de conférence ont ainsi constitué une preuve de concept auprès des communautés de chercheurs citées plus haut, tout en explicitant les contraintes de collecte de données pour prendre en compte le changement d'échelle en ACV.

### 4.3.3 Développements de recommandations dédiées à l'opérationnalisation des apports de thèse

#### Approfondir l'archétype 3 via la criticité des matières premières

Afin d'approfondir les métriques permettant de caractériser l'archétype 3 (déployer) en conception, un stage de recherche de six mois (Février-Juillet 2023) a été mené par

Liticia Labadi (en M2) sur l'aide au choix d'indicateurs de criticité pour les concepteurs. Ces travaux ont été co-encadrés avec Peggy Zwolinski (directrice de thèse) et visaient à :

- Faire un état de l'art des méthodes d'analyse de la criticité,
- Réaliser une analyse de la criticité sur le secteur du photovoltaïque,
- Identifier des points clefs pour l'application en conception de méthode d'analyse de criticité.

La méthode de recherche pour investir la pratique de l'analyse de la criticité en conception a donc été une revue de littérature et un cas d'étude. Ma contribution à ce travail a consisté en :

- La fourniture de littérature scientifique et ressources sur les méthodes d'analyse de la criticité, et la composition en matières premières de panneaux photovoltaïques,
- L'aménagement et l'orientation des activités de recherche en fonction des contraintes de temps et de disponibilité des données,
- Une collaboration sur la collecte et le traitements de données,
- L'analyse et la critique des propositions de Liticia Labadi,
- La mise en place de points d'avancement hebdomadaires et la relecture du rapport de stage.

Le stage a débouché sur un travail de rédaction d'article défini comme étant l'apport 7 de la thèse : **l'Article A** disponible au **chapitre 8** en **section 8.3**.

### Approfondir l'archétype 5 via l'AESA

Afin d'approfondir l'intégrabilité en conception de l'archétype 5 (limiter environnementalement), un stage de recherche de six mois (Février-Juillet 2024) a été mené par Valentin Girard (en M2). Ce stage a été co-encadré avec Li Fang, doctorante au laboratoire G-SCOP et G2Elab et Maud Rio (encadrante de thèse). Li Fang, développe dans sa thèse des méthodes d'éco-conception dans le secteur de l'électronique de puissance. Elle a ainsi fait le lien avec des experts techniques du G2Elab, soit des concepteurs, et pris le rôle de non-experte en AESA pour tester le déroulement de la méthode guidée. Les travaux visaient à :

- Faire un état de l'art de l'AESA,
- Réaliser une application de l'AESA sur un prototype (convertisseur Buck) dans un cas d'étude plus large dirigé par Li Fang. Le cas d'étude complet étaye une méthode d'éco-conception pour le secteur de l'électronique de puissance et Valentin et moi-même intervenons en tant qu'ACVistes et analystes environnementaux,

- Développer un guide d'application de l'AESA pour ingénieurs en identifiant les étapes clefs.

La méthode de recherche pour faciliter la pratique de l'AESA pour des ingénieurs a donc été une revue de littérature et un cas d'étude dans le rôle d'un expert ACV. Ma contribution à l'encadrement du travail de recherche a été :

- De préparer et orienter vers la littérature structurante, par exemple en demandant à se positionner par rapport aux travaux d'experts du domaine (e.g. Kara et al. (2023)),
- D'organiser une entrevue avec un doctorant de la *Denmark Technical Univ.* travaillant sur la soutenabilité absolue (Teddy Serado) et co-encadré par M. Hauschild et S. Kara,
- De veiller aux formalismes employés (étapes de la norme sur l'ACV, homogénéisation des concepts/termes utilisés, représentations graphiques des résultats) et de contribuer à focaliser le cas d'étude à l'échelle produit,
- De collecter des données (facteurs de caractérisation) et pousser à tester les deux approches disponibles en AESA dans le cas d'étude,
- D'analyser et critiquer les propositions de Valentin Girard,
- La mise en place de points d'avancement hebdomadaires.

Le stage a débouché sur un travail de rédaction d'article défini comme étant l'apport 8 de la thèse : l'**Article B** disponible au **chapitre 8** en **section 8.4**.

# 5

## Synthèse des apports de la thèse

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Les **chapitres 3 et 4** ont respectivement présentés la structure et les méthodologies de recherche de la thèse. Il en résulte trois axes de recherche : un axe de conceptualisation et d'analyse sémantique (section 5.1), un axe méthodologique (section 5.2), et un axe d'opérationnalisation en conception de certains résultats identifiés dans les deux autres axes (section 5.3). Les trois sections qui composent ce chapitre ont donc pour but de donner une vision d'ensemble des résultats de la thèse. La thèse étant une *thèse par articles*, ces sections résument les résultats de recherche et renvoient, selon l'axe de recherche traité (conceptuel, méthodologique et opérationnel), vers les manuscrits d'article disponibles respectivement dans les **chapitres 6, 7 et 8**.

## 5.1 Conceptualisation du changement d'échelle de technologies émergentes en ingénierie

Les éléments présentés dans cette section se réfèrent aux apports 1 et 2 visant à lever le Verrou 1 de la thèse (Cf **Figure 5.1**).

Ces résultats sont détaillés dans le **chapitre 6**, constitué de l'**Article de Conférence 1** nommé « *For an upscaling assessment integration in product design* » publié à CIRP Design 2022 et de l'**Article 1** soumis au Journal *Science Design* le 12 Octobre 2023 et intitulé « *Designing emerging technologies taking into account upscaling* ».

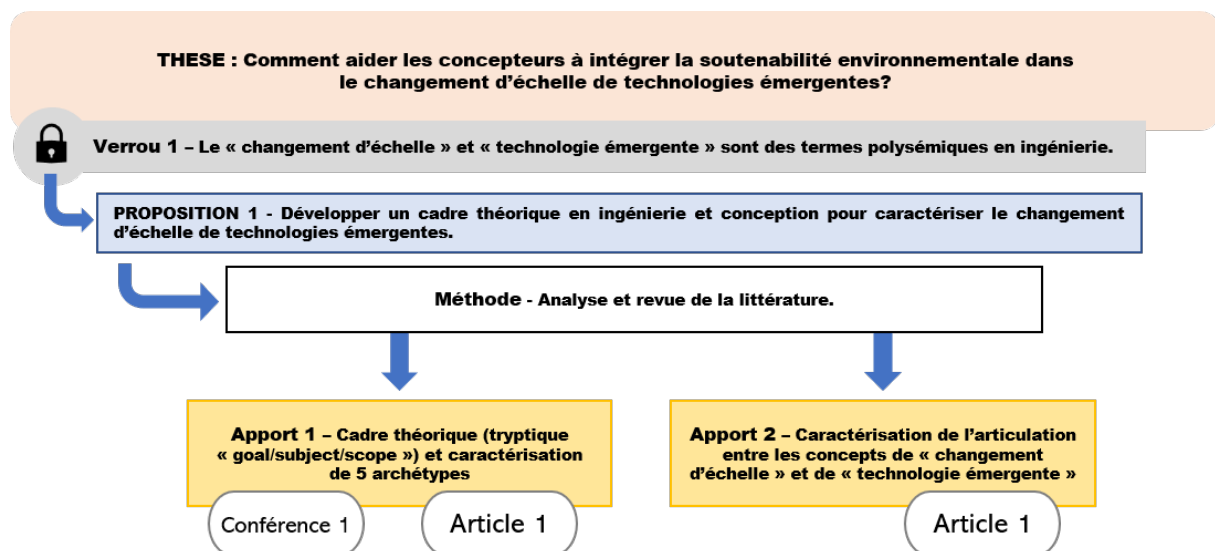


**FIGURE 5.1** – Articulation entre les apports 1 et 2 de la thèse et la communication scientifique pour lever le verrou 1.

### 5.1.1 Apport 1 : Archétypes de changement d'échelle

En s'appuyant sur la littérature scientifique nous avons défini le changement d'échelle comme un phénomène socio-technique s'appuyant sur des pratiques de conception afin d'intégrer une technologie dans la société. Nous en proposons dans cette thèse la définition suivante :

**Changement d'échelle technologique** : *phénomène techno-économique impliquant le développement d'une technologie et son déploiement dans la société pour répondre à des enjeux sociétaux (soutenabilité, sécurité, justice sociale).*

Ce phénomène présente plusieurs facettes caractérisées en cinq « archétypes » : maturer (*scaling-up*), massifier (*mass-producing*), déployer (*deploying, reaching a level*), intégrer (*integrating into a complex system*) et limiter environnementalement (*down-limiting*). Ces cinq archétypes, s'articulent autour de plusieurs visions d'une technologie en conception : techno-centrée pour les deux premiers, industrielle et sectorielle pour le troisième, socio-technique pour le quatrième et socio-environnementale pour le cinquième. L'**Article de Conférence 1** présente les cinq archétypes avec des exemples choisis (Cf **chapitre 6, section 6.1**). L'**Article 1** caractérise en détail les archétypes de changement d'échelle, en définissant notamment les « besoins méthodologiques » pour les analyser à partir de cas d'étude et de références choisis (Cf **chapitre 6, section 6.2**).

### 5.1.2 Apport 2 : Technologie émergente et changement d'échelle

Le caractère « émergent » d'une technologie est souvent mis en avant dans la littérature en ACV et un peu moins en ingénierie classique. Cette caractéristique a été identifiée comme faisant référence à trois définitions :

- Émergente car en maturation, en laboratoire,
- Émergente dans le monde industriel, comme dépassant un certain seuil industriel vis à vis de capacité de production,
- Émergente dans un système socio-technique, étant en mesure de perturber et/ou changer le comportement de l'ensemble.

Ces trois définitions correspondent à l'intégration d'une technologie en développement dans la société avec une vision techno-centrée, industrialo-centrée puis socio-technique. L'émergence d'une technologie est donc une propriété redondante avec le concept de changement d'échelle que nous proposons (Cf **section 6.2**). Autrement dit, les cinq archétypes de changement d'échelle permettent de couvrir les différents sens attribués



à l'émergence d'une technologie. En cela, le changement d'échelle de technologie émergente est par conséquent vu comme un cas particulier de changement d'échelle. Pour conclure, les apports 1 et 2 caractérisent le changement d'échelle de technologies émergentes, en sciences de la conception, en développant un cadre conceptuel (proposition 1). Les cinq archétypes qui en découlent sont structurés autour 1) de définitions inter-sectoriels, et 2) de besoins méthodologiques pour analyser les différents aspects du changement d'échelle. En cela ils contribuent à contextualiser les termes de *changement d'échelle* et de *technologie émergente* et donc lever le verrou 1 de la thèse.

## 5.2 Analyse environnementale du changement d'échelle

Les éléments présentés dans cette section se réfèrent aux apports 3 et 4 visant à lever le Verrou 2 de la thèse (Cf **Figure 5.2**).

Ces résultats sont détaillés dans le **chapitre 7**, constitué de l'**Article 2** intitulé « *Emerging technologies upscaling : a framework for matching LCA practices with upscaling archetypes* », ainsi que de l'**Article 3** intitulé « *Guidelines for environmental assessment of upscaling : LCA-based methodology for design teams* ».

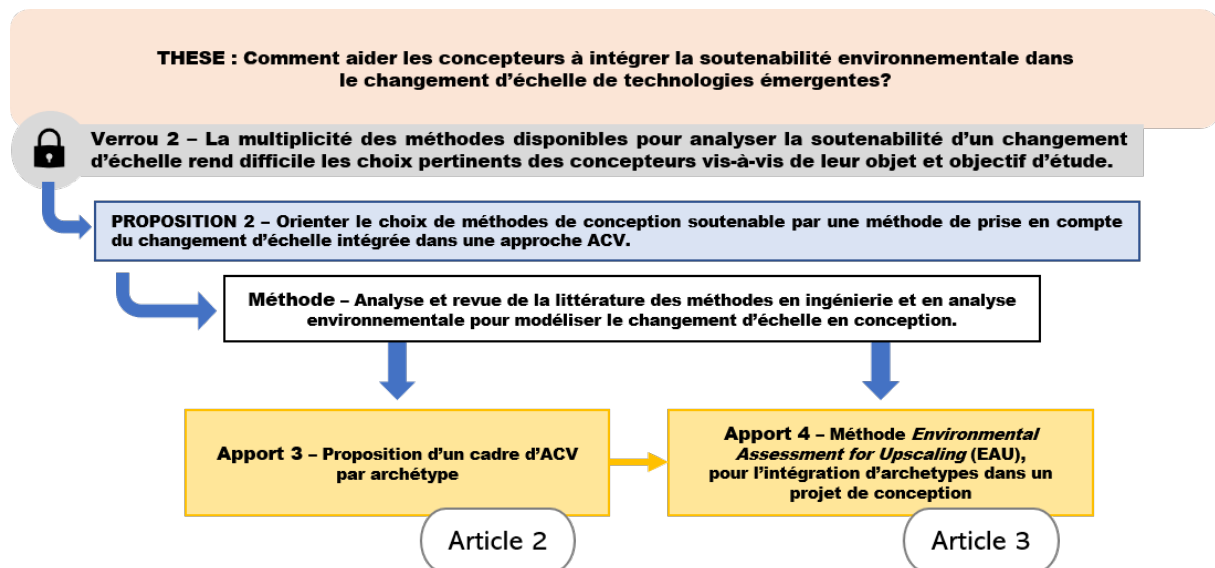


**FIGURE 5.2** – Articulation entre les apports 3 et 4 de la thèse et la communication scientifique pour lever le verrou 2.

### 5.2.1 Apport 3 : Cadre d'ACV par archétype

Le cadre d'ACV par archétype permet d'orienter un utilisateur vers la ou les modes d'ACV les plus adaptés selon l'archétype de changement d'échelle à étudier. Il fait des recommandations pour la définition du *scope* spatial et temporel et précise les spécificités auquel doit répondre l'application de l'ACV pour un archétype choisi. Ces recommandations s'appuient sur une revue de cas d'étude sur plusieurs secteurs d'ingénierie. Enfin, le cadre d'ACV regroupe des ressources bibliographiques supplémentaires pour la mise en pratique du cadre d'ACV (Cf **chapitre 7, section 7.1**).

### 5.2.2 Apport 4 : La processus EAU

Le processus EAU pour « *Environmental Assessment for Upscaling* » s'appuie sur le cadre d'ACV par archétype pour guider un processus d'éco-conception permettant la prise en compte des cinq archétypes de changement d'échelle en ACV. Il présente six étapes de recommandations : 1) définition des besoins en éco-conception relatifs au changement d'échelle d'une technologie, 2) définition des spécificités du changement d'échelle, 3) construction du modèle environnemental de changement d'échelle, 4) analyse des impacts environnementaux du changement d'échelle, 5) traitement et interprétation des résultats, et 6) exploitation pour l'éco-conception du changement d'échelle de technologie. Les étapes 2 à 5 sont intégrées dans le formalisme des quatre étapes de l'ACV. Le processus EAU indique les points de vigilance et de différenciation par rapport à une pratique classique de l'ACV (i.e. attributionnelle rétrospective). De plus, il explicite à chaque étape la ou les expertises à mobiliser dans l'équipe de conception (expertise technique, expertise en éco-conception et expertise liée à la gestion d'entreprise). L'étape de définition des spécificités du changement d'échelle à étudier (étape 2) et de modélisation du changement d'échelle (étape 3) sont le coeur du processus (Cf **chapitre 7, section 7.2**).

Pour conclure, le cadre d'ACV par archétype et le processus EAU contribuent à formaliser les méthodes disponibles, pour les équipes de conception, afin d'analyser environnementalement le changement d'échelle d'une technologie. Ces deux apports permettent donc de soutenir le choix de méthodes de conception vers la soutenabilité (proposition 2).

## 5.3 Opérationnalisation de l'analyse du changement d'échelle intégrée en conception

Les éléments présentés dans cette section se réfèrent aux apports 5, 6, 7 et 8 visant à lever le Verrou 3 de la thèse (Cf **Figure 5.3**). Le verrou « d'opérationnalisation » étant transversal aux deux autres, les contributions pour le lever sont présents dans l'entièreté des travaux de la thèse. L'apport 5 « représentation des bonnes pratiques », présenté en section 5.3.1 concentre des résultats disséminés dans les **chapitres 6 et 7**. Les apports 6, 7 et 8 sont issus de deux articles de conférences et deux articles de journaux compilés dans les **sections 8.1, 8.2, 8.3 et 8.4 du chapitre 8**.

L'apport 6, « illustrations du processus EAU », est synthétisé en deux articles de conférence publié à *CIRP LCE* en 2023 et 2024. Ils sont nommés **Article Conférence 2** et **Article Conférence 3** par ordre chronologique. Les apports 7 et 8 sont respectivement associés à l'**Article A**, à soumettre, co-écrit avec Licia Labadi, Helmi ben Rejeb et Peggy Zwolinski, et à l'**Article B**, co-écrit avec Valentin Girard, Li Fang et Maud Rio, à soumettre au journal *Design Science* le 31 Mai 2024.

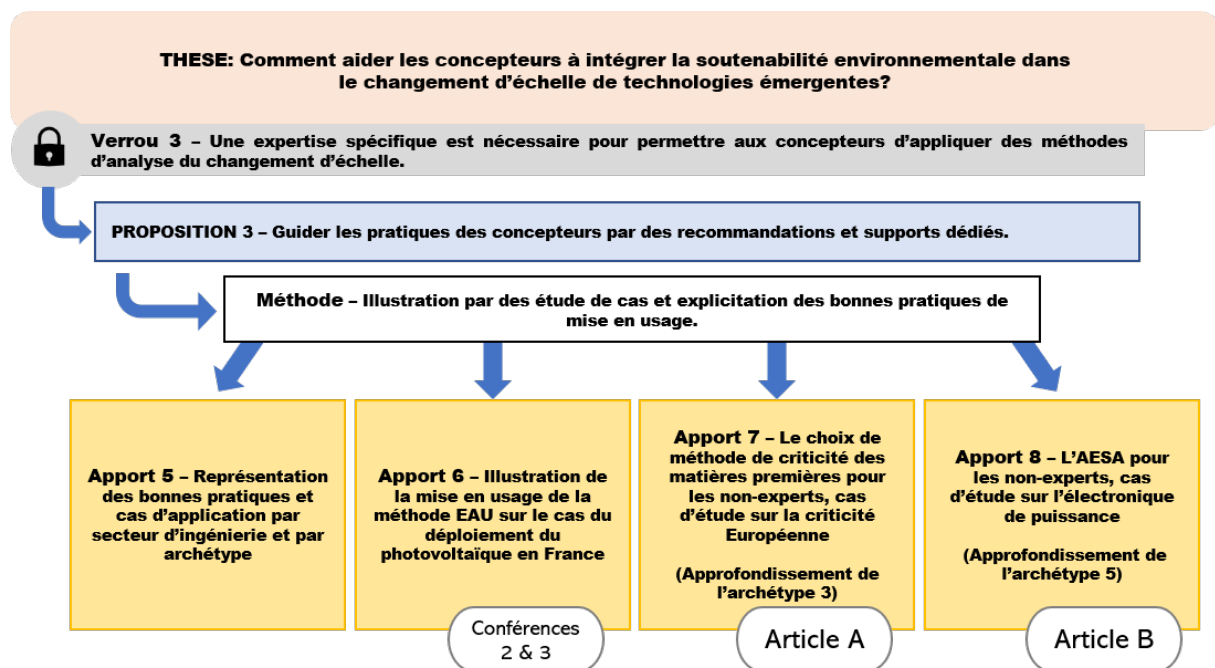


**FIGURE 5.3** – Articulation entre les apports 5,6,7 et 8 de la thèse et la communication scientifique pour lever le verrou 3.

### 5.3.1 Apport 5 - Représentations et outils pour l'opérationnalisation des archétypes

Cette section présente les deux résultats de recherche les plus évocateurs en termes de didactique afin de rendre accessibles les travaux développés dans l'ensemble de la thèse. Cet ensemble de travaux est regroupé sous l'appellation *Apport 5*.

#### Outil de dissémination : les représentations symboliques des archétypes

L'approche par archétypes du changement d'échelle a permis d'identifier des invariants en illustrant leurs manifestations à travers une grande variété d'étude de cas provenant de plusieurs champs d'ingénierie (e.g. énergie, mobilité, chimie).

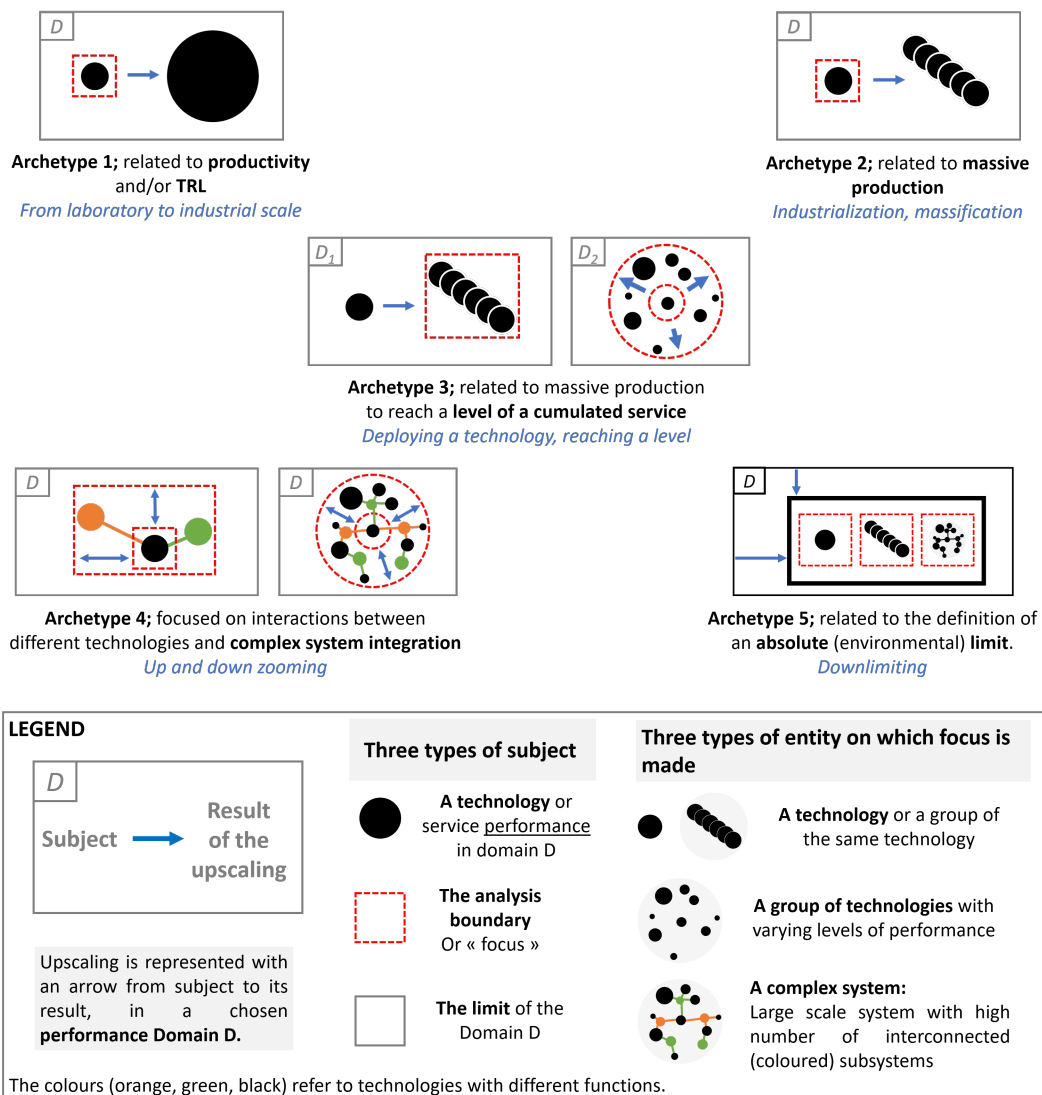


**FIGURE 5.4** – Schématisation générique pour les cinq archétypes de changement d'échelle.

Pour se départir des spécificités de chacun de ces champs d'ingénierie et gagner en généralité, des symboles ont été développés. Les illustrations des cinq archétypes sont représentées en **Figure 5.4** ainsi que la légende permettant de les lire. Ces symboles ont pour objectif d'incarner les archétypes et de montrer qu'ils sont applicables en tant que typologie à toutes technologies. Ces représentations ont été introduites pour la première fois en conférence puis complétées dans l'**Article 1** (Cf **chapitre 6, sections 6.1 et 6.2**).

### Outil bibliographique : la matrice UA-EF

La **Figure 5.5** est un outil d'organisation de la littérature scientifique. Une version pleine page est disponible en **annexe A.4**. Cette matrice a initialement été développée comme une représentation des points forts et des tâches aveugles de la revue de littérature pour les méthodes techno-économiques (**Article 1**, voir **section 6.2**) (icônes bleues) et d'analyse environnementale (**Article 2**, voir **section 7.1**) (icônes vertes) pour le changement d'échelle en 2023.

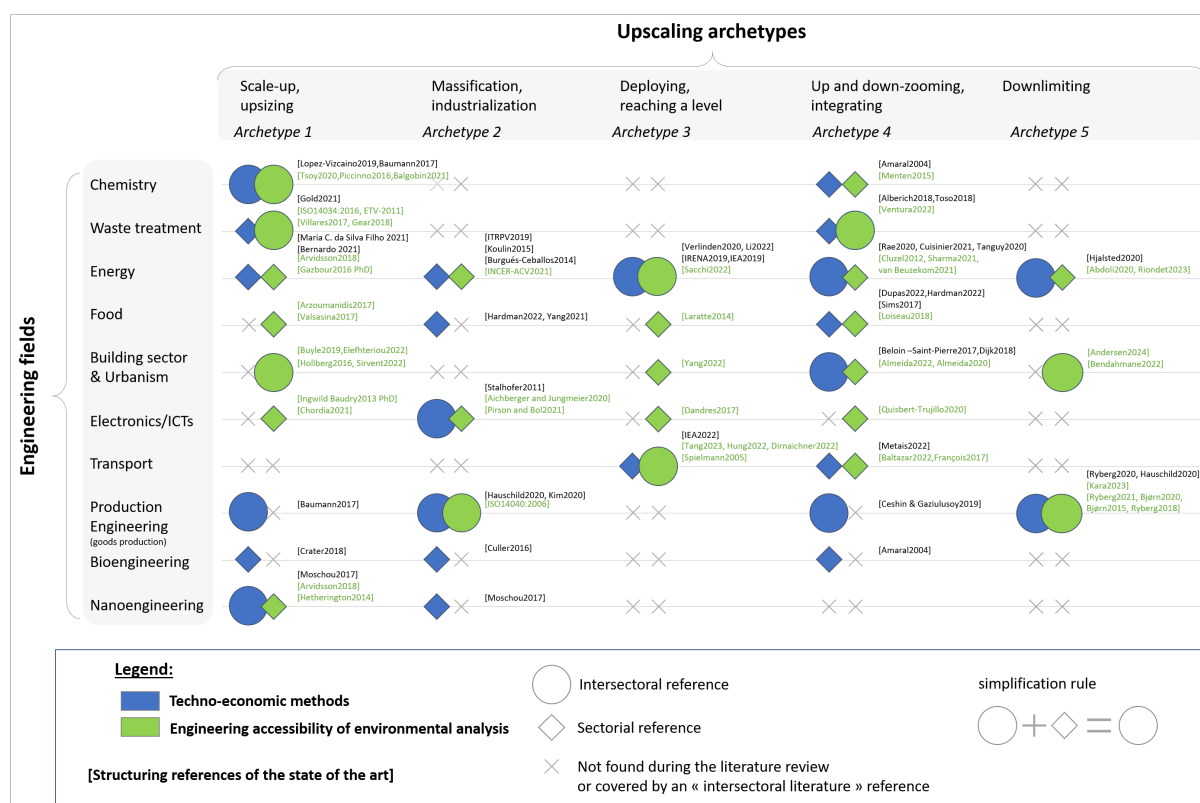


**FIGURE 5.5** – Matrice UA-EF (archétypes - Champs d'ingénierie) présentant les méthodes techno-économiques (bleu) et d'analyse environnementale (vert) identifiées dans la littérature en 2023.

Cette représentation visait à mettre en perspective les recommandations proposées par

archétypes de changement d'échelle (*Upscaling archetype* (UA)) en terme de discipline d'ingénierie (*Engineering Field* (EF)). D'où sa dénomination de matrice UA-EF.

Elle permet d'illustrer que notre processus de littérature a fait émerger plus de références dans certains secteurs que dans d'autres. Par exemple, le secteur de l'énergie est mieux documenté par archétype que celui de la nano-ingénierie en 2023. Cela permet ainsi de mettre en garde les concepteurs dans ce secteur que la genericité des recommandations ne s'applique peut être pas à leurs objets d'étude. A l'inverse, les concepteurs dans le secteur de l'énergie, du bâtiment ou de la conception produit par exemple, peuvent se référer plus facilement ces références puisqu'elles proviennent en partie de ces champs d'ingénierie. Dans un second temps, la matrice UA-EF a été transformée en outil de conception et intégrée dans le processus EAU (**Article 3**, voir **section 7.2**). Elle invite à mutualiser les recherches bibliographiques au sein de l'équipe de conception et à capitaliser sur des recherches antérieures.

Pour finir, la reprise du formalisme à quatre étapes de l'ACV, en tant que référence commune aux équipes de conception, dans le processus EAU et pour les recommandations d'application de l'AESA (apport 8, voir **section 5.3.4**) est considérée comme un résultat de notre approche didactique. Cette exigence nous a conduit à produire des visuels pour l'adoption des concepts et méthodes de la thèse.

### 5.3.2 Apport 6 : Cas d'illustration de l'analyse environnementale du changement d'échelle

La communication scientifique de la thèse orientée vers l'opérationnalisation des travaux de thèse est principalement concentrée sur le processus EAU. L'apport 6 est donc assimilé au cas d'illustration du processus EAU visant à démontrer la faisabilité de combiner la prise en compte de plusieurs archétypes de changement d'échelle en ACV.

L'**Article de Conférence 2** (CIRP LCE 2023, voir **section 8.1**) est intitulé « *Assessing energy technologies sustainability : upscaling photovoltaics using absolute LCA* ». Il présente un premier travail de combinaison entre AESA (archétype 5) et des scénarios prospectifs sur une technologie immature du photovoltaïque (tandem perovskite-silicium) et une technologie industrialisée (silicium monocristallin). Les résultats d'ACV sont issus de la littérature scientifique. Le principal résultat de ce travail est la mise en oeuvre d'une limite environnementale basée sur la limite planétaire de changement climatique, pour une unité d'énergie produite, entre 2020 et 2050. L'article fait donc la comparaison à différents horizons temporels de la limite environnementale et des résultats d'ACV.

Cette étude permet de définir un nouveau levier de conception en liant les performances techniques visées à une date donnée et les contraintes environnementales à respecter pour que l'usage de la technologie soit considéré comme soutenable.

**L'Article de Conférence 3** (CIRP LCE 2024, Cf **section 8.2**) s'intitule « *Toward eco-design for upscaling : an illustrative case study on photovoltaic technology in France* ». Elle présente un cas d'illustration du processus EAU en explicitant les activités de modélisation pour l'équipe de conception : dans cet article, un modèle simplifié du cycle de vie de panneau photovoltaïque est proposé, ainsi que l'utilisation d'une stratégie d'industrialisation pour 2050 et de la limite environnementale reprise et adaptée de la conférence 2. Le cas d'étude montre donc une combinaison de l'ACV prospective et de l'AESA permettant de prendre en compte les archétypes de changement d'échelle 1 (*maturing*), 2 (*mass-producing*), 3 (*reaching a level*) et 5 (*down-limiting*).

### 5.3.3 Apport 7 : la criticité pour les non-experts, cas d'étude sur la criticité Européenne (Approfondissement de l'archétype 3)

Nous nous sommes intéressés à la criticité pour ce qu'elle exprime des implications à un niveau sectoriel du déploiement d'une technologie. Les indicateurs de criticité constituent pour nous une métrique, potentiellement intégrable en conception, s'inscrivant dans l'analyse de l'archétype 3 (*reaching a level*) du changement d'échelle.

Durant les travaux préparatoires du cas d'étude sur le photovoltaïque, nous avons choisi d'appliquer la méthode de la criticité Européenne (EC-RMC) au secteur du photovoltaïque en France. Une version obsolète de la méthode (EC-RMC 2014, [109]) ne permet pas de « sectorialiser » l'analyse, c.-à-d. de différencier la criticité selon le secteur industriel considéré (e.g. énergie, mobilité, bâtiment). En identifiant des pratiques similaires dans la littérature, nous avons donc entrepris d'adapter la méthode pour pouvoir comparer la criticité des matières premières pour le secteur du photovoltaïque par rapport à la moyenne des autres secteurs. En nous documentant sur la version actualisée de l'EC-RMC (2017) [62], notre analyse montre que les tentatives d'adaptation de méthode, pour le cas de l'EC-RMC, sont parfois incompatibles avec les objectifs ou le périmètre d'étude de la méthode. **L'Article A**, intitulé « *A review of the application of the European Commission Raw Material Criticality Assessment Methodology : Towards a comprehensive framework for criticality assessments decision-making.* » (Cf **chapitre 8, section 8.3**), propose donc une grille d'analyse permettant à des utilisateurs non-experts de formaliser leur besoin en analyse de criticité et de le comparer avec celui d'une méthode de criticité. La méthode EC-RMC a été utilisée

comme cas d'application pour montrer que cette grille d'analyse peut aider au choix d'indicateurs de criticité pour des non-experts.

#### 5.3.4 Apport 8 : l'AESA pour les non-experts, cas d'étude sur l'électronique de puissance (approfondissement de l'archétype 5)

L'AESA permet de définir une référence avec laquelle comparer les impacts environnementaux d'un système. On peut considérer cette approche comme une forme de normalisation en ACV : cette normalisation n'est pas appuyée par une pondération des résultats par des profils d'utilisation moyen, mais s'appuie plutôt sur des modèles environnementaux (e.g ; limites planétaires) et une réflexion éthique en lien avec le système étudié. C'est précisément cette expertise, incarnée par la notion de « principes de partage » (*sharing principle* en anglais) au coeur de l'AESA, que nous nous proposons d'intégrer en conception. L'**Article B** (Cf **chapitre 8, section 8.4**), intitulé « *Sharing principles in AESA : help designers get a foot on the ladder.* », propose ainsi une méthodologie guidée pour appliquer l'AESA. Cette méthodologie, appuyée par un cas d'étude sur un système de l'électronique de puissance (convertisseur Buck), se concentre sur le choix de principes de partage en accord avec une vision produit. Pour finir, cet article propose également des recommandations génériques pour orienter l'utilisation de l'AESA à des fins d'éco-conception pour des non-experts.

Pour conclure, les apports présentés dans ce chapitre s'articulent autour d'une approche didactique permettant d'appréhender de nouveaux concepts (archétypes) et de nouvelles méthodes et pratiques d'analyse (ACV prospective, AESA, criticité Européenne) pour l'anticipation et/ou l'analyse du changement d'échelle d'une technologie (proposition 3). Les apports 5, 6, 7 et 8 de la thèse détaillent les outils développés (symboles, matrice UA-EF) et les cas d'illustration pour faciliter l'intégration en conception de trois pratiques : 1) traiter environnementalement le déploiement d'une technologie via un secteur industriel, 2) étudier la criticité des flux de matières associés, et 3) d'analyser la soutenabilité d'un déploiement de technologie ou d'une technologie en termes « absolu ». Ces apports contribuent par conséquent à l'opérationnalisation de l'analyse du changement d'échelle intégrée en conception.

Le **chapitre 9** discute les limites des apports de la thèse et structure deux grandes perspectives de recherche portant sur les archétypes et sur la pratique de l'ACV pour la soutenabilité.



# 6

## Conceptualisation du changement d'échelle de technologies émergentes en ingénierie (proposition 1)

### Sommaire

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## 6.1 Conférence 1 : Vers l'intégration en conception de produit de l'analyse du changement d'échelle

### Stratégie de communication scientifique pour la Conférence 1

L'**Article de Conférence 1** a été présenté à la conférence *CIRP Design* en le 28 Mars 2022 dans la session *Design for Sustainability* pour présenter une première forme des archétypes du changement d'échelle aux communautés de concepteurs.

Cet article s'intitule « *For an upscaling assessment integration in product design* » et constitue les **pages 78 à 84** de la thèse.

### Abstract

*Reaching 2015 Paris Agreements means targeting zero-carbon emission worldwide societies by the second half of this century. It implies a wide-ranging transformation of all industries, supported by the deployment of numerous technologies at unprecedented industrial and time scales. This paper questions the definition of the concept of "upscaling", often related to transitioning, used in different scientific communities without explicit definition shared across disciplines. A literature study is therefore carried out to investigate the characterizing factors defining "upscaling" as a transforming function applied to a studied system or a study boundary, and taking it from one state to another. The proposed analyzing framework enables us to establish five archetypes of upscaling. In addition, we itemize for each archetype, design methods used to consider and/or anticipate a "change of scale", relying on techno-economic models or dealing with environmental aspects supported by partial or a system approach. Finally, the paper concludes on the current options helping product designers assess the environmental impact generated by its design choices in the context of upscaling.*

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## For an upscaling assessment integration in product design

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### Abstract

Reaching 2015 Paris Agreements means targeting zero-carbon emission worldwide societies by the second half of this century. It implies a wide-ranging transformation of all industries, supported by the deployment of numerous technologies at unprecedented industrial and time scales. This paper questions the definition of the concept of “upscaling”, often related to transitioning, used in different scientific communities without explicit definition shared across disciplines. A literature study is therefore carried out to investigate the characterizing factors defining “upscaling” as a transforming function applied to a studied system or a study boundary, and taking it from one state to another. The proposed analyzing framework enables us to establish five archetypes of upscaling. In addition, and for each archetype, examples of methods commonly applied to consider and/or anticipate a “change of scale” in product design have been selected. They rely on techno-economic models or dealing with environmental aspects supported by partial or a system approach. Finally, the paper concludes on the current options helping product designers assess the environmental impact generated by its design choices in the context of upscaling.

**Keywords:** Upscaling, Integrated design, Design to Environment, Planetary Boundaries, Sustainability

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### 1. Introduction

Rockström *et al.* (2009) [1] complemented by Steffen *et al.* (2015) [2] defined the planetary boundaries, in which all mankind activities should be contained. Their work results in the definition of a *safe operating space* at a global scale based on the latest environmental science outcomes (including climate change). Thus, transitioning is a means to target tomorrow's activities into this space, including mitigate global warming below two degrees Celsius. As Geels *et al.* (2017) [3] note, “low-carbon transitions are goal-oriented or “purposive” in the sense of addressing the problem of climate change”. This dynamic has to be included into a systemic vision considering the interdependency between planetary boundaries. This implies a wide-ranging transformation of industrial processes and infrastructure, supported by the deployment of various technologies at unprecedented industrial space and time scales. Therefore, any designer working on such promising technologies or processes should investigate the technology capacity in reinforcing the transition phenomenon or restricting it. To do so, designers have to assess the sustainable potential of a given technology or process. More precisely they have to question the relevance of the development of a product based on its early stage performances. Questioning this relevance with accuracy would then guarantee the sustainable targets to be reached with precision [4]. In that context, the term “upscaling” is increasingly used in the literature, but seems to cover several phenomena, methods or approaches more or less related to

transitioning. In response, this article proposes (in section 2) a framework to explicitly characterize an upscaling in design discipline. Five recurrent archetypes of upscaling have been found in the literature study. Each case is documented, characterized, and associated with existing tools, preferably in design. Finally, section 8 discusses the accuracy of the theoretical framework to illustrate cumulative effects coming with upscaling, and the design methods to assess sustainability.

### 2. Upscaling characterization

In this article, design is associated to processes leading to develop a product, process or service. Likewise, upscaling is defined as a transforming function applied to a studied system or a study boundary, and taking it from one state to another. According to the literature review presented in the following sections, several characteristics are needed to fully distinguish one type of upscaling from another. As a consequence, a theoretical framework is proposed to characterize an upscaling based on three interactive components, a subject, a scope and a goal (see Figure 1);

- The subject on which the upscaling is applied, can be a physical system as well as a service provided by a group of technology. It can also be virtual as the boundary of an analysis or a theoretical limit as discussed in section 5, 6 and 7.
- The scope includes two characteristics: the type and the boundary of the analysis used to carry an upscaling.

- The type of scope can be techno-economic, environmental, social or of multiple kinds. It defines the “Domain(s)/Dimension(s)” on which the upscaling takes place, is represented and is studied. For instance, in the case of a technology upscaling, the scope is usually a techno-economic type and the domain in which the upscaling takes place is the technology Readiness level (TRL), productivity, and/or size of the system. The domain is thus a space linked to a performance or a design indicator.
- The focus of the scope, or boundary, can be centered on the subject of the upscaling but not necessarily. It characterizes the interest core of the upscaling and can be seen as its perimeter. It can also be associated with a time specification by including one or several steps of the life of the subject, such as production or use.
- The goal of the upscaling sets the adequacy and relevance between the scope and the subject of the upscaling. It is based on performance indicators, for instance, increasing the maturity of a process, which is a techno-economic goal. Finally, the goal can be future-oriented (i.e. prospective), retrospective or neither of those.

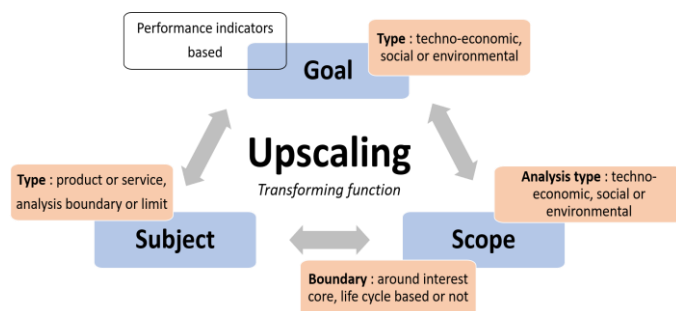


Figure 1. Scheme of the three components characterizing an “upscaling”

Five types of upscaling have been identified, each one corresponding to a recurrent set of the triplet (subject, scope, goal) seen in the literature. These types are proper to one activity sector, or on the contrary common to different disciplines and professions. To each definition corresponds several representative examples of analysis methods and tools. Some are generic, effective and well developed, others are more discipline specific and/or in development. Moreover, according to the activity sector, the term “upscaling” is replaced by “scaling-up”, “scaling”, “sizing”, or related to “massification”, “deployment” and/or vocabulary about “level” in the system engineering science.

From now on, the term “upscaling” will be used generically and one or several synonymous will be proposed in the titles of the sections dedicated to each of the five identified archetypes.

## 3. Upscaling – Upsizing: from laboratory to industrial scale – (a) type

The problematic of designing a process on an industrial scale in a laboratory context is well known in chemical industry and explicitly called “scale-up a process or a technology” [5-6].

The usual goal is then to improve the maturity of a technology/process from the laboratory to industrial scale by increasing the quantity produced per unit of machine and time while minimizing cost. The related upscaling domain is associated with a production capacity indicator. This type of upscaling is assimilated to a design process, applied to a technology, based on an empirical step-by-step method. This process corresponds to successively validate the level 4,5,6 and 7 of the TRL scale defined by the European Commission [7]. The upscaled system obtained confers larger performances than the initial laboratory system ones (i.e. the subject) as represented in Figure 2. The D plane refers to the domain of performance of one system unit. The boundary of the scope is represented by a red dashed box and the upscaling function by a blue arrow, from the subject until the result of the upscaling—so-called the system at an industrial scale. The diameter of a circle in domain D is correlated to the intensity of the technology’s performance.

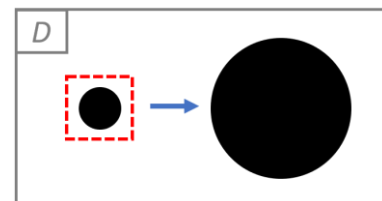


Figure 2. Scheme of the upscaling transformation (blue arrow) applied to a technology (left dot) in a domain of performance D (larger grey square), with a focus on the subject (red dashed square).

In Chemical Engineering and for processes, size is usually correlated to maturity/productivity [6] as represented in the upper part of the Figure 3. But this definition is also relevant for miniaturization phenomenon in electronic microchip industry or yield maximization in PV cells designing. In these cases, the aim is to increase performance per unit of system or surface. Thus, this first definition can be generalized as follows: upscaling a system corresponds to applying design methods to improve performance per unit of system. Note that this upscaling is observed even after reaching the industrialization state (TRL 9 scale). Some technologies, such as wind power systems, have an upsizing trend since they were first commercialized in the 1980s (cf. the lower part of the Figure 3 as an illustration of the type (a) upscaling). Finally, “giga-factory” could also be seen as a result of an upscaling applied to a classic size plant.

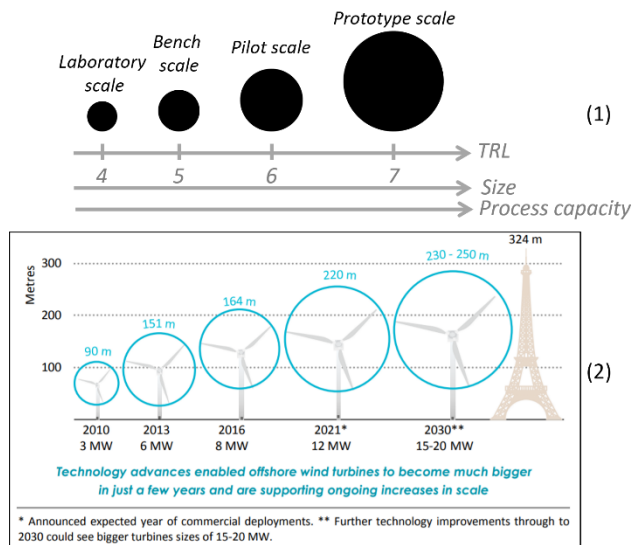


Figure 3. Examples in literature of upscaling: (1) scheme inspired from Lopez Vizcaino *et al.* 2019 [6], (2) picture extracted from IEA report [8]

## Analysis tools and methods

The type (a) upscaling is usually managed with models such as empirical power laws (so-called *scale laws*) [9] and guidelines. These guidelines are based on Design of Experiments (DoE) methods, implying the collaboration between designers of the early-stage technology, engineers, and manufacturers to ensure an operating space of the upscaling, and to guarantee the validity of the models' domain [8-10]. Therefore, upscaling is limited by physical or techno-economic limits: heat evacuation, mechanical strength (e.g. chemical vessel size) or specific limits, for instance the Shockley-Queisser limit for yield of a P-N cell in photovoltaic science. These limits can be expressed through a maximum diameter of the right circle in Figure 2.

Balgobin and Evrard (2020) [11] propose a method to implement Life Cycle Assessment at the early design stage to anticipate the potential environmental impacts of a (a) type upscaled system. The main issue being, for the chemical industry, the nonexistence of thermodynamic models to forecast characteristics of the industrial system such as its chemical yield. This uncertainty complexity the prospective analysis and prevent designers from using linear extrapolation of environmental impacts related to the upscaled technology.

## 4. Upscaling – Industrialization, massification – (b) type

In this section, upscaling relates to design methods application aiming to manage and anticipate the massive production of technology. With the (a) type, this type of upscaling is the most common meaning of the term. Its goal can be equated by aiming for the level 9 of the TRL scale. The scope is usually techno-economic, and the focus is made on the performance's subject.

This archetype of upscaling refers to the massive production of the study object (i.e. the initial technology) as illustrated in Figure 4 with similar convention as for Figure 2.

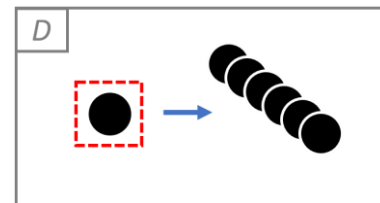


Figure 4. Scheme of the upscaling transformation (blue arrow) applied to a technology (left dot) in a domain of performance D (larger grey square) with a specific focus on the initial technology (red dashed square).

This type of upscaling expresses the different design methods applied to produce massive amounts with the same technology, constrained with techno-economic considerations; any industrialized product may contribute in its illustration.

## Analysis tools and methods

The (b) type of upscaling is managed by classic Life Cycle Engineering design methods: Design for Manufacturing, as well as any additional methods enabling designers to integrate all life cycle steps of a product during the design phase. These methods are known as the Design for X methods. For an exhaustive review, refer to Hauschild *et al.* (2020) [12].

In addition, the economy of scale models and empirical laws (so-called learning curves) are also tools to observe and possibly anticipate a (b) type upscaling. Such models and laws are commonly used in PV industry for instance to estimate future midterm trends of performances per system unit [10][13]. This category of techno-economic tools could be applied to environmental issues as implemented by Gwehenberger *et al.* (2007) [14] with the terms "ecology of scale". This approach does not, however, hinge on systemic and multicriteria analysis in contrast to Life Cycle Engineering methods. This is a serious limit preventing systemic environmental considerations.

LCE methods argued by Hauschild *et al.* [12] are particularly adapted to this upscaling archetype. Life Cycle Assessments conducted attribute the environmental impacts of a product, from the extraction of its raw materials to its end-of-life treatments (from cradle to grave). These assessments are mainly retrospective but outcomes have been raised in recent years about the prospective LCA method, also called anticipative or ex-ante LCA [15-16].

Finally, the (a) and (b) archetypes of upscaling implicitly use a boundary analysis focused on the product (cf. red dashed line in Figure 2 and Figure 4).

## 5. Upscaling – Deploying, reaching a level – (c) type

In contrast to the two previous definitions, the upscaling presented in this section is not a design method, and is not explicitly called an upscaling. However, it is carried by researchers in the energy sector and echoes with transition definition by its goal-oriented characteristic. This third type of upscaling seems similar to a classic industrialization, but its difference relies on the boundary of the analysis, as represented in Figure 5. It illustrates that, in (c) type of upscaling, focus is made on the cumulated performance provided by the multiplicity of the industrialized technology (cf. similar black dots, boxed with red dashed square in the left part of the figure) or variations of technology (cf. variable size dots in the right part of the figure). The explicit goal of this upscaling also differs from the (b) type. As this upscaling targets the sustainability of the entire activity sector considered, or at least mitigating its contribution to climate change. For instance, photovoltaic and generally renewable energy sectors intend to reach an installed power capacity to respond to a national or global demand (e.g. Verlinden (2020) [17] or IRENA reports [18]). In that context, contrary to the (b) archetype of upscaling, the industrialization is not an aim, but a means to be intensified, and market equilibrium is not reached until sustainability, if existing, happen.

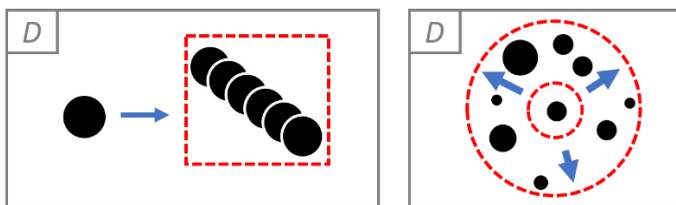


Figure 5. Scheme of the upscaling transformation (blue arrows) applied to a technology in a domain of performance D. (c) upscaling definition referring to the deployment of a technology to reach a level of cumulated performance.

## Analysis tools and methods

This type of upscaling is usually illustrated in technology deployment strategies linked with decarbonization, such as IRENA and IEA publications for photovoltaic or wind power deployments [8][18]. These reports intend to document the feasibility of such future deployments considering for instance raw materials requirements or surface consumption in addition to financial means. In that respect, Material Flow Analysis (MFA) methods are coupled with scenarios and Sankey diagrams can be used to illustrate cumulative effects as raw material criticality [19]. These approaches are sometimes

associated with learning curves and systemic modeling of the value chain of the technology.

It should be noted that this upscaling transformation relies, more than others, on the foresight approach. This particularity bears on the fact that so far, there are no examples of successful country-wide transitions. It therefore requires some strong developments in sustainability prospective methods. A point for reflection could be guidelines to merge MFA with LCA to adapt to the goal and scope of the upscaling.

## 6. Upscaling – Up and down zooming – (d) type

For the present type of upscaling, it is necessary to introduce the concept of complex systems, defined by F. Cluzel [20], as a large geographical scale system including several interacting subsystems. One of the main difficulties to study a complex system is to justify the boundary analysis of the assessment. The building and energy sectors are dealing, with different vocabulary, with the common concept of up and down zooming on a studied system that is part of a larger one. In system engineering, the term “Multi-level analysis” is frequently used to appoint this design thinking. Figure 6 presents a complex system as a group of different technologies with different functions (dots with different colors), interacting (lines between dots). The goal of this upscaling is usually to design or study the entire system or one of its subsystems from a techno-economic and sometimes from the social and environmental point of view. The focus is consequently made on both a subsystem and the system as a whole. The analysis boundary, or the field of study, is considered as the subject of the upscaling (cf. blue two-way arrows). In the Figure 6 upscaling is two-way conducted, from a subsystem to the whole and inversely. There is no starting “state” neither a temporal evolution in this type of upscaling. This archetype rather addresses a change of paradigm in the design method used. In that context, design should be based on systemic approaches considering any system as part of a macro-system, called complex system.

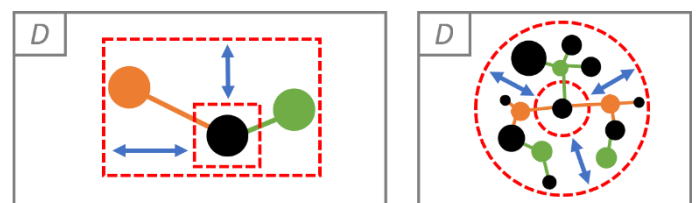


Figure 6. Scheme of the upscaling transformation (blue arrow) applied to the analysis boundary in a domain of performance D. Focus is made on interactions (coloured lines) between different technologies (represented in different colours).

In building and urbanism sectors, following the “urban metabolism” theory of Dijkstra *et al.* (2017) [21], complex systems

can be cities, districts as well as interacting industries. In the energy sector, power plants, transporting and distributive systems and storage systems interact and form an energy system, sometimes named “hybrid energy system” [22].

## Analysis tools and methods

This type of upscaling requires network system modeling approaches to deal with complex system issues. Concerning the building sector, methodological developments are promoted by Beloin-Saint-Pierre *et al.* (2017) [23]. For the moment, however, no methodological consensus has been reached. In the energy and water distribution contexts, mathematical optimization is more and more implemented for dimensioning systems [24-25]. These methodologies require a specific mathematical expertise but software solutions are developed or under development in support to integrate them in design.

Kim *et al.* (2020) [26] present perspectives for eco-design based on a retrospective literature review adapted to multi-level analysis and environmental assessment. The main stake being that LCA applied to complex systems requires large-scale modeling and consequently a huge amount of data. In parallel, a consequential LCA approach has been developed on a national scale to consider techno-economic interactions between systems and resulting environmental impacts [27]. This latest example should be, however, adapted to design practice.

## 7. Downscaling – Down-limiting – (e) type

This type of transforming function comes from the idea of applying absolute environmental limits (global or local) such as planetary boundaries to define a safe operating space. Implementing this space in the design process would lead, as a goal, to an “absolute” sustainability as mentioned by Hauschild *et al.* (2020) [12]. Figure 7 illustrates this concept. The absolute limit is represented by the edges of the domain D. The upscaling is expressed through the transfer of this limit (cf. blue arrows) at the scale of a complex system (1) such as the energy sector; in a subsystem scale (2) or at a unit technology scale (3). Focus is made on the studied system or service provided by a macro or subsystem (cf. red dashed squares). This change of scale archetype can be interpreted as a local expression (black

squares) of a limit that should not be crossed to stay in absolute terms and at macro/global scale in a safe operating space.

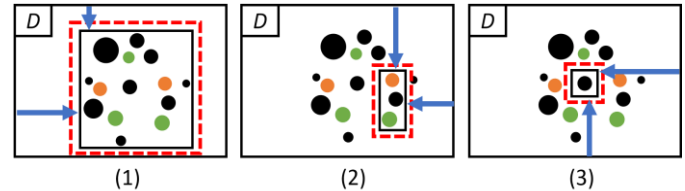


Figure 7. Scheme of the downscaling/upscaling transformation (blue arrows) applied to the limit of a domain of performance D (larger black square) and a complex system (case 1), a subsystem (case 2) or a specific technology/service (case 3).

## Analysis tools and methods

Ryberg *et al.* (2020) [28] present a review of applied methods to “downscaling the planetary boundaries” in the literature. These methods follow distributive justice theories and express ways to share (or not) limited resources, including CO2 emissions as carbon budgets.

Complementary to these methods, Bjorn *et al.* (2020) [29] set out a methodological framework to apply environmental boundaries in LCA and to the process level.

## 8. Discussion

The provided framework has the following added value for product designers: first, it allows to assimilate a phenomenon to one of the five archetypes identified in this article, or to create a new one by characterizing a set of the triplet (subject, scope, goal). Second, it is possible to combine archetypes as elementary functions to describe multiple dynamic phenomena that compose a transition. For instance, where (a) type is focused on the initial subject, (c) type happens later in the process of industrialization, and deals with its macro effects. Therefore, the combination of both, represented in Figure 8, may help to study cumulative effects such as criticality of raw materials or rebound effect [30]. In our case, the rebound effect refers to the discrepancy between two effects: on the one hand the increase of technology’s efficiency results in the reduction of resources’ consumption per system. On the other hand, total consumption is still rising because of massification and deployment of the technology. This second dynamic is sometimes driven by unpredicted usages. These two dynamics happen successively and are usually studied separately with different tools, by different professions. Thus, representing



them as a whole could facilitate the identification of rebound effect phenomena during the design process.

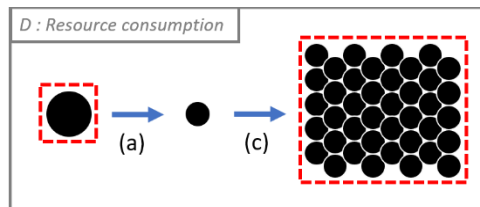


Figure 8. Illustration of composition of two types of upscaling, (a) type and (c) type, resulting in a rebound effect in resource consumption domain, aiming to an integrative design with a focus on cumulated effects.

Finally, this framework enables us to represent what could be a design method in the absolute sustainability paradigm [12] [31]: on the one hand, by analyzing an upscaling (for instance (a) type) from several perspectives illustrated by economic, social and environmental domains in the left part of Figure 9. Note that this upsizing can be assimilated to a downsizing in another domain than the techno-economic one usually chosen.

On the other hand, this framework promotes a design by constraints of different natures (i.e. economic, social and environmental). This supports the creation of a sustainable “solution space” for designers. An illustration of this design by constraint method is proposed in the right part of Figure 9: a techno-environmental limit is built in the productivity domain (cf. green square) to lessen the result of an upsizing transformation (1). To do so, a carbon budget (cf. black square in GHG emissions domain) would be produced by a down-limiting (2), as a local expression of the absolute limit in the GHG emissions domain. Then this local limit would be transferred to the productivity domain as a techno-environmental limit.

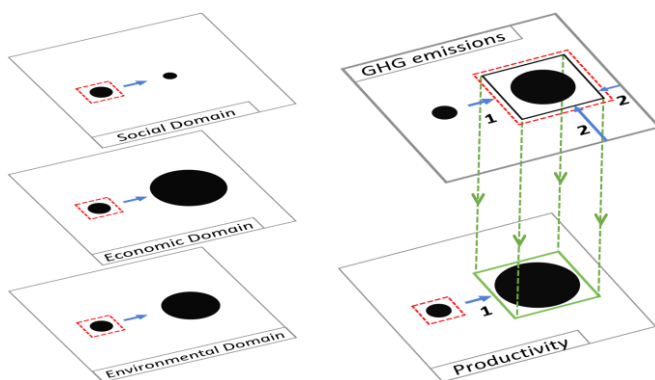


Figure 9. Scheme of a multi-domain representation of an upsizing in several domains (left) and the use of a down-limiting transformation (2) to define a productivity operating space (green square) for an upsizing (1), limited by environmental absolute limits transfer (right).

Lastly, and concerning the limits, this framework does not enable the clarification of the scope in terms of life cycle phase. In other words, a picture for studying a system in its manufacturing phase or in its whole life seems identical. There is also no distinction of time amplitude associated with each upscaling archetype.

## 9. Conclusion

This article proposes a theoretical framework characterizing the upscaling as a transforming function. Five archetypes of upscaling have been identified in the conducted literature review. Type (a) and (b) could be defined as current integrative design methods, type (c) and (d) as systemic analysis methods and type (e) as a method in progress to deal with absolute sustainability in design. This study shows the diversity of disciplines and sectors communications in current years, historically techno-economic oriented, that intend to integrate environmental aspects in the design process. It has been noted that LCA is implemented in each archetype. These application cases open methodological development opportunities, particularly for prospective and consequential LCA. The proposed framework can be used to combine archetypes together helping designers to identify potential rebound effects that would result from their solutions after being upscaled. Finally, this framework offers a way to illustrate a solution space during the design process in an absolute sustainability thinking.

## Acknowledgements

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## Chapitre 6 – Conceptualisation du changement d'échelle de technologies émergentes en ingénierie (proposition 1)

L. Riondet, M. Rio, V. Perrot Bernardet, P. Zwolinski

SECTION 6.1 – CONFERENCE 1

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## 6.2 Article 1 : Conception pour le changement d'échelle de technologie émergente

### Stratégie de publication pour l'Article 1

L'**Article 1** a été soumis au Journal *Science Design* le 12 Octobre 2023 et accepté le 06 Juillet 2024. Ce journal présente, pour la date du 10 Octobre 2024, un h-index de 25, un impact factor de 2.4, et est catégorisé Q1 pour le domaine de l'ingénierie généraliste (Miscellaneous Engineering) selon la banque *Scimago*. Il a été choisi pour sa ligne éditoriale diversifiée à l'attention des concepteurs. Une première version avait été soumise à *Journal of Cleaner Production* (h-index 309, impact factor 11.1) le 21 Février 2023 et rejetée le 04 Aout 2023 après une première révision. L'objectif de cette première version était de réunir une vision techno-économique et une vision environnementale du changement d'échelle dans un même article pour constituer un langage commun aux communautés de conception et d'analyse environnementale. Ce premier manuscrit, intitulé « *Upscaling of emerging technologies and environmental assessment : review and perspectives for designers and LCA practitioners.* » a alors été scindé en deux manuscrits distincts pour donner l' **Article 1** et l'**Article 2**. Les **Annexes A.4 à A.4** présentent des agrandissements de tableaux et Figures de ces deux articles. l'**Article 1** s'intitule « *Emerging technologies upscaling : a framework for matching LCA practices with upscaling archetypes* » et constitue les **pages 87 à 112** de la thèse.

### Abstract

*Under the umbrella concepts of upscaling and emerging technology, are examined a wide variety of phenomena partly related to societal imperatives (e.g. environment, safety, social justice). The design literature does not provide an explicit common theoretical and practical framework to clarify the assessment method to handle "an" upscaling. In this nebulous context designers are struggling to identify the characteristics to anticipate the consequences of emerging technology upscaling. This article therefore first proposes a structuring framework to analyse the literature in a wide range of industrial sectors (energy, chemistry, building, etc). This characterization brought to light five prevalent archetypes clarifying the concepts of upscaling and emerging technology. Then, a synthesis of invariants and methodological requirements for designers is proposed to deal with upscaling assessment according to each archetype, based on a literature review of existing design methods. This literature review process showed a disparity in treatment for some archetypes, regarding the industrial sector. A discussion*

*is consequently proposed in the conclusion to guide design practices.*

## ARTICLE 1 - Designing emerging technologies taking into account upscaling

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### Abstract

Under the umbrella concepts of upscaling and emerging technology, are examined a wide variety of phenomena partly related to societal imperatives (e.g. environment, safety, social justice). The design literature does not provide an explicit common theoretical and practical framework to clarify the assessment method to handle “an” upscaling. In this nebulous context designers are struggling to identify the characteristics to anticipate the consequences of emerging technology upscaling. This article therefore first proposes a structuring framework to analyse the literature in a wide range of industrial sectors (energy, chemistry, building, etc). This characterization brought to light five prevalent archetypes clarifying the concepts of upscaling and emerging technology. Then, a synthesis of invariants and methodological requirements for designers is proposed to deal with upscaling assessment according to each archetype, based on a literature review of existing design methods. This literature review process showed a disparity in treatment for some archetypes, regarding the industrial sector. A discussion is consequently proposed in the conclusion to guide design practices.

Keywords: Upscaling, Emerging technology, Integrated Design, Literature review, Absolute sustainability

### 1 Introduction

The upscaling of emerging technologies in design and engineering science seems to be regularly examined ([1–3]). However, the assessment of upscaling embodies multiple facets that mobilize in practice a wide scientific literature and multiple areas of expertise. Some of these areas of expertise are not integrated into the identified traditional design framework. Societal imperatives (environment, safety, social justice) are increasingly demanded to be considered in innovation ([4]). In addition, a heterogeneous vocabulary referring to “scales” is used in the engineering literature to designate the relationship between technology and the society adopting it. The literature diversity associated with technology upscaling raises questions about the means that designers can identify to assess this phenomenon. Investigating how these resources align with societal ambitions is also crucial. This motivates the need for a literature clarification, to propose guidelines to designers that are relevant about the technology upscaling they are willing to study. This research paper therefore aims to answer the question: How can the phenomenon of “upscaling of emerging technology” be studied from the new perspectives of design communities? We split our research into two sub-questions: (1) How to characterize the concepts of emerging technology upscaling in the design communities? and (2) What are the engineering methods, practices and guidelines for assessing the “upscaling of an emerging technology” from a design integrative perspective? Section “*State of the art: the “upscaling of an emerging technology” as a catch-all phrase*” presents the context and the formalism developed in previous research. Section “*Method*” details the literature review process used to answer the two research questions. Section “*Results*” develops the results in four parts: First, subsection “*Definitions of archetypes*” addresses the research question (1) by elaborating five definitions for “upscaling”. These characterizations rely on visions from different design communities. Some are specific to one or several engineering sectors, others are generic and transdisciplinary. Second, subsection “*Interactions between upscaling and emerging technology concepts and archetypes*” presents the interactions between the two phenomena of ‘upscaling’ and ‘emerging technologies’ and proposes a synthesis of their respective main characteristics. This research concludes that “archetypes” must be used by designers to fully characterize the “upscaling of emerging technology” in response to question (1). Third, to answer research question (2), subsection “*Upscaling assessment methods for designers, by archetype*” provides an overview, for each upscaling archetype, of assessment methods and practices available in the scientific literature. Multiple examples are provided with an emphasis on interdisciplinary assessment approaches.

Fourth, subsection “*Synthesis for upscaling archetype assessment*” synthesizes some comprehensive guidelines for designers to apply an upscaling assessment.

Section “*Discussion*” challenges the generic character of the findings and the literature review process followed in this paper. A representation of the main structuring references available in the literature review is detailed in the subsection “*A framework for visualizing the selected literature for upscaling assessment*”, coupled with an engineering field perspective. Finally, section “*Conclusion*” summarizes the paper’s findings for designers developing emerging technologies.

## 2 State of the art: the “*upscaling of an emerging technology*” as a catch-all phrase

Upscaling is a polysemic word and used in the scientific literature ([5–10]) in conjunction with number of terms related to scale: *scaling up* ([3, 11, 12]), *growing* ([13]), *deploying a technology* ([14]), *scaling* ([15, 16]), *reaching a level or an industrial/commercial scale* ([17–19]), *improving the scalability* ([20, 21]), using a *scaling law* ([15]), *downscaling* ([7, 22]), *ecology/economy of scale* ([23]), etc. The abundance of keywords alone does not help to clearly define the upscaling and therefore turns this word into an umbrella term. As such, upscaling has a different meaning depending on the design community and the disciplinary field (e.g. chemical engineering ([24]), waste treatment sector ([25]), energy sector ([26]), food sector ([27]), building sector ([16]), goods production engineering ([28]) or nanoengineering ([29])). Indeed, *upscaling a technology* or system can refer to technology maturity issues, industrial techno-economic optimization, technology deployment strategies or technical integration and/or social acceptance issues.

### 2.1 Definitions of an emerging technology

The same polysemy, identified for “upscaling”, goes for the concept of “emerging technology”. Three definitions of an *emerging technology* coexist in common designer language and are often concomitant with the terminology of an upscaling ([30–34]): emerging technology as a promising but unmaturing technology, a minor but growing technology, and emerging from a socio-technical vision.

- ***A promising technology in a laboratory or a maturing technology***: in chemical and bioengineering fields the subject of the upscaling refers to an emerging technology or a process, to be understood as an early-stage technology in a laboratory. “Early-stage” and “emerging” are consistently used as synonymous by the life cycle assessment community [30, 35]. Additionally, institutions such as the European Commission or the *International Energy Agency* ([36]) develop assessments and planification focused on technology maturity, relying on operational performance improvement together with lower cost (e.g. [37] plan). These two types of sources are in line with defining an emerging technology as a promising and novel technology in a maturing process. Both push towards a definition mainly focused on the technological maturity. An emerging technology is thus an immature technology with promising technical and/or environmental performance. This concept is not limited to the improvement of an existing technology. An emerging technology refers in that case to a non-mature technology poised to have a disruptive impact on society with regard to its supposed deployment.
- ***A minor but growing technology, deployed in a market***: also, from IEA publications, the necessary so-called “energy transitions” pull the development of technologies to satisfy a large part of the future energy needs of populations. Thus, an emerging technology in this context is not necessarily a novel or an early-stage technology but more an industrialized technology which is still marginal in the market. For instance, renewable energy systems such as wind power and photovoltaic are considered as “early adopted” technology by IEA (i.e. not *early-stage* technology). Both systems account together in 2020 for less than 4% of the world energy mix ([36, 38]). They are, however, purposed to become dominant in national energy mixes to satisfy carbon emission policies to tackling climate change. In addition, the concept of “materiality” defines the point at which a technology reaches 1% of the world’s energy mix. Thus, the requested development of renewable energies in the transition scenarios, turns them into emerging technologies in terms of market/energy mix integration ([39]). This definition is consequently affiliated to the terms “technology adoption” and “materiality”. [32] detail five items from the scientometric domain to characterize an emerging technology: “Radical novelty, relatively fast growth, coherence, prominent impact and uncertainty and ambiguity”. “Prominent impact” is relative to expectations, imaginary and “preferred technological future” that designers promote, “relatively fast growth” associated with rapid abundance in literature and “coherence” resulting

from a normative phenomenon on vocabulary structuring the state of the art of the studied emerging technology. [34] reuse three of them to detect emerging technologies in literature (relatively fast growth, radical novelty and prominent impact). Remarks that these characteristics are not specific to *any particular field of engineering or scientific literature*.

- **A technology emerging in a (socio-technical) system:** This interpretation of emerging technology is related to integration in a so-called socio-technical system (*i.e.* society) as illustrated by [40]. The Authors present “technology niches” emerging or not in a socio-technical system depending on its compatibility with the incumbent regime (*e.g.* regulations and policies, road infrastructure, industry structure, market and user practices, etc). It is not a designer perspective but emergence-focused with a systemic vision. Integration issues are for instance addressed in the energy sector, where technologies must adapt to the power grid with geographical and techno-economic constraints. “Smart technologies” are in that context, defined as technologies helping new ones to be integrated (*i.e.* emerging technologies in the network) ([26]). The food sector uses a different terminology (*e.g.* “technological innovations” and “food system”) and emphasizes the social aspect of the emergence ([27]). The emergence of technology is therefore both a technical and a social challenge, dealing with adoption by local populations, for example.

To summarize, terms relating to *upscaling* (or scale) and *emerging technologies* are used in the design and engineering literature repeatedly, without necessarily being connected to a clear definition. Our approach therefore aims to clarify the design vision by building a robust framework for analysing the upscaling according to identified characteristics, as generic and cross-cutting as possible. We define such characteristics as “invariants”. Then, the objective is to empower designers with guidelines directing towards assessment methods for the upscaling of emerging technologies regarding a set definition.

## 2.2 Conceptual framework: upscaling as a transforming function

In previous research, [41] proposed a hypothesis of literature reading to characterize an upscaling process. The upscaling is assumed to be a “transforming function”, meaning a phenomenon applied to a subject and bringing it from one state to another. Based on the elements to be defined in techno-economic analysis (TEA) referring to it, we proposed three interdependent characterization pillars for the upscaling of emerging technology: “*Subject*, *Goal* and *Scope*” (see **Figure 1**).

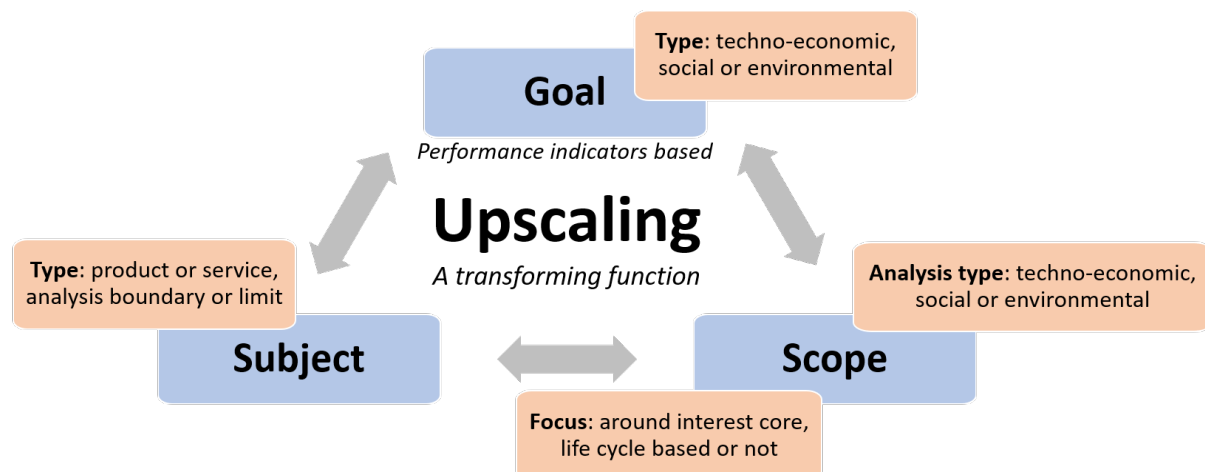


Figure 1: Hypothesis of literature reading: upscaling as a transforming function composed of three interdependent pillars, adapted from [41].

The goal is based on a performance indicator. This means that the transforming function (*i.e.* the upscaling) can be represented on an indicator scale or domain. Moreover, the upscaling subject can be of a different nature, tangible or intangible (*e.g.* a product or service, an analysis boundary or a limit). Whether discipline-specific or not, methodologies

to carry an upscaling rely on the scope defined linked to the goal. The subject is not necessarily the interest core of the scope. However, the scope is fully characterized by a type and the analysis boundary (or focus) pointing to the interest core. This analysis framework enables designers to better define what they mean by *upscaling a technology* by characterizing “archetypes”, *i.e. for a set subject, goal and scope*. However, according to our knowledge, no paper explicitly characterizes the *upscaling of emerging technologies* in design to societal expectations, including sustainability. Additionally, no paper defines the different engineering approaches and methods to deal with the identified archetypes.

### 3 Method

**Figure 2** illustrates the different stages of the applied methodology structuring this article, and shows the four ensuing results providing elements to address the research questions (1) (*i.e.* 1a and 1b) and (2).

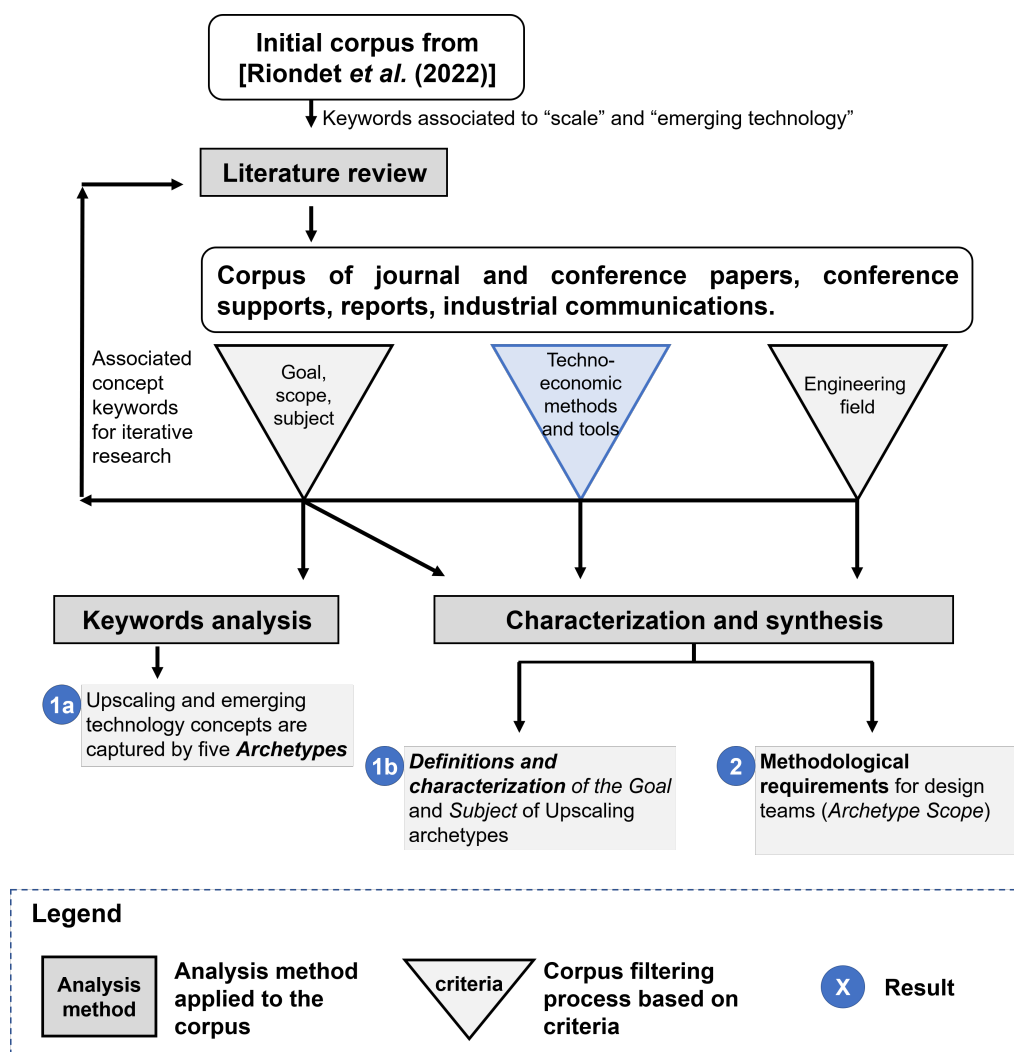


Figure 2: Overview of article methodology and ensuing results. Results 1a and 1b are responses for research question (1), and result 2 for the research question of the same number.

As evoked in the section “*State of the art: the “upscaling of an emerging technology” as a catch-all phrase*”, *upscaling* is considered as a techno-economic phenomenon that can be characterized via the characteristics of the analysis methods



used to assess it. To do so, an “invariant” approach has been carried out, *i.e.* the identification of elements common to several situations, enabling us to generate the missing homogeneous definition of a phenomenon. This analysis brings about the proposition of five upscaling archetypes, based on a review of a limited corpus of articles (fewer than 40 references). This paper proposes to confront this hypothesis with a larger corpus and to use it to structure our literature review process. Indeed, because of the large number of articles using vocabulary referring to scale, it was not possible to use “classical” literature review methods. Thus, the methodology of literature reviewing can be described as follows: starting from the references provided by [41], we iteratively expanded the number of reviewed references (corpus) based on two levers: specific search query strings based on keywords and search of reference affiliation in the corpus. Initially key words were chosen related to “upscaling”, “scale”, “scale-up”, “scale up”, and “emerging technology”, and progressively driven by the selected articles (*e.g.* “deployment”, “massification” or “downscaling” related to “planetary boundaries”). The search queries were conducted on Web of Science and Elsevier over the years 2022 and 2023. The affiliations were processed manually on the references of previously selected papers, following successive criteria: “Are the terms *upscaling*, *scaling* or *scaling-up* used in the abstract or the text?”, “are there any words related to *scale* in the text?”, “is the meaning of a keyword like *upscaling* in other related articles used in this article and through which other keywords?”. The reference is kept if the answer to these questions is positive. Additionally, the newly identified keywords are added to the search query strings. This process covers research works that, with a stricter keyword search, would have been ignored due to different vocabulary use. In addition, the selected literature has been restricted to the ten following engineering fields: Chemical Engineering, Waste Treatment, Energy, Food, Building sector and Urbanism, Electronics and *Information and communications technologies* (ICT), Transport, Bioengineering, Nanoengineering and Production engineering. Were therefore excluded from the study upscaling definitions referring to numerical methods in fluids modelling science as a scientific field out of the design literature. For a review in this direction, consult ([6]). The literature review process was maintained until a decrease of new information related to four criteria: *Goal*, *Subject*, *Scope* associated with new upscaling definitions, and new identified approaches or assessment methods referring to it. It ended with a corpus of 270 references, including research papers, conference supports and scientific reports. Then, an analysis was carried out on the corpus to identify the co-occurrences between keywords of articles which were associated with upscaling and emerging technology (*i.e.* words of the research queries). This process has been partially automated with the software “VOSviewer”. This brought about the state (result 1a) (see **Figure 2**) that upscaling archetypes are consistent concepts in the literature, also covering the three “emerging technology” definitions. To complement this state, a systematic characterization of each archetype has been conducted on the Corpus. This led to an exhaustive definition of each of the upscaling archetypes, with examples from several engineering fields. Moreover, a synthesis of the invariant elements, *i.e.* textitGoal, *Subject* and *Focus* as a constituent of the upscaling *Scope* has been provided. (result 1b). In parallel, design and engineering assessment methods for upscaling have been collected. Design guidelines have been extracted from them, based on methodological invariants for each upscaling archetype. These generic guidelines have been produced independent from the engineering field (result 2). An engineering discipline filter has been added to assess the sector or activity influence on the availability of dedicated literature to upscaling.

## 4 Results

This section presents the results obtained from the research questions leading this research paper. Sections “*Definitions of archetypes*” and “*Interactions between upscaling and emerging technology concepts and archetypes*” detail respectively the result 1b and 1a, characterizing the *upscaling emerging technologies* in the design communities. The sections “*Upscaling assessment methods for designers, by archetype*” and “*Synthesis for upscaling archetype assessment*” are dedicated to support and guide the designer to assess an upscaling based on the given definition.

### 4.1 Definitions of archetypes

Structuring the reading of the design literature on upscaling, the following section deepens the definition of five archetypes of upscaling outlined in [41]. These updated definitions are based on a robustness test of the reading hypothesis (see introduction) given on a larger number of references than the one originally proposed. As a result, **Table 1** synthesizes the definition and characterization of these five archetypes in terms of goal, subject and upscaling focus. Each archetype is also associated with keywords, to ease further research on this topic, and is illustrated referring to the nomenclature provided by



[41]. The five following subsections clarify and deepen each archetype definition by providing several engineering-based case study examples.

#### 4.1.1 Archetype 1 - From laboratory to industrial scale: A productivity focus

The first archetype identified is assimilated to design processes turning a “prototype”, usually developed in laboratories or *Research and Development* (R&D) departments, into a device/technology with industrial performances ([12, 17, 42, 43]). The “scale” characterizing the evolution between the laboratory to the industry is systematically identified as a maturity scale, often equated to the *Technology Readiness Level* (TRL) ([11, 44, 45]). This indicator has various definitions according to institutions and purpose ([46]). However a maturity scale usually evolves between 1 to 9, the latter corresponding to the industrialization phase. In the European Commission’s definition of TRL (Council of Europe, 2019) the upscaling can therefore be described as the process enabling a technology turn from the 4th level (prototyping) to the 7th level (prototype at the industrial scale), in one step or several if necessary ([8, 43]). Remark that, the IEA also employs TRLs to categorize the technologies that will be used for the energy transition. Then, the TRL are grouped into four levels: prototype, demonstrations, early adoption and mature (IEA, 2020). In other terms, to move “from laboratory scale to industrial scale” means increasing the technology maturity which can be transposed to productivity and/or size ([42, 47]). In the PV industry, as another example, upscaling is assimilated to “upsizing”, meaning, to increase the size of a solar cell, for a new technology (*i.e.* for OPV technology ([48]) or perovskite technology ([49])), implying to adjust concomitantly its structure design to optimize its performances, such as the mechanical and thermal stability. Thus, the upscaling subject consequently refers to the performance of a technology/production unit (*i.e.* size, productivity, stability, maturity). The objective of the upscaling is to increase the intensity of the production unit performance studied, to be considered as an “industrial” intensity.

It can be noted that, on the one hand, the “industrial scale” supposedly reached TRL 7 depends mainly on the discipline and technology, and can vary from two ([12]) to ten or more orders of magnitude ([42]). For instance ([49]) in photovoltaic engineering, refers to cell area upscaled from 0.1 cm<sup>2</sup> to 10 or 100 cm<sup>2</sup>, while ([42]) in bioengineering, increases the production capacity of a fermentation process from 0.5-10 L to 20 kL to 200 kL with a scale factor of several thousand orders of magnitude. On the other hand, some technologies are upscaled continuously (*e.g.* increased in size) even after their industrialisation (TRL = 9). For instance, commercial wind turbines are intended to measure 230-250 meters and account for 15 to 20 *megawatt* (MW) of installed capacity in 2030, compared to respectively 220 meters and 12 MW in 2021 ([36]). In that regard, the initial definition can also encompass the miniaturization process and yield maximization in photovoltaic cell engineering for instance, as a process leading to increase the productivity per unit of device. Finally, this archetype definition can be expanded to the production unit itself. For instance, [50] use this definition to designate the expansion of a “repair workshop”, remaining on an artisanal scale. Conversely, the term “gigafactory” refers to the idea of increasing the productivity of an industrial process unit or system. In other words, “megafactories” can be assimilated to the result of the upscaling of classic factories to improve their productivity, sometimes up to an explicit scale (*i.e.* the “megawatt” or “gigawatt-scale” of yearly produced battery capacity ([51])).

#### 4.1.2 Archetype 2 - Mass-producing: A producibility and manufacturability focus

The second archetype of upscaling refers to the mass production of given products and design processes. The upscaling would be carried out to facilitate and amplify this mass production. While the first archetype is rather associated with research activities, archetype 2 (*mass-producing*) is predominantly represented in industrial engineering. This implies more specific approaches depending on the industrial sector or the companies. Consequently, examples are numerous but transverse properties conferred by archetype 2 are “learning by doing” culture, being supported by standards, well-established methods, as well as empirical industrial knowledge.

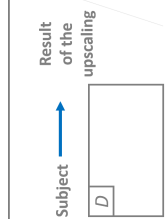
Indeed, according to [39], “scale-up means learning by doing, which takes time in the energy industry”. Depending on the industrial sector, a longer temporality than the previous archetype, up to decades, is applied. Concerning the link with standards, authors call for the creation of dedicated databases (*e.g.* Bioengineering Platform to Industrialize Biotechnology ([52]) and/or creation or alignment with existing standards ([28, 29]). Regulatory uncertainty and lack of standards are an

Table 1: Synthesis of upscaling archetypes definitions with associated keywords and symbolic illustration.

| Upscaling archetype                                | Definition                                                                                            | Usual goal                                                         | Usual subject                                                                  | Focus                                                                           | Associated keywords                                                                                                                                                                                                                                                                                                                                                                                                       | Illustration adapted from nomenclature provided by [41] |
|----------------------------------------------------|-------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------|--------------------------------------------------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------|
| <b>Archetype 1</b><br>Upsizing, scaling-up         | Phenomenon generating a "prototype" at industrial or commercial scale.                                | Maximize maturity (often associated with productivity)             | Technology/service upscaled (e.g. maturing technology)                         | Technology upscaled                                                             | Technology Readiness Level (TRL), Maturity, Industrial scale, Scale-up, Pilot Prototype, Size, Gigafactory, Miniaturization, Early-stage technology, Scalability, Novel technology, Commercial scale, Scale up, Emerging technology, Upscaling                                                                                                                                                                            |                                                         |
| <b>Archetype 2</b><br>Mass-producing               | Phenomenon adapting a technology to be mass-produced                                                  | Maximize productivity                                              | Technology/service upscaled (e.g. novel technology)                            | Technology upscaled in manufacture                                              | Manufacturing Readiness Level (MRL), Learning by doing, Mass-manufacturing, Commercialization, Design standardization, Massification, Industrialization process, Economy of scale, Scalability, Novel technology, Commercial scale, Scale up, Scaling, Emerging technology, Upscaling                                                                                                                                     |                                                         |
| <b>Archetype 3</b><br>Reaching a level, deploying  | Phenomenon translating transitions requirements into technology sector perspective.                   | Reaching a sufficient level of cumulated service                   | Technology upscaled (e.g. early adoption-diffused technology/niche technology) | The service of the group of produced technology                                 | Large-scale deployment, Market penetration, Technology diffusion, Market Readiness Level (MRL2), Planification, Terawatt level (TW), Growth dynamic, Reaching 'materiality', Large-scale production, Raw material criticality, Transitioning, Low-carbon transition, Energy transition, Levels, Niche technologies, Deployment, Technology adoption, Infrastructure, Scale up, Emerging technology, Scaling up, Upscaling |                                                         |
| <b>Archetype 4</b><br>Integrating a complex system | Integration phenomenon of a technology as a part of a larger and complex system.                      | Maximize the efficiency of a complex system                        | Boundary of analysis                                                           | The teroperability to support its systemic integration                          | Grid integration, Interoperability, Acceptability, Network, Smart technology, Complex system, Urban metabolism, Socio-technical systems, Societal transformation, Multi-level, Transition pathways, Territory scale, Transitions, Levels, Niche technologies, Deployment, Technology adoption, Infrastructure, Scaling, Upscaling                                                                                         |                                                         |
| <b>Archetype 5</b><br>Down-limiting, downscaling   | Phenomenon tending to restrict technologies or activities according to sustainability considerations. | Assess the sustainability of a technology, service, human activity | Science-based limit of the domain (environmental limit)                        | The sustainability of a service provided by one or several products, or systems | Planetary boundaries, Safe Operating Space (SOS), Downscaling, Carrying capacity, Share of SOS (SoSOS), Absolute Environmental Sustainability Assessment (AES), Justice principle, Science Based Target (SBT), Absolute Sustainability Ratio (ASR), Eco-effectiveness Planetary scale, Regional scale, Product scale, Allocation factor, Characterization factor, Normalization factor, Scaling                           |                                                         |

#### DIAGRAM LEGEND

- Upscaling is represented with an arrow from subject to its result
- Upscaling takes place in a chosen performance Domain D



- Three types of subject
  - A technology or service performance in domain D
  - The analysis boundary Or « focus »
  - The limit of the Domain D

- Three types of entity on which focus is made
  - A technology or a group of the same technology
  - A group of technologies with varying levels of performance
  - A complex system: Large scale system with high number of interconnected subsystems/technologies

identified barrier to upscaling, especially for certain domains such as food supply with new products (*e.g.* edible insect in the United Kingdom ([53])).

The focus is made on “fabricability” and “producibility” in this upscaling archetype, which means integrating in design additional economic and industrial constraints. For instance, the “panelization” in electronics (*i.e.* units connected as a single array to be manufactured simultaneously) is identified as a means to upscale a product by adapting its shape to processes for mass production ([29]). As a consequence, and based on the model of indicator TRL, the *Manufacturing Readiness Level* indicator (MRL1) is used to reflect a manufacturing capability risks scale from 1 to 10. It notably incorporates material, costs and funding, quality, standards and facilities aspects ([54]). In this framework, the goal of upscaling could be expressed as reaching the 10th level titled “Full Rate Production demonstrated and lean production practices in place”. Other metrics such as Maturity Life Cycle (or Product Life Cycle Stage) from 0, passing to 30 (Industrialisation) to 90 (obsolete technology) in microelectronics seem to transpose the MRL from the point of view of the technology developed ([55]). In this case, the indicator integrates the decline of the studied technology, which is not the case for MRL or TRL.

Thus, the upscaling addressed in this subsection aims at finding the optimal process configuration to massively produce something, while reducing the associated production costs ([29, 53]). To summarize, the goal of archetype 2 is to massively duplicate a product (*i.e.* at “industrial scale”, under profitability implicit conditions), and the subject is the product to be massively produced.

#### 4.1.3 Archetype 3 - Reaching a level and/or managing a deployment: A cumulative service focus

The third archetype identified is assimilated to the processes enabling and managing a technology deployment. This deployment, as a transition, is “purposive” ([40]), which means that products manufactured are considered as a group or fleet, having to satisfy a certain level of requirements. In other terms, upscaling in this subsection could be considered as the implementation of transitioning for a sector or a technology (*i.e.* Photovoltaic industry or *Electric Vehicles* (EV)). This level of cumulated service can be defined relatively to:

1. Past technology deployments observed in other industries. Historical dynamics, following an S-curve trend, give orders of magnitude of critical mass to reach. Also called “materiality”, this quantity can be used to study current or future technology deployment ([13, 39]).
2. A maturity or a share of the market. An example could be increasing renewable energy sharing in the energy mix. The *Market Readiness Level* (MRL2) is an indicator of assessing the risks for emerging technology deployment in an emerging market ([30]) and can be used to characterize a level to reach in this example. In the line, Sims *et al.* (2017) use the indicator current technology adoption rate ([33]).
3. An environmental pressure such as climate change and following scenarios to struggle climate shifts. For instance, the “terawatt (TW) level” in the renewable energy industry sector refers to the order of magnitude of one Tera Watt of capacity installed, and is considered as a titanic industrial and political challenge, but essential to achieve ([19]). The electrical vehicle industry, and more broadly technology industries involved directly in energy transition face similar constraints.

In practice, these three ways to define the thresholds/goals of cumulated service are independent and not necessarily coherent with each other. For instance, [13] confronted “materiality” for wind and solar power with 1.5°C-compatible scenarios and concluded that “some 1.5°C and 2°C pathways pose serious feasibility concerns”, which supposes a premature slowdown of the deployment dynamic or a different political and industrial context of deployment.

Thus, and more than for the others, archetype 3 (*reaching a level*) relies on the foresight approach and future-oriented scenarios. Archetype 3 expresses a phenomenon of form of long-term technology deployment (*i.e.* several decades) on a global ([14, 36, 56]) or national scale ([57]). In other terms, and unlike the second archetype of upscaling, “the industrialization is not an aim” in itself ([41]). Archetype 3 equates industrialization as a means to intensify to reach a (sufficient) cumulated service threshold for a specific technology sector. This sufficiency threshold is defined by societal requirements, including sustainability constraints.

#### 4.1.4 Archetype 4 - integrating a complex system: A interaction focus

The fourth archetype requires first to define a “complex system”. A complex system, according to [58], integrates a large number of units or subsystems, interacting strongly with each other and their environment. Subsystems need not to be “neither structureless nor identical”. They can evolve at different time scales and have different lifetimes. [59] added that complex systems are large-scale systems with a very limited long-term predictability during the design phase and are “supervised by human decisions and management”. Such systems can be entirely technical (*i.e.* a national electricity grid) or socio-technical. Also referred as “networks”, complex systems involve interactions with human behaviour and social and political phenomena ([5]). The concept of “urban metabolism”, in the building sector and urbanism, is another designation to define a complex system with material or energy loops. The objective of the upscaling in archetype 4 is to integrate a system into a complex system or an urban metabolism, and then to improve its efficiency and/or its extent. It is the case for new public transport design in a city ([60]) or city farming implementation into the food system ([27]) for instance. To implement this integration, the upscaling is applied considering the boundary of the analysis. [60] define this process as “broadening the scope of analysis from product-level assessment to national and global levels”. Archetype 4, in a wide framework, applies an “up-and-down zoom” focusing iteratively on the complex system and the designed technology as a subsystem. In other words, archetype 4 gives an expression of the study scope variation (*i.e.* its scale). This archetype highlights the technology integration issues by varying the scope of the study.

#### 4.1.5 Archetype 5 - Down-limiting or downscaling: An absolute sustainability focus

The fifth archetype appears strongly linked to the planetary boundary framework and the concept of absolute sustainability: [61] proposed a theoretical framework based on environmental and systemic Earth science-based results. The so-called planetary boundaries depict limits that mankind should not cross to guarantee habitability on Earth. The planetary boundary paradigm hinges on the concept that human activities are included in a planetary system regulated by nine socio-ecological phenomena, including climate change. Humanity, including industrial development, is therefore summoned to stay in a Safe Operating Space (SOS) to ensure the stability of this bio-chemical system. This framework has been updated four times between 2009 and 2023 ([62], [63], [64], [65]). As presented by [66] referring to absolute sustainability, the goal is not to design a more sustainable product but a sustainable one. [67] set the basic principles for targeting “eco-effectiveness”, as a trade-off between the societal value of the product and the related environmental damages. In that context, “downscaling” and “down-limiting” refer to generating local expressions of global environmental limits (such as planetary boundaries) on the technology scale to limit its unsustainability. This process is also called operating a share of the Safe Operating Space (SoSOS) or defining *carrying capacities*. Those environmental limits the product must not exceed are defined by designers. This challenges the relationship between technology, society and the environment by raising technical and environmental constraints with social justice expectations ([7, 22, 68]). A well-known example would be the concept of “carbon budget” allocated to a country, a specific human activity or a product, to limit global warming below two degrees Celsius (*i.e.* the global threshold associated with the SOS). Each environmental impact indicators are addressed in this approach, not only the climate change. The down-scaling is applied to an absolute environmental limit to assess the sustainability of a product, a system or a human activity. Archetype 5 (*down-limiting*) captures, more than the others, the imperatives associated with sustainability expectations from society. Until recently, it has been identified as a research field in development.

## 4.2 Interactions between upscaling and emerging technology concepts and archetypes

As mentioned in the introduction, archetypes represent facets of the phenomenon of upscaling. They are sometimes evoked as characteristics in a given definition. [26] exemplify this aggregated vision on the case of *Smart Local Energy System* (SLES). Authors provide a definition for upscaling comprising four characteristics overlapping the first four archetypes: “growing” (archetype 1), “replication” (archetype 2), “accumulation” (archetype 3) and “transforming” (archetype 4). This latest characteristic reflects the adaptation of the studied object to the surrounding context of its implementation. This fits well to the archetype 4 definition, by defining the context as the complex system to be integrated. The first four archetypes could also be interpreted as visions of the upscaling from different disciplines’ points of view or different activity-skill perceptions: research and development, manufacturing engineering, planning and industrial management,

systemic engineering, and finally, environmental engineering and justice. Based on such definition process the associated keywords in the related domain literature material have been collected (see **Table 1**, column 6). This content is organized on **Figure 3** based on each archetype identified literature co-occurrence (represented as grey circles). Keywords at the center of the figure are shared by several archetypes. For instance, “Scaling [2-4-5]” means that the word “scaling” is used in relation to upscaling archetypes 2, 4 and 5. Words framed in red are explicitly related to scale or level concerns. This figure therefore aims at helping designers to identify upscaling archetypes interactions and to reinterpret keywords in the light of the established archetypes’ definitions.

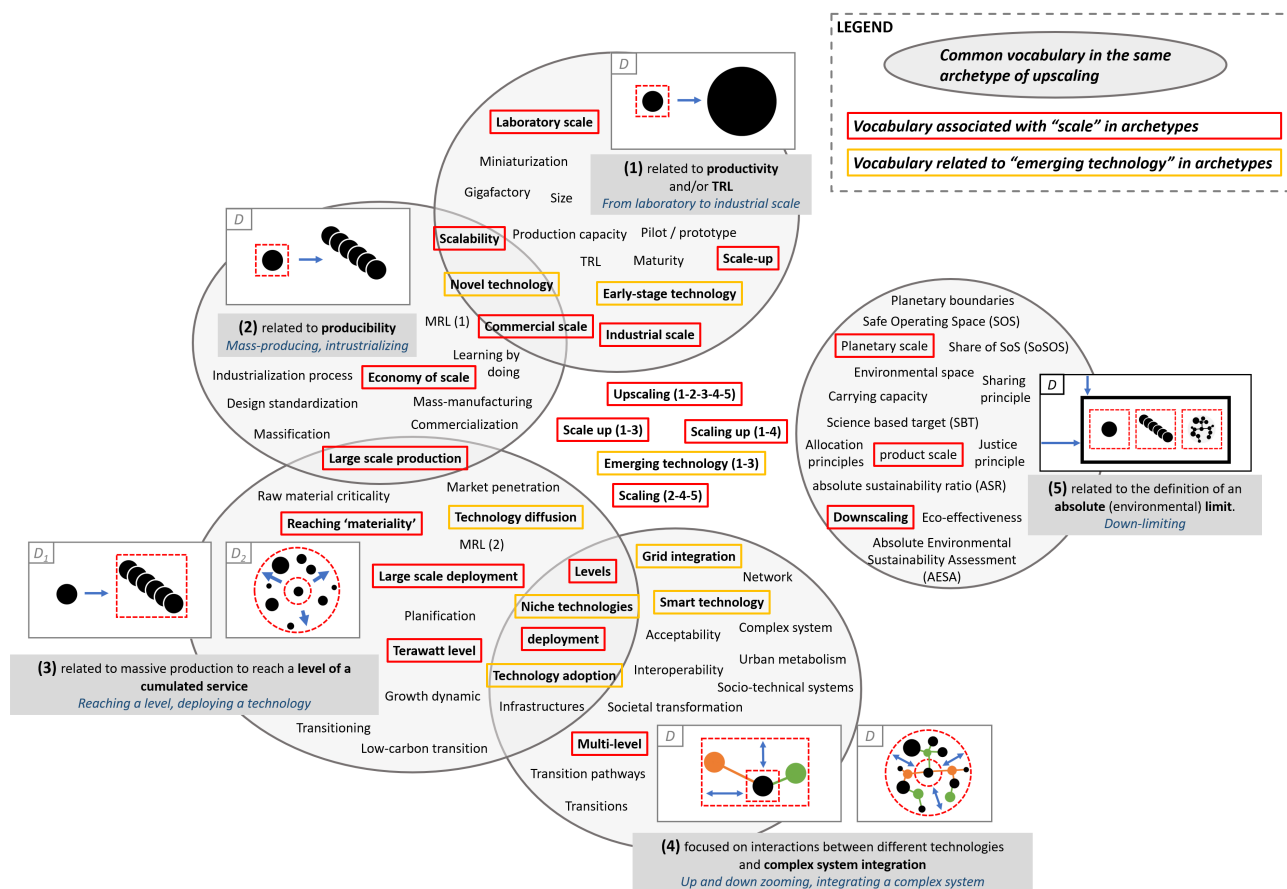


Figure 3: Representation of interactions between archetypes illustrated by their associated lexical fields.

#### 4.2.1 Upscaling archetype interactions

Four main observations can be drawn from this proposed vision of the literature findings:

- Arch 1 and 2 are linked with the scalability property, as the hybridization of upsizing and massification and vocabulary associated with a “commercial scale” and economic consideration.
- Arch 2 and 3 are linked with vocabulary related to “large-scale production”.
- Arch 3 and 4 are linked with “large-scale deployments”, “levels” and “infrastructures” considerations.



- Archetype 5 is isolated from the others which is justified by the fact that it is a relatively new sustainability paradigm, not particularly integrated in the design process or engineering communities. The vocabulary used in the literature material consulted is therefore different despite the term “upscaling” in common with other archetypes.

Note that this representation justifies the use of “upscaling” as a generic term, because it appears in the lexical fields of all archetypes. The term “scale-up” coming from chemical engineering, seems specific to archetype 1, unlike “to scale up” which is a more widespread verb.

#### 4.2.2 Emerging technology definitions and interaction with upscaling archetypes

Complementarily to the “scale” vocabulary analysis, the words framed in black in **Figure 3** are explicitly related to emerging technology concerns. This representation reveals in the literature study the interactions between upscaling and emerging technology concepts, in line with the three main definitions provided by the literature and detailed in section “*State of the art: the “upscaling of an emerging technology” as a catch-all phrase*”; an emerging technology as a promising but unmaturing technology, a minor but growing technology, and emerging from a socio-technical vision. Now confronting upscaling archetype to the concept of “emerging technology”, our main observations are:

- “Emerging technology” and “upscaling” are aligned concepts with the first definition–“maturing technology”–included in archetype 1.
- The second definition–“growing technology”–is covered with the first three archetypes with “novel technology” and “technology diffusion”.
- The third definition–“emerging in a socio-technical system”–is related to archetypes 3 and 4 with “niche technology” to be deployed, and “technology adoption” associated challenges.
- More broadly, the three definitions are more or less divergent and not necessarily consistent with each other as the defined object differs. It depends on the context, discipline study and authors.

Finally, the concept of upscaling archetypes, in addition to characterizing the upscaling, captures the different definitions of emerging technology. From this state and to study the upscaling of emerging technology, archetype will be used as a unifying analysis tool. In other words, assessing the upscaling of an emerging technology involves studying upscaling archetypes.

#### 4.3 Upscaling assessment methods for designers, by archetype

Designers need to be familiar with the methods available to analyse or anticipate the upscaling of a technology. In other terms, the scope of an upscaling (see subsection “*Definitions of archetypes*”) is based on analysis methods and tools. This section therefore tends to characterize the scope of upscaling and establish generic methodological principles, depending on the archetype. The literature study was extended to identify the methods for researchers, engineers and planners (as designers), to assess or anticipate a technology/service upscaling. A synthesis of these methods and principles is available in subsection “*Synthesis for upscaling archetype assessment*” in **Table 2**. The findings detailed in this section show that the existing methods are mainly driven by technical-economic or socio-technical considerations, and rarely by environmental aspects rigorously. Only archetype 3 and archetype 5, present environmental considerations.

##### 4.3.1 Archetype 1 - From laboratory to industrial scale

Increasing productivity/size/stability and increasing maturity from laboratory scale to industrial scale, both require in the chemical industry some discussions between researchers and chemical engineers. This process leads to “empiric rules” and guidelines to deal with upscaling hazards. This discussion appears necessary because of the intrinsic risks induced by the upscaling to the production site (*i.e.* heat evacuation for exothermic reactions). Each context forces R&D teams to “choose the correct conditions to scale” ([69]).

On the one hand, empirical rules and guidelines both illustrate the predominance of *Design of Experiments* (DoE) found in the methods associated with scaling-up a process or a system ([15, 70]). For instance, [43] carried out a step-by-step upscaling on a chemical process (e.g. electrochemically-assisted soil remediation) with four experimental setups based on different capacity productions. The aim was to determine the effect of scale on techno-economic parameters, including the total annual cost of a processing unit. Their work illustrates a “scaling law” development. This model usually translates a simplified relationship between design parameters and characteristics of the designed system, often in the form of a power law. These extrapolation models are sometimes combined with techno-economic limits to qualify their validity domain (i.e. mechanical strength limit for the size of a vessel in the chemical industry or thermodynamic yield of reverse electrodialysis process) ([8, 15]). The Shockey-Queisser limit is another example of a theoretical limit used in research. It represents, in photovoltaic science, the maximum yield value obtainable for a specific cell technology. Researchers, such as [18], use it to characterize the remaining room for improvement in a cell yield according to its structure/composition. Different types of PV technologies are then responses to overtake the limit associated with incumbent individual Si cells (i.e. tandem technology).

On the other hand, due to the cost engaged by such experimentations, numerical tools are also used to simulate, optimize, or study a system ([8, 10, 17, 71]). The main characteristic of optimization is the looping of energy and/or material fluxes. The structure of the laboratory system switches from linear but inefficient, to a more efficient, parallelized and looped structure ([72]). This approach is embedded in the *Systems-Oriented Design* (SOD). In this speciality, the pinch-analysis is an example of thermodynamic assessment enabling designers to minimize the energy consumption of a system by reusing residual heat (or cold) for pre-heating steps. Note that these numerical tools hinge on theoretical models and empirical know-how that have been capitalized during anterior (or parallel) experimentation phases. Consequently, a combination of experimentation and numerical simulations strengthen the upscaling management ([11, 49]).

Several requirements to carry a scaling-up could be summarized as follows:

- Control the technology maturity level and plan accordingly;
- Consider the specific technical expertise of the technology to be upscaled (i.e. theoretical law and/or scaling law, identification of leverages of improvement in the performance design);
- Integrate the design of Experiments expertise, to produce lacking data and documents upscaling models;
- Ensure a strong interaction between researchers in laboratories and engineers in the industry (leading to guidelines and preventive lock-in identification in case of upscaling).

These specificities are mostly relevant in the chemical industry and are transmutable to other sectors.

#### 4.3.2 Archetype 2 - Mass-producing

Mass-producing a technology relies on industrial engineering known how. It aims at developing the corresponding value chain, or adapting the structure of the technology to the existing value chains in an economic model-based perspective. In other terms, archetype 2 follows a normative process driven by industrial planning. This planning is historically based on “learning by doing” methodologies (i.e. industrial sector specific) and usually based on trend extrapolation models.

For instance, in [9] two groups of upscaling strategies related to additive manufacturing are compared: one optimizing the existing production system parameters (operative strategy) and the second focused on the production system change in terms of machine or technology chosen. Each of these strategies is characterized according to several performance indicators (time, cost, quality, “sustainability” and flexibility). This comparison results in a confrontation between three processes and guidelines depending on the economic model chosen (i.e. produced volume desired). In this case the so-called sustainability indicator reflects the energy demand of the machine. This indicator in our view is inappropriate and reveals the difficulties of integrating environmental assessment methods in design, which should involve multiple environmental impact categories (e.g. the nine Planetary Boundaries), as well as sustainability issues that include additional socio-cultural criteria.

Another example of product design adaptation to mass production constraints based on a numerical model can be taken from [28]. The shape of a product (wind power) has been adapted (optimized) to eliminate an energy-cost-effective manufacturing step (a rolling process), and then facilitates mass production by enabling its automation.

Panelization, in electronics, is also a shape optimization to facilitate the mass production of microchips. This production organization for discontinuous processes imposes non-functional shape standards to products to increase the number of produced units per batch. In that context, adapting an emerging technology, even from a different industrial sector (*i.e.* bioengineering), to this production technique would accelerate its upscaling by capitalizing on existing production means ([29]).

Learning curves, such as Moore's Law, remain the most representative methodology to support this upscaling archetype. However as with any extrapolated model, hypotheses sustaining the identified trends are not always explicit (*i.e.* validity domain). They reflect an improvement phenomenon over time, up to decades, as a consequence of production system optimization and industrial know-how development. Such model is used in several industrial sectors for midterm planification (*i.e.* electronics, photovoltaics, agriculture) ([73, 74]). In other terms, learning curves are phenomenological models used to continue a historical trend. They do not, however, provide a systemic understanding of the factors maintaining the trend. The contextual information to interpret their validity domain is rarely presented.

Complementarily, databases concerning the product's process parameters and value chain structure are developed to enhance the skills related to massification. Such available database (if any) can be interpreted as an indicator of the maturity of the upscaling management in a specific industrial sector ([52, 53]). Archetype 2 (*mass-producing*) is based on past centuries of industrial developments, linked to globalization. The business model associated with the mass production scheme is therefore a key parameter linked to the industrial sector(s) involved. This context has motivated the emergence of life cycle engineering, a group of methodologies based on a systemic and integrative approach in industry to support designers with "Design for X" (X stands for manufacturing for instance). It enables the implementation of the industrialization of a product while minimizing cost and externalities ([66]). Industrial engineering know-how, market regulation, policies, trading rules, labour standards, supply chain organization (etc.) are crucial factors that push designers to explore product and process developments, as well as include value-based perceptions in the upscaling assessment they conduct ([53]).

To conclude on, methodological requirements associated with the mass-producing upscaling archetype to designers are the following:

- Control of the manufacturing maturity level and conduct development planning accordingly,
- Design with integrative and normative approaches developed in industrial engineering,
- Define the product's life cycle and its evolution over time associated with a chosen business model (Cf. Design for Life Cycle Engineering methods),
- Choose relevant indicators of performance/value, clarify data collection on purpose, and integrate the ongoing technical/industrial/economic planning, to the upscaling model (*e.g.* evolution of processes, varying product design over time, correctly identifying costs and benefits).

### 4.3.3 Archetype 3 - Reaching a level and/or deploying a technology

Deploying a technology to reach a level of a cumulated service hinges, more than other archetypes, on a foresight approach from a technology sector perspective. Foresight (or prospective) approach uses models to study potential futures and assess their plausibility (as well as their desirability). Archetype 3 (*reaching a level*) follows consequently a decision-support approach, mainly based on scenarios. Some typologies exist but there is no consensus on the way to produce scenarios ([75]). This situation leads to a great diversity of models and the associated indicators of feasibility or reliability.



On the one hand, sectorial consortium (*e.g.* [14]) or specialized researchers (*e.g.* [19, 39, 76, 77]) propose a desired deployment of technologies (*i.e.* renewable energy, electric vehicle) often represented as an S-curve (or exponential curve) from now to a specific time horizon (2030, 2050 or 2070). This model is phenomenological (*i.e.* descriptive for a past trend) and could be considered as one scenario of deployment among others.

On the other hand, more holistic models assess the co-emergence of groups of technologies. For instance, electricity storage technologies are intended to emerge in parallel with renewable energy technologies to struggle with their intermittency. However, their developers, mainly institutional (*i.e.* IEA, ADEME), usually set some performances or some cumulated service targets, for each separated industrial sector assessed ([36, 78]). For instance, the *Réseau de Transport d'Electricité* (RTE), the French electricity transmission system operator presented in 2021 six power production pathways to reach carbon neutrality by 2050 ([57]). Other organisations, focusing for instance on Agriculture technologies include milestones without stating a particular pathway ([33]). [79] present a literature review of prospective criticality for 48 chemical elements. These elements are presented sorted by ten technology categories, making explicit the link between material, product's scale and technology expected deployment.

These two types of propositions are often criticized in terms of feasibility or reliability with regard to historical trends ([13, 80]) and to the associated raw material demands ([31, 81, 82]). A material demand analysis is usually carried out with a *Material Flow Analysis* (MFA). Note that different methodological formats of MFA exist according to the perimeter of the study (*e.g.* national, industrial, enterprise or product level). A synthesis of these methods and their specificities is available in the guide of the *Organisation for Economic Co-operation and Development* (OECD) published in 2008 ([83]). In the archetype 3 case, *Material System Analysis* (MSA) and an Economy-wide MF Analysis (EW-MFA) are usually conducted. Relying on the analysis provided by this method, the “Criticality of raw material” appears as the main constraining feasibility indicator to elaborate plausible scenarios of technology deployment in the energy, digital or mobility ([84, 85]). Again, no consensus has been found in literature to characterize the criticality of a material, leading on again to multiple methodological choices. [86] and more recently [87] documented some non-exhaustive lists of methodology according to the goal, the scope, the outcomes and the operability of the criticality assessment methods targeted. [88] point out, however, the difficulty for materials scientists and engineers to adopt such assessment methods, deeming that the political and environmental issues these methods adress do not fall within the scope of their expertise. In addition, temporal validity of indicators involve regular update of data and a fine understanding of their computation. In addition, the temporal validity of indicators involves regular updates of data and a fine understanding of their computation. It is important to note that MFA and criticality assessments hinge together on material demand data, which was not systematically documented in the European Union before 2012 prior to the Commission Decision has defined the roles and responsibilities of the organism “Eurostat” ([89]). More generally, assessments at such scales are data intensive and consequently studies are made possible generally by public organizations with data collection authorities. Additionally, [88] note that criticality assessment better corresponds to the scale of the product, than of the material. [90] endorse this vision providing an example of the integration of criticality indicators in classic material selection for product design. Criticality assessment would therefore benefit from life cycle engineering, for instance, to evaluate the dissipation of resources (*e.g.* [91]).

Finally, and concerning data management issues, [92] presented a framework to characterize uncertainties in a prospective approach: “Thinking about future uncertainty in terms of multiple plausible futures, rather than probability distributions, has implications in terms of the way uncertainty is quantified or described, the way system performance is measured and the way futures strategies, designs or plans are developed”. This transitioning archetype is thus associated with long-term planification methods, supposing existing models to support decision perspective by providing criteria of go/nogo or at least validity/reliability indicators. This vision is usually referred to as the prospective or foresight approach and relies on:

- A control of the market maturity level and/or a clear goal with a time and spatial perimeter focus on a technology or an industrial sector (*e.g.* carbon neutrality of China for 2060, terawatt (TW) photovoltaic installed capacity in Europe in 2050),
- A technology's performances characterization (implying data collection difficulties),

- Industrial sector data and engineering models (*i.e.* capacity production, material and/or power flows),
- A scenario expertise and a specific data uncertainty management (quality, accuracy, sensitivity) and a model validity domain investigation (*i.e.* hypothesis review). Ideally with a distinction between fields of possible evolution of technological, and industrial including the background context. More broadly, it refers to foresight (or prospective) expertise belonging to a long tradition of thinking ([93]).

#### 4.3.4 Archetype 4 - integrating a complex system

Designing complex product systems or integrating technology into a complex system relies, more than other upscaling archetypes, on a systemic approach focused on subsystem interactions between the designed product and its socio-technical environment (more or less technical or social).

An intelligible example is for designing and managing a power plant or a storage site, both depending on existing grid characteristics ([94]). Concerning the optimization approach, many different models exist (LP, MILP, Master investment algorithms) and are applied to different geographical scales, from city to global scale, with varying optimization horizons (*e.g.* from an hour to several years). For more detailed information about optimization models dedicated to energy system planning, refer to [95]. [16] present a very literal study case of up-and-down zooming on a port city, identified as an urban metabolism interacting with other regions of varying geographical scales (local, national and global). MFA and network representation (*e.g.* Sankey diagram) are very suitable for such assessments. Commercial software is also used to design a digital twin of a local grid composed of power sources, storage and consumer sites (*e.g.* industrial site, houses) and size of it, based on simulations covering several years ([96]).

Another example of complex system design is given by [97] investigating the three different modelling possibilities to consider the performance dependency between charging infrastructures and batteries for electrical vehicles (*i.e.* Node-based, Path-based, Tour-based approach). The key parameters reviewed in 287 articles applied to that study case are the charging station location, its power capacity and its interoperability carried out by interface devices (AC/DC converters) that can be partly embedded in each vehicle. The optimization goal, however, varies in the literature: some studies aim at maximizing the number of EVs charged, others at minimizing the infrastructure cost for a given demand and some, fewer, intend to minimize the distance to a charging station. The design trade-off resulting from these optimizations drastically differ, which consequently highlights the importance of stating the goal of the optimization study and the design parameters chosen to conduct this optimization.

Optimization can also deal with interdisciplinarity, for example with an agriculture-energy system, developed by [98]. This complex system is composed of three subsystems: an irrigation network, crops and an electricity microgrid. Designing the microgrid implies consequently to quantifying the energy demand for water pumping and households, which itself depends on crops. Thus, minimizing electricity cost in this model leads to optimizing the irrigation subsystem. The authors regret economic profit to be used as the indicator, and rather argue in favour of “social benefit” optimization. One of the main drawbacks of the optimization approach is to set predefined rules/constraints that could not be effective all along the simulation which reduces its accuracy for long-term forecasting. This drawback is especially significant in models depending on climate assumptions, for renewable energy planning for instance ([99]). The robustness of the conclusions of such optimization can then be threatened if data assumptions concerning climate change evolve. Evaluation methods therefore exist to assess the “credibility” of a model and are applied to complex systems modelling, including so-called multi-agent models ([100]). System dynamic models are another type of model used at varying scale (*e.g.* house to global scale) to describe and define evolution pathways depending on design or planning decisions.

On the one hand, for local scale (*e.g.* house or city scale), complex system analysis hinge on network biophysical models and also on Local System Analysis (LSA) assessing the fluxes between urban area and nearby ecosystems ([83]). These models are used in the system design approach, illustrated by Toso *et al.* (2018) giving multiple examples of food waste and water treatments ([25, 101]). This approach focuses on the product's service integrating design interactions with its environment (*e.g.* rainwater or heat) and stresses the valuation of co-products to satisfy human needs.

On the other hand, on a larger scale (*i.e.* national or global scale) global biophysical models are completed by socio-economic modelling (*e.g.* IMAGE, REMIND, MEDEAS, WORLD3) to do long-term prospective exercise concerning

climate or resources management ([102–104]). For instance, the “*Shared Socio-economic Pathways*” (SSPs) are scenarios used by the *Intergovernmental Panel on Climate Change* (IPCC) to model five global socio-economic pathways driven by climate policy assumptions distributed between mitigation and adaptation to climate change.

Note that these two developments of system dynamic models are both less, but still, affected by the long-term assumption’s uncertainties. This implies recurrent upgrading to meet upscaling assessments and designers’ road maps.

The literature study investigated in this research shows that in general terms, human behaviour and social aspects, in the energy or mobility sector, are less studied with social science methodologies compared to urban, waste or food/agriculture sectors where they are more prevalent.

The example of the upscaling (*i.e.* integration) of urban farming in the food system given by [27] illustrates this phenomenon. Barriers have been characterized such as the financial one, soil contamination and interactions with urban areas (*i.e.* vandalism or on the contrary involvement of the community). The Authors call for a data-driven approach to identify “market opportunities and revenue streams” to strengthen the business model and best practices. [33] added social organization (*e.g.* social norms, collective actions and private-non-governmental issues) as a key barrier to the adoption of climate technologies in the agri-food sector.

Finally, [105] review multiple examples of models used to consider a product environment, including a system design approach, in a design for sustainability goal, and elaborate a multi-level analysis framework of product design methods. It encourages designers to assess their product based on multi-scale vision, from material or component, to socio-technical systems, and even product-service system vision. This up-and-down zooming on product requires different modelling skills, from technical expertise to social-science-based analysis (*e.g.* consumption habits, community practices, socio-technical system dynamics). By framing the design problem and the scope of the design intervention, this framework pushes for interdisciplinary practices of design and supports designers to integrate into their practices other expertise models. Thus, archetype 4 (*integrating*) is associated with network models and/or techno-social approaches hinging on:

- System dynamic engineering, requiring specific resource management (data and computing) due to the high complexity of models with different levels of integration (product/service),
- Interoperability between models linked to the product/service integrated in a complex system,
- Culture of trade-offs from optimization modelling or socio-economic expertise,
- Multidisciplinary approach.

#### 4.3.5 Archetype 5 - Down-limiting or downscaling

As opposed to the first four archetypes, archetype 5 (*down-limiting*) is intrinsically bound to an environmental sustainability paradigm as it is associated with the planetary boundary (PB) framework. [22] develop the main assessment method supporting this archetype, called *Absolute Environmental Sustainability Assessment* (AESA). It discusses the sustainability of a product calculating an *Absolute Sustainability Ratio* (ASR). This implies for the numerator the Life Cycle Assessment (LCA) application to collect the product’s environmental impacts. The denominator of the ASR is the allocated the environmental space (SoSOS or carrying capacity) associated to the product’s scale. These two quantities have to be computed in the same environmental indicators. This necessity brought about two approaches: [22] developing PB indicators for LCA and [106] translating PB framework into classic LCA indicators. Both promote the definition of the carrying capacities at the product’s scale supported by sharing principles and the analysis of the resilience capacities of the environment. A sharing principle is an allocation rule founded on ethics, economic and social expertise. [22] identify seven distributive justice theories (utilitarianism, prioritarianism, difference principle, luck egalitarianism, egalitarianism, sufficientarianism and libertarianism) and define recommendations for assigning a SoSOS depending on the studied system and geographical and temporal constraints. Following the clause and constraints of the chosen justice theory, the SoSOS assigned to human beings on the geographical and temporal scope is then assigned to industrial units based on the value created for humans on this scope. This expertise is also referred to as defining *Science-Based Targets* ([107]). Finally, [108] advocate the operationalization of such an approach by proposing a 6-step methodology, including a LCA. This research work synthesizes the design levers to integrate the PB framework into the design with optimization perspectives.

Thus, archetype 5 (*down-limiting*) is associated with an absolute sustainability framework hinging on:

- Justice principles to define and allocate a SoSOS aligned to the technological system being upscaled;
- Methodological developments for AESAs, lifecycle-based;
- A focus on human activity and not only on industrial activities.

The result of the chosen method is then injected into an environmental method to assess the absolute environmental sustainability of the technology-based product or service under development.

#### 4.4 Synthesis for upscaling archetype assessment

**Table 2** presents a synthesis of the techno-economic methods, as a summary for designers of methodological requirements identified in the literature study conducted in the previous sections, combined with the recommendations for scope and for each archetype. This table is therefore intended to guide design teams in the assessment of upscaling. Designers are encouraged to question their upscaling objectives and compare them with those of the archetypes. Further research findings could complete and revise the recommendations in the coming years by the interested communities, according to new methods, case studies, demonstrating feasibility or incompatibility.

Table 2: Synthesis for designers of assessments, methodological requirements and recommendations for scope, according to upscaling archetypes.

| Upscaling archetype                                | Techno-economic assessments (TEA)                                                                | Methodological requirements                                                                                                                                                                                                                                                                                                                                       | Recommendations for scope<br>Geographical/Temporal                                                                                                                                                                  | Clauses and constraints                                                                                                                                                                                                                                                                                                                        |
|----------------------------------------------------|--------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Archetype 1</b><br>Upsizing, scaling-up         | Scaling laws, expert guidelines, theoretical limits, thermodynamic optimization (pinch analysis) | <ul style="list-style-type: none"> <li>Define the specific technical expertise;</li> <li>Ensure strong interactions between researchers and engineers;</li> <li>Implement a future-oriented design.</li> </ul>                                                                                                                                                    | Mainly use phase focused, integrative life cycle. Studied: the product. Expertise's timescale is over months.                                                                                                       | <ul style="list-style-type: none"> <li>Due to maturity focus, attention must be paid to which incumbent technology the emerging technology is compared;</li> <li>Foreground system modelling caution and clear scenario of use phase, implying data production and data collection challenges.</li> </ul>                                      |
| <b>Archetype 2</b><br>Mass-producing               | Design for X (e.g. Manufacturing)                                                                | <ul style="list-style-type: none"> <li>Follow an integrative and normative approach;</li> <li>Develop techno-economic expertise;</li> <li>Identify the stakeholders of the value chain;</li> </ul>                                                                                                                                                                | Lifecycle-based, regionalized approach if possible over the value chain. Studied: The product system. Expertise's timescale is over the years.                                                                      | <ul style="list-style-type: none"> <li>Industrial trend focus;</li> <li>Standardization challenges;</li> <li>The more lifecycle-based (End of Life issues) possible.</li> </ul>                                                                                                                                                                |
| <b>Archetype 3</b><br>Reaching a level, deploying  | Scenario-based approach, stock-flow modelling (MFA analysis), mathematical optimization          | <ul style="list-style-type: none"> <li>Develop a market maturity and sectorial long-term expertise;</li> <li>Characterize a cumulative technology's performance;</li> <li>Set up scenario expertise and specific data uncertainty management.</li> </ul>                                                                                                          | Large spatial/social scale (regional, national - sectorial or group of technology). Studied: The industry sector associated with the product. Phenomenon's timescale is over decades.                               | <ul style="list-style-type: none"> <li>Rigorous scenario hypothesis and natural resources focus;</li> <li>Sectorial modelling and data issues;</li> <li>Background system modelling caution. The more lifecycle-based possible.</li> </ul>                                                                                                     |
| <b>Archetype 4</b><br>Integrating a complex system | Multi-level analysis, network approach, mathematical optimization                                | <ul style="list-style-type: none"> <li>Mobilize a system dynamic engineering with interoperability focus;</li> <li>Adopt a culture of trade-offs from optimization modelling or socio-economic expertise;</li> <li>More broadly, develop a multidisciplinary approach.</li> </ul>                                                                                 | Large geographical scale (the one of the complex system). Studied: the complex system interacting with the product. Spatial/geographical properties focus. Phenomenon's timescale varies from real-time to decades. | <ul style="list-style-type: none"> <li>Interaction modelling and data issues;</li> <li>Constraints strongly dependent on case studies and engineering field (possibly compatible with a product-service system vision).</li> </ul>                                                                                                             |
| <b>Archetype 5</b><br>Down-limiting, downscaling   | Justice/ social and physical principle Economic allocation (Input-Output modelling)              | <ul style="list-style-type: none"> <li>Observe fair allocation methods (i.e. justice principles) and strictly define the service being studied;</li> <li>Manage the data collection associated with the service (usually techno-economic-based).</li> <li>Monitor methodological development (for product) from AESA (Indicators, sharing principles).</li> </ul> | Focused on services provided to humans, lifecycle-based with possible regional focus (national/sectorial).                                                                                                          | <ul style="list-style-type: none"> <li>Focus on human activity, not industrial activities or products specifically;</li> <li>Modelling and sharing principle challenges (techno-economic-based and/or social science-based);</li> <li>Refer to Ryberg <i>et al.</i> (2020). To apply as soon as possible in technology development.</li> </ul> |

## 5 Discussion

### 5.0.1 How to apply archetypes while designing technology upscaling?

For each upscaling archetype, definitions, tools, practices and methodological invariants have been detailed in the previous sections. The literature review process also revealed a disparity in the practices of designers depending on their object of study and their engineering field. This disparity questions the practical relevance of upscaling archetypes presented above. This section therefore proposes a visual framework to detail this disparity of methods adoption regarding the archetype and the engineering field involved. It depicts a representation of our literature review and could help designers to deal with upscaling archetypes use.

### 5.0.2 A framework for visualizing the selected literature for upscaling assessment

**Figure 4** synthesizes the content of the subsection “*Upscaling assessment methods for designers, by archetype*” with an engineering field perspective. This representation is called the “matrix UA-EF” for Upscaling Archetypes (UA) by Engineering Fields (EF). This framework aims to identify available and most relevant methods for upscaling assessment. Each geometric shape represents one or more references identified as fruitful during the literature review. These references are articles and scientific reports and are sorted by related upscaling archetypes and engineering fields. The proposed references have been selected according to the criteria of being synthetic or dense in terms of information. This structure aims to guide the reader towards the most structuring literature. Interdisciplinary methods (large dots) are distinct from disciplinary-specific methods (small squares). Dots refer as much as possible to review articles.

Crosses reveal the non-emergence of relevant references in a specific engineering field, or default in the process of literature review. Crosses do not mean that literature is non-existent, but rather that it is not sufficiently structured or prevalent to be identified as dedicated to the upscaling assessment. Such figure may also indicate that cross-field or generic methods from another engineering field encompass this upscaling application. In that case, large full dots in the corresponding upscaling archetype column would cover this lack.

Thus, archetypes 1 (*upsizing*) and 4 (*integrating into a complex system*) are the most widely documented in the selected domains of engineering. Both also have multiple structuring references due to the diversity of approaches (e.g. techno-economic or socio-technical) and differences of skills and representations that can be inter-sectorial but not necessarily compatible with all engineering fields. Archetype 2 (*mass-producing*) appears to be more clustered around the production of engineering and electronics due to intrinsic methodologies that are widespread in all other engineering sectors. Archetype 3 (*reaching a level*) appears to be less documented than others due to its link with planning methodologies of climate change mitigation, which are more recent and can therefore be less common in engineering. Likewise, Archetype 5 (*down-limiting*) covers recent research developments but potentially concerning every engineering field. Archetype 5 is for the moment affiliated with a small number of structuring references ([7, 22, 66, 108, 109]). Case studies are expected to be developed over coming years.

### 5.0.3 Use of the matrix UA-EF as a support tool for designers

As for **Table 2**, **Figure 4** is non-exhaustive and is meant to be completed by the design communities as any design method. This methodological framework is adapted for design teams wishing to identify the relevant (or at least existing) methods adapted to study all facets of an upscaling (i.e. archetypes). It enables readers to determine if an upscaling archetype is addressed or not in the scientific literature according to two criteria: by sector or engineering field (horizontally) or by archetype (vertically).

A horizontal reading implies to consider if all archetypes are addressed in a specific activity sector. It leads to the expectation of a common vocabulary in the design team (due to the object of study) and possibly a “simpler” appropriation if the goal is to integrate new practices.

If a node is missing from this reading, the vertical reading is required. This cross-reading process brings about an interdisciplinary practice: users emphasize on assessment methodologies potentially transferable or adaptable from other engineering fields. In that regard, **Figure 4** offers enough sources to ensure a cross-reading and cover all the archetypes for each engineering field.



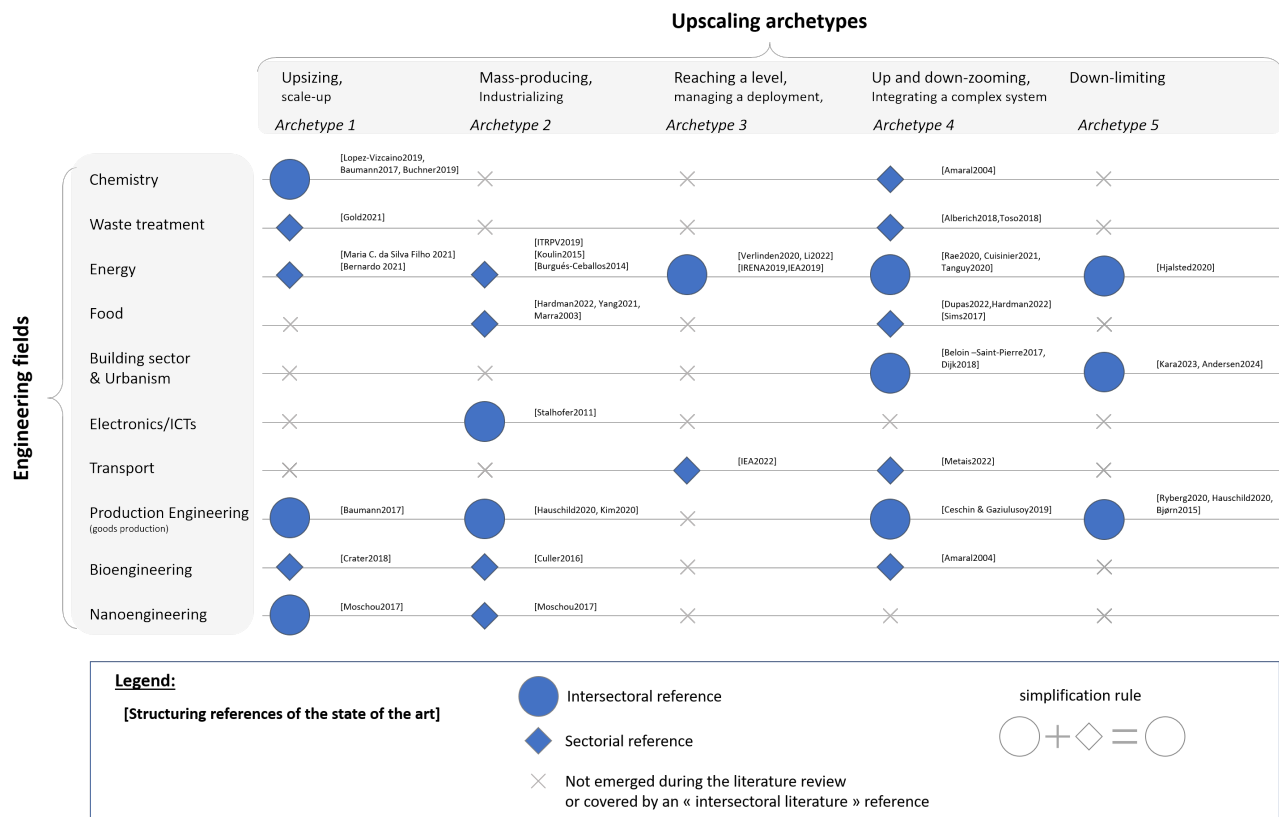


Figure 4: The Matrix UA-EF, presenting a selected literature for upscaling assessment according to the upscaling archetypes and engineering fields. For simplification, when several references are identified, only the most inter-sectorial (circle) is represented.

Ideally, as many of these five archetypes should be assessed to monitor the upscaling of a technology in a complete way. In practice, products and their uses lend themselves more or less well to existing assessment methods. Moreover, engineering fields have varying degrees of maturity in applying the selected TEA. In that context, **Figure 4** depicts the treatment of the upscaling phenomenon from engineering and design point of view. In case of lack of literature, this socio-technical phenomenon may exist in the corresponding engineering field, and perhaps these aspects have not (yet) been captured by engineering and design approaches. Future research may refine the specifics of upscaling assessment in each engineering domain. More broadly, despite archetype 3 (*reaching a level*) and archetype 5 (*down-limiting*) being related to socio-environmental aspects, only techno-economic methods and practices have been compiled in this review. This offers therefore a partial overview of the upscaling assessments that may need to be carried out to anticipate and design it. Complementing this review with similar work but from other types of analysis (*e.g.* environmental, political, social) related to upscaling archetypes would also be fruitful for design teams aiming for the sustainability of their practice.

## 6 Conclusion

The aim of this paper was to clarify the definition of the sentence “upscaling of emerging technologies” for designers. This paper proposed a characterization formalism. Based on it, five archetypes are identified in the literature of design and engineering: *scaling-up* or *upsizing*, *mass-producing*, *reaching a level* or *deploying*, *up-and-down zooming* or *integrating in a complex system* and *down-limiting*. Each of them is associated with a specific meaning and definition embodying a perception of the upscaling. Each archetype relates to an inner and coherent lexical field, sometimes interacting with another archetype. The emerging technology concept is also, relatively to the upscaling phenomenon, polysemic. Three definitions, available in the literature, are therefore criticized from each upscaling archetype perspective. The paper

demonstrates that upscaling archetypes cover all of them. Additionally, the majority of engineering and design literature referring to anticipating or managing an upscaling of a product are techno-economic or socio-technical assessments. Thus, this paper compiles methods and practices available in the design literature to assess the upscaling of a(n emerging) technology, depending on the five archetypes. Some methods are generic and interdisciplinary, and some are specific to an engineering field (*e.g.* chemical engineering). Moreover, Design guidelines are proposed to support upscaling assessment practices by designer. These guidelines include examples of methods and tools, methodological requirements and recommendations for study scope. Finally, the paper offers as a discussion medium an illustration of the identified most structuring literature references (*e.g.* reviews or case studies). This formalism is named “Matrix UA-EF”. It enables readers to consult the disparity of available methods and practices adoption regarding the Upscaling Archetype (UA) and the Engineering Field (EF). Matrix UA-EF can be considered as an attempt to guide designers in finding the best available techno-economic assessments to assess their upscaling case. In that regard, this representation paves the way to interdisciplinary additions purposed to study the phenomenon of technology upscaling from other perspectives (*e.g.* environmental, social).

## 7 Credit authorship contribution statement

Lucas Riondet: Conceptualization, Methodology, Investigation, Data curation, Writing - original draft. Véronique Perrot-Bernardet: Formal analysis, Supervision, Writing - review & editing. Maud Rio: Formal analysis, Supervision, Writing - review & editing. Peggy Zwolinski: Validation, Supervision, Writing - review & editing.

## 8 Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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# 7

## Analyse environnementale du changement d'échelle (proposition 2)

### Sommaire

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## 7.1 Article 2 - Cadre d'ACV par archetype de changement d'échelle

### Stratégie de publication pour l'Article 2

L'Article 2 a été soumis au Journal *Sustainable Production and Consumption* le 06 Juin 2024 et accepté le 31 Juillet 2024. Ce journal présente, au 10 Octobre 2024, un h-index de 76 et un impact factor de 12.1. Il est catégorisé Q1 pour les domaines de l'ingénierie environnementale et de la soutenabilité (Renewable Energy, Sustainability and the Environment) selon la banque Scimago. Il a été choisi pour sa ligne éditoriale portée sur les analyses environnementales et les liens entre ingénierie et soutenabilité.

L'Article 2 s'intitule « *Emerging technologies upscaling : a framework for matching LCA practices with upscaling archetypes* » et constitue les pages 116 à 143 de la thèse.

### Abstract

*Society asks engineers and designers, though sustainability targets, to be highly concerned with socio-technical and environmental consequences generated by the technology they develop or use in products. Regarding technology upscaling, we proposed in previous research five related archetypes in engineering : upsizing, mass-producing, deploying, integrating a complex system, and down-limiting (Riondet et al., 2022). However, these five facets of the upscaling of technology are not explicitly associated with LCA practices. More precisely, usual upscaling technology LCA guidelines mainly focus only on the two first archetypes. Clarifying LCA approaches available in the literature is, therefore, necessary to match LCA practices with the five upscaling archetypes. This research paper is based on the characterization framework for upscaling assessment presented in previous research, completed by an LCA practices literature review in terms of addressed questions, theoretical basement, required expertise, and applicability issues. Then, this characterization of available LCA approaches and their applicability is confronted concerning a given goal of upscaling environmental assessments. The sorted references have been characterized in terms of "engineering field" to identify whether any guidelines they provide are generic or attached to a specific discipline or a type of product. This literature review produced three main results : first, fifteen LCA modes are characterized in terms of definition, addressed questions, studied objects, the expertise required, scope specificities, and structuring references. Second, guidelines have been extracted from selected case studies or reviews from different engineering*

*fields (e.g. chemistry, energy, transport). This constitutes a generic LCA framework to environmentally assess each upscaling archetype. Third, the LCA references are ranked by the related engineering fields. Finally, the challenges of extending these three results are discussed, especially concerning the emergence of new LCA modes in reaction to specific needs for environmental assessments (e.g. transition LCA) and in an eco-design perspective based on environmental upscaling assessment. The proposed synthesis, guidelines and representation provide practical recommendations for LCA practitioners considering the upscaling of emerging technologies. This overview can be completed with currently adopted LCA practices in literature and companies. This work paves the way for two kinds of further research : first, to refine theoretical and practical LCA modes compatibility based on developments by LCA experts. Second, to produce operational guidelines for LCA practitioners to transfer ongoing and future LCA developments and bring comprehensiveness to the environmental assessment of upscaling.*



# Article 2 - Emerging technologies upscaling: a framework for matching LCA practices with upscaling archetypes.

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## Abstract

Society asks engineers and designers, though sustainability targets, to be highly concerned with socio-technical and environmental consequences generated by the technology they develop and deploy in society. Life Cycle Assessment (LCA) as a methodology can be a tool for assessing the sustainability of technological change of scale, however, the diversity of LCA approaches hinders their adoption by engineers, including LCA practitioners in product design teams.

Therefore, clarifying LCA approaches available in the literature is necessary to deal with the environmental assessment of emerging technology upscaling. To this end, this research paper carries out a literature review of LCA practices and characterises them with conceptual and operational characteristics. This characterisation provided the basis for matching the available LCA approaches with the different facets (also known as archetypes) of a technology upscaling to be environmentally assessed, based on their common characteristics.

This literature review produced three main results: first, fifteen LCA modes are characterised by definition, addressed questions, studied objects, the expertise required, scope specificities, and structuring references. Second, guidelines have been extracted from selected case studies or reviews from different engineering fields (e.g. chemistry, energy, transport). This constitutes a generic LCA framework to environmentally assess each upscaling archetype. Third, the LCA references are ranked by the related engineering fields. Finally, the challenges of extending these three results are discussed, especially concerning the emergence of new LCA modes in reaction to specific needs for environmental assessments (e.g. transition LCA) and in an eco-design perspective based on environmental upscaling assessment.

This work paves the way for two kinds of further research: first, to refine theoretical and practical LCA modes compatibility based on developments by LCA experts. Second, to produce operational guidelines for engineers and designers practicing LCA to transfer ongoing and future LCA developments. This would bring comprehensiveness to the environmental assessment of emerging technology upscaling and a sustainability vision of technology development and production.

**Keywords:** Upscaling archetypes, Life Cycle Assessment modes, Emerging technologies, Environmental Assessment for Upscaling, Absolute sustainability, Integrated Design for Sustainability.

## Abbreviations

|        |                                                  |       |                                      |
|--------|--------------------------------------------------|-------|--------------------------------------|
| AESA   | Absolute Environmental Sustainability Assessment | LCA   | Life Cycle Assessment                |
| BIPV   | Building Integrated Photovoltaics                | LCI   | Life Cycle Inventory                 |
| DFS    | Design for Sustainability                        | LCSA  | Life Cycle Sustainability Assessment |
| EAU    | Environmental Assessment for Upscaling           | MFA   | Material Flow Analysis               |
| ETV    | Environmental Technology Verification            | PB    | Planetary Boundaries                 |
| EV     | Electric Vehicle                                 | PEFCR | Product Environmental Footprint      |
| FCE    | Final Consumption Expenditure                    | PSS   | Product Service System               |
| GHG    | Greenhouse gas                                   | PV    | Photovoltaic                         |
| GIB    | Green Incentive-Based                            | SOS   | Safe Operating Space                 |
| IO-LCA | Input-Output LCA                                 | SoSOS | Share of Safe Operating Space        |
| IoT    | Internet of Things                               | TRL   | Technology Readiness Level           |

## 1. Introduction

Given the daunting environmental challenges our societies face and the ensuing need for radical change (*e.g.* climate change (IPCC, 2022), biodiversity erosion (Ceballos *et al.*, 2015), material depletion (Vidal *et al.*, 2021).etc.), multiple organizations develop transition scenarios for sustainability. The scale of these scenarios can be sectorial (IRENA, 2019; RTE, 2022; Sims *et al.*, 2017), national or continental (ADEME, 2021; AEE, 2019) or international scale (IEA, 2020; IPCC, 2022). These scenarios offer a wide range of sustainability pathways but all have in common being supported by technological developments. Paradoxically, “clean/climate/green technologies” and all technologies that are supposed to be beneficial regarding the reduction of environmental negative impact are often so-called “emerging”, meaning that their effects on the environment have not yet been observed on an extensive scale and sometimes, therefore, are hypothetical (Buyle *et al.*, 2019; Cucurachi *et al.*, 2018). Under these circumstances, the estimation of environmental benefits of immature product systems comes from anticipative environmental Life Cycle Assessments (LCA) by engineers or design teams. LCA practice is, therefore, crucial to assess the environmental sustainability potential of a technology before its upscaling.

Thus, on the one hand, the LCA literature related to upscaling and emerging technology has not stopped being enriched since the 2010s to deal with LCA applied to prototypes, also called ‘ex-ante LCA’. Cucurachi *et al.*, (2018), for instance, emphasise in that context the importance of referring to an incumbent technology or service. Therefore, the studied emerging technology has to be compared to existing technologies or services, by conventional methods and guidelines (ISO 14040, 2006). Arvidsson *et al.*, (2018) develop the theoretical basement of ex-ante LCA by raising specific challenges, such as temporal correlation and scenario management. Bergerson *et al.*, (2020) point to the interaction between technological maturity and the maturity of the target market and the associated LCA results uncertainties. The authors therefore identify four situations that combine a level of maturity for the technology (techno-economic uncertainties) and the market it fits (socio-economic uncertainties). Bergerson *et al.* develop then uncertainty management strategies according to the situation, *e.g.* comparing the prototype with an incumbent technology, producing scenarios, or studying potential social acceptance with agent-based models to simulate the emergence into a market. Thonemann *et al.*, (2020), and Moni *et al.*, (2020) complete these developments with structuring review articles presenting methodological guidance for ex-ante LCA. These works contribute to the clarification of the new methodological requirements (*e.g.* uncertainty challenges and technology maturity elicitation) associated with such LCA mode. In parallel, authors focused on practical aspects such as data availability and uncertainty management (Buyle *et al.*, 2019; van der Giesen *et al.*, 2020; Santos *et al.*, 2022), task organisations and integration in the design process (Tan *et al.*, 2018; Tsoy *et al.*, 2020) or maturity technology management (Tsoy *et al.*, 2020). These works will be discussed in detail in this paper. They, however, focus only on aspects of the upscaling identified in design and engineering literature, *i.e.* the upscaling archetype “from laboratory to industrial scale” (Riondet *et al.*, 2024, 2022). These guidelines, for instance, do not provide information on how to analyse the interactions (expected or not) between the technology upscaled and territories or socio-technical societies. Another point is that guidelines focus on one unit of product/technology. These methodologies do not give insights into cumulative effects resulting from future product/technology massification. Guidelines do not explain either how to characterize the scope of the study for a given deployment strategy or a purposed use. These considerations (anticipating socio-technical interactions and extending the boundary system beyond product level), by contrast, are considered necessary for designing sustainable systems (Ceschin and Gaziulusoy, 2019). These findings show that the upscaling assessment in the literature on LCA confers some methodological lacks. Conversely, many LCA approaches have been designed to address these upscaling properties, but are not identified as enabling analysis of a technology's upscaling. Hauschild (2015) for instance, goes further the classic LCA approach by questioning the absolute sustainability paradigm of the technology development. Absolute sustainability refers to the planetary boundaries that should not be crossed to warrant a safe operating space for humanity. The applicability of this theoretical framework at the product level with LCA is referred to as the Absolute Environmental Sustainability Assessment (AES). Few articles present an overview of the diversified approaches and the context in which each can be used. Guinée *et al.*, (2018) categorise 8 LCA “modes” in a synthetic three-page article titled “Digesting the alphabet soup of LCA”: *attributional, consequential, backcasting, decision, integrated, anticipatory, prospective and scenario-based LCA*. The authors intended to clarify general definitions and associated theoretical principles (*e.g.* used allocation method and scope). Onat *et al.*, (2017) reviewed with a bibliometric analysis the life cycle sustainability assessment literature, for educational purposes. Authors called for defining common vocabulary and then interconnections and feedback between LCA practitioners of different approaches (social, environmental and economic

assessments). Ventura, (2022b) is a third example of an article covering multiple LCA approaches. This paper develops a new approach so-called “Transition LCA”, dealing with environmental aspects of a transition applied to a territory. This is supported by properties of other LCA approaches (*e.g. attributional, consequential, hybrid, input-output, organizational, and territorial LCA*) examined and synthesized by the author. This paper therefore contextualizes and elaborates on the future development of LCA based on a retrospective review. It provides also examples of the application of a Transition LCA to illustrate the novelty of the approach and the associated constraints (*e.g. stakeholders identification, data collection, scenario management*). These examples of structuring literature in LCA (Guinee *et al.*, 2022; Ventura, 2022a) are not, however, specifically oriented to the assessment of a technology upscaling. Second, similar resources are not always purposed to design teams of emerging technologies, more and more interested in environmental upscaling assessments, but rather to LCA experts. Our research work has therefore targeted groups of design teams (*e.g. engineers, technology experts, and team managers*), including LCA practitioners. Thus, this paper aims to address LCA practitioners need for clarification on the different LCA approaches within an upscaling assessment perspective, structured with the formalism of “upscaling archetypes” (see Table 1 in “Method” section) proposed for design communities (Riondet *et al.*, 2022). This research paper aims to answer the question: *how LCA could help to assess or anticipate the environmental sustainability of the upscaling of a technology*, using the archetype formalism of Riondet *et al.*, (2022)? This research question can be partitioned into two sub-questions: (RQ1) *Which existing LCA approaches, available in the literature, are related to upscaling properties?* And (RQ2) *how should design teams be equipped to carry out or anticipate the upscaling of an emerging technology with regard to environmental sustainability?* Section 2 details the literature review methodology and the formalism to answer these two research questions. Section 3.1 presents the collection, definition and characterisation of relevant LCA approaches for upscaling assessment to address RQ1. It concludes with a synthesis enabling LCA practitioners and technology designers to identify the expertise and resources required to apply a particular LCA mode. Section 3.2, to answer RQ2, illustrates LCA practices by examining case studies for each of the five upscaling archetypes. Illustrations from several engineering fields are given to exemplify archetype specificities (see subsections 3.2.1 to 3.2.5). Based on this review, subsection 3.3 presents guidelines for design teams to help them select the most appropriate LCA “modes” regarding the upscaling specificities (*i.e. upscaling archetype*). Methodological and practical requirements are expressed. Then, subsection 0 analyses the literature reviewed in terms of engineering fields to stress the “disciplinary” bias of current upscaling archetype assessments. Finally, subsection 3.4 deals with the integrative role of LCA in ecodesign practices for technology upscaling and section 4 sums up the contributions of this article regarding the environmental upscaling assessment.

## 2. Methods

### 2.1. Formalism of upscaling archetypes

In previous research, we proposed a framework to define the “upscaling of a technology” in a design and engineering paradigm (Riondet *et al.*, 2024, 2022). A technology upscaling is therefore defined as a techno-economic phenomenon involving the development and deployment of a technology in society to meet societal imperatives (*e.g. sustainability*) (Riondet *et al.*, 2024). This research work, additionally, splits the upscaling definition into five *facets*, so-called “archetypes”, identified in the design and engineering literature. The upscaling archetypes reflect different visions of a technology upscaling based on techno-economic expertise and engineering field perspectives. Table 1 introduces the names of each upscaling archetype, their definitions, along with their respective usual goals, subjects and focuses. This synthesis provides also an illustration for each archetype. Thus, the five archetypes are identified as follows: (1) *scaling-up* (from laboratory to industrial scale), (2) *mass-producing or industrializing*, (3) *reaching a level of cumulated service or deploying a technology*, (4) *integrating a complex system*, and (5) *down-limiting or downscaling the planetary boundaries to the technology level*.

As shown in Table 1, archetypes embody mainly techno-economic and engineering visions of a technology upscaling and are not specifically associated with sustainable assessment. LCA engineers, however, have to be sensitized to techno-economic vision and models to be able to properly define the “goal and scope” phase (*i.e. system boundary and functional unit*) and to collect data during the lifecycle inventory step of the LCA. In other words, LCA practitioners, in the case of a technology upscaling, have to cooperate with other experts (technical and economic experts for instance) to define a robust environmental model.

Table 1 - Synthesis of upscaling archetypes definitions, adapted from (Riondet *et al.*, 2024, 2022).

| Upscaling archetype                                                                               | Definition                                                                              | Usual goal                                                      | Upscaling subject                                             | Focus associated with the scope                                                 | Illustration                                                                                                                                                                                                                                                    |
|---------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|-----------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Archetype 1</b><br>Scaling-up, from laboratory to industrial scale                             | Phenomenon generating a “prototype” at industrial or commercial scale.                  | Maximize maturity (often associated with productivity)          | Technology or service upscaled                                | Technology upscaled                                                             | Research and development of a new material or technology to be commercialized ( <i>e.g.</i> electrical vehicle, emerging renewable energy, superconductor).                                                                                                     |
| <b>Archetype 2</b><br>Mass-producing, industrializing                                             | Phenomenon adapting a technology to be mass-produced.                                   | Maximize producibility                                          | Technology or service upscaled in manufacture                 | Standard performances of the technology upscaled                                | Development of a value chain and adaptation of the technology to be mass-produced.                                                                                                                                                                              |
| <b>Archetype 3</b><br>Reaching a level of cumulated service, deploying a technology               | Phenomenon translating transition requirements into technology sector perspective.      | Reaching a sufficient level of cumulated service                | Technology upscaled and boundary of analysis                  | The cumulated service provided by the group of produced technology              | Planning and management of the industrial capacity to reach a cumulated service for a given time horizon ( <i>e.g.</i> reaching a terawatt of installed capacity for electricity production in 2030, covering the mobility park for electric vehicles in 2040). |
| <b>Archetype 4</b><br>Integrating a complex (socio-technical) system                              | Integration phenomenon of a technology as a part of a larger and complex system.        | Maximize the efficiency of a complex system                     | Boundary of analysis                                          | The technology interoperability to support its systemic integration             | Management of interactions at variable geographical and temporal scales between the designed technology and other technologies or systems ( <i>e.g.</i> identification of energy stockage requirements to annually support photovoltaic deployment in France).  |
| <b>Archetype 5</b><br>down-limiting, downscaling the planetary boundaries to the technology level | Phenomenon tending to restrict technologies according to sustainability considerations. | Assess the sustainability of a technology or associated service | Science-based limit of the domain (socio-environmental limit) | The sustainability of a service provided by one or several products, or systems | Defining the sustainability of a technology ( <i>e.g.</i> is an energy production system (and its life cycle) sufficiently carbon-free to comply with the Paris agreements?)                                                                                    |

Moreover, most of the “new” approaches in LCA (consequential, territorial, absolute, transition) do not necessarily hinge on the same system boundary or functional unit as in a classic LCA (attributional retrospective LCA). This means that using “upscaling rules” directly on the inventory is not sufficient. LCA practitioners have to use a systemic vision to adapt the system boundary, the functional unit and the corresponding lifecycle inventory. This paper aims therefore to guide design teams towards LCA approaches and practices likely to provide an environmental assessment of the upscaling archetype they are focusing on.

## 2.2. Literature review process to match LCA approaches with upscaling archetypes

To question the potential alignment between available LCA approaches and the upscaling archetypes, a three-step literature review was carried out.

First, search queries were applied on Web of Science and Elsevier over the years 2022 and 2023 with the keywords “LCA” OR “Life Cycle Assessment” AND “emerging technologies” OR “emerging technology” AND “upscaling”, “scaling-up”, “scale”. This first step was dedicated to pointing out the LCA practices in the literature already identified as suitable to assess a technology upscaling. The suitability of the identified practices was checked by comparing their study objectives, subject and scope with the goal, subject and focus of the upscaling

archetypes. Case studies have been set apart in this step, and review articles and methodological discussions were preferred. This step brought out 14 references on emerging technology environmental assessment.

As these references were mainly focused on archetype 1 (*scaling-up, from laboratory to industrial scale*), the reference selection criteria have been relaxed to include LCA approaches suitable for environmentally assessing the other archetypes. The second step of the literature review therefore looked for additional LCA approaches. Two review articles summarising the variety of LCA approaches (Guinée *et al.*, 2018; Ventura, 2022a) were mobilized and additional keywords were included in the research queries in combination with “LCA”, such as “deployment”, “industrial scale”, “absolute sustainability”, “prospective”, “ex-ante”, “anticipatory”, “transition”, “AESAs”, “territorialized”, “consequential”, “parametrized”, “spatialized”, “PB-LCA”, “downscaling”, “planetary boundaries”. Each new LCA approach identified was compared with the characteristics of the archetypes (goal, subject, scope) to determine their compatibility. Complementary references have been compiled, based on our expertise or following discussions with LCA experts from consequential, prospective, territorialized and absolute LCA, leading to a corpus of 100 references with at least two references per LCA approach. This corpus includes review articles and case studies from various engineering fields (chemistry, energy, transport, waste treatment).

Finally, each LCA approach has been characterized based on the diversity of case studies over different engineering fields, the availability of practical tools, software and guidelines and the age of the structuring references). This characterisation led to propose the following classification: “classic” or “historical” for LCA practices with a wealth of literature and associated software and guidelines, “LCA modes with a temporal or geographical focus” for LCA approaches developed in the literature but not generalised in practices and addressing issues requiring theoretical and operational developments, and more “emerging LCA approaches” with limited number of structuring references or case studies (less than 10) or with methodologies still maturing, according to the literature or the experts consulted. This third step, based on existing frameworks provided by the authors Arvidsson *et al.*, (2024), Cucurachi *et al.*, (2018), Guinée *et al.*, (2018), and Ventura (2022a) carries out the characterization of each LCA approach with a definition, a generic addressed question and an usual studied object. Moreover, the type of expertise to operate the LCA approach and additional structuring references (*e.g.* references providing guidelines or methodological precisions) complete the literature review process. This characterization led ultimately to the proposal of a LCA framework for design teams to link LCA approaches to the upscaling archetypes depending on their upscaling objectives and study objects. In other words, this framework helps design teams to environmentally assess the upscaling archetype they are interested in.

## 3. Results and discussion

### 3.1. LCA modes suitable for upscaling assessment

This section presents the outcomes of the literature review to address RQ1 “Which existing LCA approaches, available in the literature, are related to upscaling properties?”. Since the 2000s, different “modes” of LCA have appeared in the literature to meet different objectives based on variable modelling methodologies and scope of application (*e.g.* product or value chain focused, service, regional, global). Several publications intend to guide LCA practitioners in their practice by categorizing these current or under-development “modes”, in a synthetic way (Guinée *et al.*, 2018), for contextualisation of new LCA developments (Ventura, 2022a), or about the future-oriented assessments (Arvidsson *et al.*, 2018; Buyle *et al.*, 2019).

This section details the definitions and characteristics of available LCA approaches in the scientific literature suitable for upscaling assessment. Thus, the following modes can be used to analyse and anticipate the upscaling of a technology: i) *attributitional and consequential*, ii) *prospective, retrospective, ex-ante, post-ante, anticipatory, simplified, streamlined and parametrized*, iii) *dynamic*, iv) *regionalised, spatialized, territorialized*, v) *hybrid, absolute and transition one*. The first columns of Appendix 1 provide a synthesis of the definitions of these LCA modes, classified as *classic* or *historical* approaches, approaches *focused on temporal aspects* or *geographical aspects* of the analysis and more emerging approaches, including *hybrid or combined* approaches.

#### 3.1.1. Attributitional and consequential LCA

The ISO 14040:2006 standard and the UNEP-SETAC have proposed suitable frameworks for both modes of consequential and attributitional LCA (“ISO 14040,” 2006; UNEP-SETAC, 2011). The UNEP-SETAC defined in

2011 a consequential and an attributional approach. The consequential approach is defined as an environmental analysis assessing the impacts resulting (directly or not) from a decision (*e.g.* change in demand for a product) and the attributional approach as environmental assessment methodologies focused on allocating from the global environmental burdens apart to a life cycle of a product or service (UNEP-SETAC, 2011). These two approaches are not in opposition, and Schaubroeck *et al.* (2021) systematically list the conceptual characteristics they have in common or that differentiate them. Schaubroeck *et al.* insist on the fact that several conceptual properties between the ISO-14040 and UNEP-SETAC are not always consistent. The practices and LCA modelling choices depend on some practical assessment needs, and on the practitioners' understanding of the theoretical frameworks (Schaubroeck *et al.*, 2021). In other terms, knowing a LCA is attributional or consequential is not sufficient to fully define it and identify for instance on what model it lies. Such standards recommend practitioners provide information about the question addressed in the LCA (Guinée *et al.*, 2018), the system boundary (normatively) chosen, and therefore the mass and value conservation preserved (Weidema *et al.*, 2018).

### 3.1.2. Prospective, ex-ante, anticipatory and simplified LCA

One can associate the two modes (attributional or consequential) with other properties, for instance, whether future-oriented or not. The terms “prospective” and “ex-ante” are therefore usually opposed to respectively “retrospective” and “post-ante”. The idea is for both terms that LCA aims at studying an object, already existing or not, in a future context, as opposed to a LCA performed on an existing object, at a past or present period (*i.e.* retrospective or post-ante). Both attributional and consequential LCA can be designated as prospective (Arvidsson *et al.*, 2018). Some authors identify these two terms (prospective and ex-ante) as synonyms (Buyle *et al.*, 2019; Guinée *et al.*, 2018), while others emphasize the difference in terms of the object of study considered. van der Giesen *et al.*, (2020) and Cucurachi *et al.*, (2018) define *ex-ante* LCA as a particular case of prospective LCA applied to an emerging technology (*i.e.* technology in early-stage of development) and therefore strongly aligned with the Technology Readiness Level (TRL) indicator. The word “anticipatory” is also used in this context, often considered synonymous with ex-ante (Buyle *et al.*, 2019). Both are future-oriented approaches assessing the field of potential futures for immature technologies considering socio-technical hypotheses. However, anticipatory LCA is sometimes differentiated by the notion of organization and integration in a risk management process (Wender *et al.*, 2014; van der Giesen *et al.*, 2020; Cucurachi *et al.*, 2018). According to these authors, differences between ex-ante and anticipatory would not be on the scientific methodological aspect but rather on the articulation of the LCA practice within a decision-making process. In other words, anticipatory LCA focuses on decision theory and the organizational requirements to operationalize LCA practices with a forward-looking perspective. This approach questions the integration of the stakeholders impacted by the assessment into the decision-making. The distinctions between prospective, ex-ante and anticipatory LCA over time are deepened by Arvidsson *et al.*, (2024). In particular, the authors show that the term *prospective* has been more common in the literature since 2018 than *ex-ante* and even more than *anticipatory*. Arvidsson *et al.*, (2018) mention three scenario-based postures of forward-looking perspective:

- *predictive*, purposed to identify the “likely scenario”;
- *exploratory*, aiming at revealing the range of possibilities with a “what if” approach;
- *normative* or *back-casting*, *i.e.* “start from a vision of the future and develop pathways to it” (Arvidsson *et al.*, 2018);

It should be noted that the theoretical requirements in terms of uncertainty management vary according to the posture, due to the different nature of the associated uncertainties.

Often associated with ex-ante LCA, to map technology candidates in the early stages of development (Hung *et al.*, 2020), simplified approaches like *streamlined* LCA are dedicated to “be used by different actors without the need for expert knowledge on LCA” (Eleftheriou *et al.*, 2022), including *parametric* LCA (Hollberg and Ruth, 2016). *Streamlined* LCA can also be used for redesigning or integrated into a label framework (Perez-Lopez *et al.*, 2021). Nevertheless, *simplified* LCA stands on fewer indicators and its results are less robust than a full ISO 14040 standard-based LCA (Hung *et al.*, 2020). *Streamlined* LCA is not peer-reviewed and cannot be published. It can be seen as a first step to identifying the environmental impact hotspots generated by a process or product under design. Still, to integrate LCA into the design, the second step after conducting a *streamlined* LCA could be about identifying the parametrization of the Life Cycle Inventory (LCI) with design-oriented categories (*e.g.* component level, product level, End-of-Life). Thus, *parametrized* LCA enable designers to control, optimize and monitor the potential environmental impacts resulting from their design choices (Kamalakkannan and Kulatunga, 2021).

3.1.3. *Dynamic LCA*

A LCA can also be referred to as “dynamic” if the impacts of the object studied are varying. Impacts can vary due to a time dependency of the LCI data (e.g. energy mix consumption or varying input in an industrial process). In this particular case, the term *dynamic LCI* is also used instead of *dynamic LCA*. Most of the time, the results of a(n *attributorial*) LCA are presented by life cycle stages, but their implementation assumes that they all take place at the same time, i.e. in a static way (Cardellini *et al.*, 2018). The longer the life cycle is, the more dynamic effects would need to be considered. For example, the energy consumed to assemble a product with a lifespan of several decades could be associated with more impact generated, as it is potentially more carbon intensive than the energy consumed to dismantle it at the end of its lifespan (in the same country) due to the decarbonization of the energy mix over time that should be happening. Taking into account the temporal dimension in LCA can also be refined with a dynamic weighting of the impacts (i.e. dynamic characterization factor) to represent for instance cumulative effects of successive emissions (Laratte *et al.*, 2014; Ventura, 2022b). However, this approach is usually only applied to one indicator (often greenhouse gas emissions) because it requires supplementary expertise in biochemistry mechanisms. Consequential LCA is sometimes associated in the literature to dynamic or prospective LCA, as it relies on systemic models requiring updates to describe techno-economic causal chains propagating the consequences of a decision or an unusual event over time (Cucurachi *et al.*, 2018; Roux and Peuportier, 2013). This prompts LCA experts (e.g. Schaubroeck *et al.*, 2021; Weidema, 2004) to make the temporality of causality modelling explicit for consequential and attributorial LCA.

3.1.4. *Regionalized, spatialized and territorialized LCA*

Other properties often mentioned in the literature are “*regionalization*” and “*spatialization*”, respectively associated with “describe the representativeness of the processes and phenomena of a given region” (e.g. regionalize the inventory based on multiregional input-output tables, material flow analysis, data from institutional bodies or literature data) and “act of assigning a location to” quantities, to represent their spatial variability (e.g. associating geographical information systems to environmental impacts) (Patouillard *et al.*, 2018).

In other terms, regionalization, also mentioned as *contextualization*, tends to define more regional properties for the product system (e.g. energy mix, raw material providers) while *spatialization* is related to the geography of a site, with, for instance, the associated characterization of material flows from and to the ecosphere (i.e. elementary flow). To deepen the regionalization in LCA, refer to the recommendations provided by Mutel *et al.*, (2019). Moreover, the *territorial* approach is defined as the fact of considering environmental impacts on a given geographical area, either to study the geographical area in question (territorial type A) or to study a product that would influence several areas to be identified (territorial type B) (Loiseau *et al.*, 2018). *Territorial* LCA is therefore a subcategory of *regionalized* LCA and mainly concerns the attributorial approach.

Ultimately, *dynamic* and *regionalized* modes aim respectively to manage the temporal or spatial uncertainties associated with the inventory (Patouillard *et al.*, 2018), or associated with the characterization factors (Patouillard *et al.*, 2018; Potting and Hauschild, 2006). The *spatialization* intends to represent the spatial attribute geographic information to emission factors for characterization.

3.1.5. *Hybrid, absolute and transition LCA and LCA mode combinations*

The integration of multi-impacts and multistage methodology with other modelling approaches has also been developed. Guinée *et al.*, (2018) refer in these cases to “integrated LCA”, while other authors refer to it as *hybrid* LCA. Hybridizing may refer to input-output models (hence the designation IO LCA), or other kinds, such as MFA for instance or technico-social models (e.g. IMAGE, REMIND) (Sacchi *et al.*, 2022a; Ventura, 2022a). In that respect, *absolute* and *transition* LCA (see next paragraphs) can be likened to *hybrid* LCAs as they involve external models of life cycle engineering. This category combines distinct modes from the “classic LCA” practices, i.e. *attributorial*, *retrospective*, *partially regionalized* and *relative* LCA.

AESA aims to compare the environmental impacts of an object/service or human activity with environmental limits defined by sustainability science and allocation rules (i.e. proceeding from an attributorial approach) and usually based on the planetary boundaries (Bjørn *et al.*, 2020a). This approach, also mentioned as Planetary Boundaries (PB) LCA, is opposed to “relative” assessment, i.e. comparing the studied object with another technology (often incumbent) and uses the planetary boundary framework as an absolute reference to be compared

with the service provided by the studied object. It seeks to move from "better" to "good enough" regarding environmental impact mitigation (Hauschild, 2015). To this end (Ryberg *et al.*, 2020) proposed the AESA to help LCA practitioners select the sharing principles, among those available (Hjalsted *et al.*, 2021), to be applied to the "Safe Operating Space" (SOS, *i.e.* absolute environmental limits on a global scale) in a particular case. This method brings about the definition of Share of the Safe Operating Space (SoSOS) to be used as an absolute reference in the comparison of environmental impacts. It can be considered as a hybrid mode of LCA, as it adds upscaling models and assumptions to an attributional LCA to implement an "absolute" comparison. This results in two main ways to proceed regarding the indicators and associated characterization factors: either by directly using planetary boundary indicators (Ryberg *et al.*, 2018a) or by using carrying capacities, meaning transposed environmental limits in the "classic" LCA indicators (Bjørn and Hauschild, 2015; S. Sala *et al.*, 2020). Moreover, attention must be paid to the LCI modelling: to be compared to a SoSOS, the reference flow that supplies the inventory is measured in kg per unit of time (usually per year). It reflects the continuous yearly pressure of human activities on the biochemical fluxes of the planetary boundaries and therefore requires a dynamic LCI or at least a date-dependent LCI (Ryberg *et al.*, 2018a). As a maturing LCA mode, several theoretical and practical challenges remain to be overcome (*e.g.* temporal mismatch, boundary system, reference flows) to achieve an absolute assessment of sustainability (Guinee *et al.*, 2022).

*Transition LCA* is close to the consequential framework as it attempts to assess a change in the current socio-technical system, however, it proceeds from a territorial approach, the aim being to study the transition of a given territory (Ventura, 2022a). This is a recent approach that takes LCA even further outside the product system framework (including functional unit definition), close to the "product" vision in engineering. Instead, it focuses on cumulative and interactive services provided in a given geographic area, implying a significant amount of data and a large boundary system.

Finally, it is important to understand that the category "Hybrid and combined" approaches (see Appendix 1), even more than the others, is not frozen in time and evolves accordingly to theoretical contributions, methodological and operational means, as well as academic and industrial practices. New combinations might appear in this category and then turned into a stand-alone "LCA mode". With regard to combinations, *attributional/consequential, regionalized/non-regionalized prospective/retrospective, and absolute/relative* can be seen as well-established continuums, and possibly as orthogonal properties. As such, these four continuums are, *a priori*, combinable. For instance, a *prospective, regionalized, consequential* LCA could therefore be adopted (*e.g.* assessment of the environmental consequences of rooftop photovoltaic deployment in the UK, Jones and Gilbert (2018)), as well as a *prospective attributional absolute* LCA (*e.g.* assessment of the environmental impacts of the photovoltaic electricity production in France in 2050 considering the Paris Agreement, Riondet *et al.*, (2023)) or a *non-regionalized, retrospective, attributional* LCA (*e.g.* assessment of the average environmental aspects of a bottle, Marathe *et al.*, (2019)). Such combinations therefore depend on the objective and scope of the assessment. In contrast and as evoked with *consequential* LCA and time consideration, *dynamic* and *prospective* modes are associated in the literature. They explicitly focus on the time-sensitivity of LCA results in the modelling.

Appendix 1 gathers the previous definitions and presents LCA modes and their characteristics for the upscaling assessment. Column 1 and 2 presents the usual names of LCA modes and their associated definitions extracted from the literature. Column 3 proposes a generic formulation of the question addressed by the LCA modes (main challenges, associated goal). These identified LCA modes are associated with the goal of the upscaling or the studied upscaling archetype (see Table 1). Columns 4 and 5 characterise the LCA modes with two elements of the scope: the usual studied object or the foreground system, and the temporal dimension. This second characteristic must be reconciled with the approaches to assess or anticipate the upscaling of a product. It sets the question "*Is it dedicated to anticipating (future-oriented) environmental impacts, taking stock of environmental aspects from an existing object (past-oriented), or both?*" This characteristic is crucial for LCA practitioners to select a LCA approach: it implies data availability conditions and/or scenario management requirements. Column 6 questions the existence of a standard for the LCA mode standard. This is congruent to the definition of the proposed category "historical/classic" of our LCA mode categorisation. Being covered by the ISO standard 14040:2006 facilitates the application of the corresponding LCA modes into "classic" LCA practices (*e.g.* in a company or for labelling purposes). Column 7 details the required expertise and number of actors involved in the LCA mode application. This can provide an idea of the type of stakeholders and therefore can help guide LCA practitioners towards a



specific upscaling archetype. Columns 8 and 9 propose additional resources, either to deepen concepts and definitions (column 8) or to apply the LCA mode (column 9).

## 3.2. LCA practices suitable for upscaling archetype assessment

Based on the review of LCA modes presented in the previous section, this section presents the outcomes of the literature review, related to the (RQ2) “*How should design teams be equipped to carry out or anticipate the upscaling of an emerging technology with regard to environmental sustainability?*”. Thus, one of the difficulties faced by LCA practitioners in design teams is to choose the more adequate method(s) among the available ones (cf. Appendix 1). As a result, this section associates each upscaling archetype (cf. Table 1) with environmental methods, mainly multi-criteria and systemic, compatible based on shared analysis characteristics. This intends to guide LCA practitioners and their associated design teams in assessing and anticipating the environmental implication of an upscaling, depending on the analysis goal and the typology of upscaling studied (*i.e.* archetype). This association of upscaling archetypes and LCA modes is illustrated with multiple case studies from varying engineering fields.

### 3.2.1. Archetype 1 – Scaling-up, from laboratory to industrial scale

The upscaling archetype 1 sets the question “*How to manage the prototype maturation process?*”. The suitable LCA approaches for dealing with the environmental aspects of this archetype are therefore future-oriented and focused on a technological product level. The environmental assessment of the scaling-up of a prototype can be supported by three complementary approaches:

- Environmental Technology Verification (ETV)
- Simplified LCA
- Ex-ante LCA (including parametrized LCA)

The ETV aims at testing and providing a certification that claims the environmental performance of an emerging technology as a competitive advantage to reach a market. The ISO 14034:2016 standard establishes the framework for this assessment, suitable for a large panel of products and sectors (*e.g.* water treatment, waste and resources, energy and agriculture) (European Commission, 2022; “ISO14034 (2016) - Environmental management - Environmental technology verification (ETV),” 2016). It is, however, not explicitly based on LCA methodology and a priori rather retrospective, meaning that the analysis is applied at the end of the design process and does not support the design choices (*i.e.* post-ante assessment).

By contrast, ex-ante LCAs, are precisely dedicated to integrate environmental analysis during the design development process. Simplified and parametrized LCAs allow, to a limited extent, to consider the incremental improvement of a technology, often relative to a technology reference. The lower cost in time and the pre-selection of the scope, the background data, and sometimes parameters, imply that it can be used by non-LCA-expert designers (Arzoumanidis *et al.*, 2017; Eleftheriou *et al.*, 2022). Nevertheless, in case of a pre-constrained framework, designers are less able to deviate from the design architecture of the reference product, hindering disruptive innovations. Moreover, this partitioned organization of the design process also implies the need for an external LCA expert to apply regular updates of the database used and a monitoring of deviations from the initial hypothesis of the method (Arzoumanidis *et al.*, 2017; Gazbour *et al.*, 2018).

As mentioned at the beginning of the section, the definition we use here for ex-ante LCA is the one associated with the study of an emerging technology that does not exist on an industrial/commercial scale. Buyle *et al.* (2019) propose a generic theoretical framework for such assessments and detail the set of methods to apply in that case (*e.g.* proxies, scaling laws and extrapolations). The authors also described when these methods can be mobilized to build the data inventory, according to the level of maturity of the technology to be studied (*i.e.* TRL) (Buyle *et al.*, 2019). Among them, participatory methods are defined as the collection of multiple points of view and opinions from experts and more generally from stakeholders. These methods are spread out over the maturation process of a technology (*i.e.* from TR3 to the diffusion of the technology, after TRL9) (Buyle *et al.*, 2019; de Souza *et al.*, 2023). This implicitly requires LCA practitioners to interact with researchers, or engineers and actively participate in the design process. Arvidsson *et al.*, (2018) recommend generating prospective scenarios for design parameters

from a current value: predictive scenarios are then combined with an exploratory approach to identify the “scenario range” for the set parameter value.

To deepen the LCA-expert integration into the design process, procedures and organizations of interactions between a technology expert (usually the designer) and a LCA practitioner, based on existing practice in chemical engineering are published. For instance, Tan *et al.* (2018) developed a hybridization of LCA with Environmental, health and safety (EHS) screening promoting multi-disciplinary designer teams (Tan *et al.*, 2018), while Tsoy *et al.* (2020) reviewed 18 case studies to characterize analysis invariants for different engineering sectors and create a generic decision tree for the upscaling of emerging technologies with scenarios and constraints defined collaboratively (Tsoy *et al.*, 2020). Except for design projects with a very identified location of the use phase (mainly in urban design or energy sector), a few ex-ante LCA are regionalized (Douziech *et al.*, 2021), and even consequential (Buyle *et al.*, 2019). However, some of the methods and tools presented (*e.g.* learning curves) introduce a consideration of dynamic phenomena in the LCA practice.

Finally, the converging point of the literature is the clarification of the targeted service that the emerging technology is supposed to fulfil. Cucurachi *et al.*, (2018) insist on the comparison of the studied emerging technology with an incumbent technology, *i.e.* a commercialised technology that already fulfils the targeted service. Thonemann *et al.*, (2020), based on a literature review, develop on LCA modelling consistency depending on the nature of the data collection. Authors specify for ex-ante LCA the matrix pedigree provided by Ciroth *et al.*, (2016) for classic LCA data management challenges. Some indicators correspond to classic LCA practices (*e.g.* ‘Reliability’ and ‘completeness’ of data) and others require particular consideration (*e.g.* ‘temporal’ and ‘geographical correlation’ ) and may impose to be handled together. Additionally, the fifth criterion called ‘further technological correlation’ helps designers to question the accuracy of extrapolating data from other contexts in the studied scenarios when there is a lack of data concerning the emerging technology under study. Therefore, comparing the studied emerging technology to the best available technology (BAT) as the future incumbent technology is a common way to deal with midterm anticipation and functional unit consistency. However, comparison with one or more incumbent technologies should prompt specific reflection on an accurate functional unit, that may also evolve over the design process. Based on these elements, the authors provide a methodological framework to deal with the specificities of the ex-ante LCA concerning the four steps of LCA (goal and scope definition, LCI, LCIA and interpretation of results).

To conclude, the modelling requirements and LCA specificities to carry the environmental assessment of the scaling-up of a technology could be summarized as follows:

| Upscaling archetype                                                           | Methodological requirements to model the archetype profiles                                                                                                                                                                                                                                                                                                           | Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype                                                                                                                                                                                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                               |                                                                                                                                                                                                                                                                                                                                                                       | Geographical and Temporality scopes                                                                                                                                                                                                                                                  | LCA specificities                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| <b>Archetype 1</b><br>Scaling-up, upsizing from a lab. to an industrial scale | <ul style="list-style-type: none"> <li>Define the domain-technical expertise required to model the processes (Buyle <i>et al.</i>, 2019),</li> <li>Ensure strong interactions between researchers and engineers (eg. technologist, chemist) (Tsoy <i>et al.</i>, 2020),</li> <li>Implement a future-oriented design (Arvidsson <i>et al.</i>, 2024, 2018).</li> </ul> | <ul style="list-style-type: none"> <li>Mainly use phase-focused scopes units integrated in a life cycle scope,</li> <li>Object studied: a product.</li> <li>Expertise’s timescale: over months,</li> <li>Geographical scale: from laboratory scale to an industrial site.</li> </ul> | <ul style="list-style-type: none"> <li>Foreground system caution and clear scenario of use phase in the comparative framework: “to which incumbent technology the prototype is compared?” (Cucurachi <i>et al.</i>, 2018; Thonemann <i>et al.</i>, 2020),</li> <li>Data production and collection challenges (Erakca <i>et al.</i>, 2024),</li> <li>Parametrization of the LCI with design parameters (Kamalakkannan and Kulatunga, 2021; Tan <i>et al.</i>, 2018; Tsoy <i>et al.</i>, 2020).</li> </ul> |

Table 2: Modelling recommendations for Archetype 1: confronting methodological requirements to model the archetype to the Modelling constraints given by the LCA mode(s) that would best fit this archetype profile.

### 3.2.2. Archetype 2 – Mass producing, industrializing

The upscaling archetype 2 sets the question “*How to manage the mass-production of a technology?*”. The suitable LCA approaches for dealing with the environmental aspects of this archetype are therefore future-oriented and focused on a technological product level and its lifecycle. The environmental assessment of the mass-production of a technology can be supported by three complementary approaches:

- ISO Standards-based LCA (attributinal, consequential)
- Prospective dynamic LCA
- Regionalized and dynamic LCA

Mass producing a product deals with a value chain perspective and industrial engineering, compliant with an attributional approach. Consequently, many of the LCA performed in this upscaling archetype are carried out within the ISO 14040 standard (“ISO 14040,” 2006; “ISO 14044,” 2006).

In addition, in Europe, the Product Environmental Footprint (PEF) reports give product-specific instructions to apply LCA. For instance, Wade *et al.* (2018) give details about the process of PEF elaboration concerning Photovoltaic devices. It provides advice on functional unit and perimeter selection and cut-off rules. It also informs LCA practitioners about the modelling of end-of-life treatments and pinpoints emerging rules for new use of the studied product, including Building Integrated photovoltaics (BiPV), *i.e.* PV devices used to replace material for the structure of a building while producing energy (Task12, 2019; Wade *et al.*, 2018). Both standards are usually read as an ex-post (or retrospective) attributional framework, used to validate a design structure and the associated value chain (van der Giesen *et al.*, 2020). However, PEFs are not deployed for every type of product. Critical reviews in the literature specific to the production of a product can thus make up for this shortcoming. (*e.g.* Martin *et al.*, (2023) for vertical farming).

Regarding scale effects integration, Gwehenberger *et al.*, (2007) give an example of the ecology of scale assessment, by considering the effect of scale on price and environmental impacts generated. It can be considered as a retrospective LCA, but such methodology could be applied prospectively, by using methods identified by Buyle *et al.*, (2019) and suitable after or during TRL 9, such as learning curves. Since the environmental impacts are, in many cases, mostly related to material consumption, reduction phenomena per unit produced lead to the reduction of the LCA inventory (in amount) and thus ultimately to the reduction of its resulting impacts generated.

In the context of anticipating the implementation of an incremental change on a technology that already meets an existing market (*e.g.* new product design based on a previous form), and if the question is about choosing a material supplier, for instance, to increase production capacity, the consequential approach of LCA seems accurate. In that case, the levers for eco-design of a product, meaning to alleviate its environmental impact responsibility, can be relied on supplier choices or strategies outside the value chain of the designed system (*e.g.* to improve the production of the marginal supplier of a resource or invest to increase the capacity of its recycling process) (Weidema *et al.*, 2018). Thus, this broadens the scope of possible levers for eco-design in return for an increase in the number of stakeholders involved in the analysis of the LCA results.

To conclude, the modelling requirements and LCA specificities to carry out the environmental assessment of a technology mass-producing are synthesized in Table 3, as follows:

| Upscaling archetype                                   | Methodological requirements to model the archetype profiles                                                                                                                                                                                                                                                                            | Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype                                                                                                                                                                                                                                                                                                               |                                                                                                                                                                                                                                  |
|-------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                       |                                                                                                                                                                                                                                                                                                                                        | Geographical and Temporality scopes                                                                                                                                                                                                                                                                                                                                                                              | LCA specificities                                                                                                                                                                                                                |
| <b>Archetype 2</b><br>Mass producing, industrializing | <ul style="list-style-type: none"> <li>• Follow an integrative and normative approach (Hauschild <i>et al.</i>, 2020; “ISO 14040,” 2006),</li> <li>• Refer to techno-economic expertise (Buyle <i>et al.</i>, 2019) ,</li> <li>• Identify the stakeholders of the value chain (life cycle engineering) (“ISO 14040,” 2006).</li> </ul> | <ul style="list-style-type: none"> <li>• Life cycle-based, regionalized approach over the value chain (Weidema <i>et al.</i>, 2018),</li> <li>• Studied system: a product system included in an industrial context (Hauschild <i>et al.</i>, 2020),</li> <li>• Expertise’s timescale: over years.</li> <li>• Geographical scope: adjusted to the mass production and worldwide industrialized system.</li> </ul> | <ul style="list-style-type: none"> <li>• Industrial trend focus (<i>e.g.</i> favour dynamic LCI),</li> <li>• End-of-life modelling challenges, data collection/extrapolation challenges (Zargar <i>et al.</i>, 2022).</li> </ul> |

Table 3: Modelling recommendations for Archetype 2: confronting methodological requirements to model the archetype to the modelling constraints given by the LCA mode(s) that would best fit this archetype profile.

## 3.2.3. Archetype 3 - Reaching a level, deploying a technology

The upscaling archetype 3 sets the question “*How to reach a cumulated service provided by a group of technology at a targeted time horizon?*”. The suitable LCA approaches for dealing with the environmental aspects of this archetype are therefore future-oriented, time-dependent and focused on an upper level than the technological product level (e.g. regional or national level). Conducting an environmental assessment of the deployment of a technology can be supported by multiple complementary approaches depending on the system boundary and the targeted time horizon:

- Prospective, attributional and dynamic LCA
- Integrated LCA - dynamic modelling
- Attributional, consequential LCA
- Regionalized LCA
- Transition LCA

Similarly to the techno-economic methods, the environmental assessment of a technology used in a transition is based on prospective scenarios. Consequently, the attributional mode of LCA is accurate for the assessment of this upscaling archetype, because suitable for studying a technology that would have become an incumbent technology in a transformed system. For instance, Hung *et al.*, (2022) propose a generic life cycle model, named ECOPT<sup>2</sup>, to optimize the deployment of a technology, considering life cycle impact minimization. It integrates stock flow minimization and cumulative consumption of raw materials. It is illustrated in a case study on electrical vehicles (EVs) but authors assure that it could be suitable for technology deployment assessment in other activity sectors (e.g. energy production, waste management, multimodal passenger transport). In the topic of EVs, Tang *et al.*, (2023) tend to assess a “European electric-mobility transition” on environmental criteria. They provide technology mixes over the period 2015-2040, following three deployment scenarios developed relatively to GHG reduction targets at the scale of the European Union. It also uses, to build their LCI, a model of dynamic material flow analysis and mathematical optimization. With regard to the energy sector, Cassoret *et al.*, (2022) apply a prospective attributional LCA on the electricity production of France based on four institutional scenarios of energy transition. The authors present different material consumptions per unit of installed capacity according to power technologies and then aggregate them to finally compare the overall impacts of the power generation systems following the four transition scenarios. The results of this kind of work, as for any prospective LCA, must be analysed in light of the assumptions made (e.g. fixed lifespan, technological improvements neglected). Another example of this prospective and cumulative approach is given by a similar case study applied in the Netherlands building sector (Yang *et al.*, 2022). A systematic prospective LCA framework is developed by Steubing and de Koning, (2021). They provide an interfacing tool (so-called superstructure) between future scenarios concerning the background system and the corresponding LCI database supporting the results of an attributional prospective LCA. Its implementation in an open-access software (i.e. Activity Browser) asserts the author’s willingness to facilitate LCA practicing. From then on, new methodologies are expected to attest to the robustness of the results, mainly related to the assumptions made in scenarios. Once again, this requires the involvement of various stakeholders to ensure the consistency of many hypotheses that may not be within the competence of a technical expert, an LCA practitioner, or even of the product company itself.

In addition, in a cumulated perspective, MFA can be applied simultaneously with the usual “per unit” impact assessment.

In contrast, if no market exists yet for the studied technology, or if the market is in a fast expansion (e.g. the lithium market), it becomes difficult to apply a prospective consequential LCA, due to the limits of underlying models (e.g. equilibrium models) will become an issue. However, it is possible, with strong assumptions on energy regulations, to identify a marginal electricity mix for instance (cf. demonstration for Denmark on the website consequential-lca.org (Muñoz and Weidema, 2021)).

To conclude, the modelling requirements and LCA specificities to carry out the environmental assessment of the deployment of a technology are summarized in Table 4, as follows:

| Upscaling archetype                                                                 | Methodological requirements to model the archetype profiles                                                                                                                                                                                                                                                                                                                                          | Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype                                                                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                      | Geographical and Temporality scopes                                                                                                                                                                                                                                                                                    | LCA specificities                                                                                                                                                                                                                                                                                                                                                                                                                  |
| <b>Archetype 3</b><br>Reaching a level of cumulated service, deploying a technology | <ul style="list-style-type: none"> <li>Develop a market maturity and sectorial long-term expertise (Muñoz and Weidema, 2021),</li> <li>characterize a cumulative technology's performance (Hung <i>et al.</i>, 2022; Laratte <i>et al.</i>, 2014; Menten <i>et al.</i>, 2015),</li> <li>Set up scenario expertise and specific data uncertainty management (Langkau <i>et al.</i>, 2023).</li> </ul> | <ul style="list-style-type: none"> <li>Large spatial/social scale (regional, national - sectorial or group of technology),</li> <li>Scope studied: the industry sector where the products are deployed,</li> <li>The phenomenon's timescale is over decades. Expertise's timescale is over months or years.</li> </ul> | <ul style="list-style-type: none"> <li>Background system accuracy challenges: rigorous scenario hypothesis is required (Langkau <i>et al.</i>, 2023),</li> <li>Avoidance of temporal mismatch (<i>i.e.</i> favour dynamic LCA) (Mendoza Beltran <i>et al.</i>, 2020),</li> <li>Natural resources focus, and more broadly cumulative properties of the environmental impacts (Charpentier Poncelet <i>et al.</i>, 2022).</li> </ul> |

Table 4: Modelling recommendations for Archetype 3: confronting methodological requirements to model the archetype to the Modelling constraints given by the LCA mode(s) that would best fit this archetype profile.

### 3.2.4. Archetype 4 – Integrating a complex system

The upscaling archetype 4 sets the question “*How to manage the integration of a technology into a complex (socio-technical) system?*”. The suitable LCA approaches for dealing with the environmental aspects of this archetype are therefore focused on the complex system modelling with a boundary system accordingly designed (*e.g.* electricity network, industrial or urban metabolism). The environmental assessment of the integration of a technology into a complex system can be based on multiple complementary approaches depending on the type of interaction and the type of complex system to be studied:

- Regionalized/spatialized LCA
- Consequential LCA
- Transition LCA
- Integrated LCA - Optimization modelling

Broadening the perimeter of the studied object is accessible with an attributional approach, given the concept of Product-Service System (PSS). This approach focuses on the service provided by one or more products instead of one unit of product. Kjaer *et al.*, (2018) developed in that case guidelines to deal with associated challenges (scope, functional unit, perimeter). It is consistent with a normative approach based on the ISO 14040:2006. This framework is, however, applicable to relatively small systems (*e.g.* fleet of bicycle sharing, leasing of soil compactor). Assessing the environmental implications of the integration of a technology in an existing complex system seems for the least congruent with the consequential approach. The consequential perspective focuses indeed on the technical and economic consequences of a decision on the techno-economic structure of human societies (Ventura, 2022a). In that regard, and given the common way that consequential LCA is implemented, the economic system can be considered as the complex system under study in which a technology is inserted. As such, Almeida *et al.*, (2020) reviewed 25 studies of consequential LCA in the building sector and characterized the underlying economic models in terms of the scale of the studied economic consequences (small, medium, large) and their time horizon (short-term, mid-term, long-term). Authors state that Agent-based models (ABM), “bottom-up, nonlinear and dynamic socio-economic models” are increasingly used to study interaction between economic agents. This type of model combined with multi-regional input-output table (*i.e.* EXIOBASE) and stock-flow consistent model can be used to investigate the economic rebound effect associated with income redistribution (Almeida *et al.*, 2022). These valuable insights for designers (and companies) to assess the introduction of a technology to a specific audience can only be produced with the assistance of an economist expert, in addition to an LCA practitioner. Other authors, through case studies, investigate the technical consequences of the integration of a specific technology on a technical complex system.

Menten *et al.*, (2015) developed a case study of prospective consequential LCA on the production of synthetic diesel from biomass in France. The analysis is supported by a bottom-up long-term energy model (TIME-MIRET).

The authors decided to consider time-dependent characterization factors for GHG on the Global warming potential (GWP) between 2007 and 2030. This study aimed to help policymakers to identify how the economy could be impacted at a national level while focusing on a specific technology. Despite the limits of this analysis (*e.g.* mono-indicator), several accurate methodological recommendations for upscaling assessment can be retained, including taking into account non-linearity in the functional unit and system boundary definition. Menten *et al.* stress the importance of defining the system boundary in relation to the functional unit and magnitudes of expected consequences and warn about the representation of the results to avoid a linear reading of the results (*e.g.* X emissions per unit of product means X emissions times 2 for 2 products).

Note that this case study could be characterized as a (dynamic) prospective consequential LCA and as a hybrid LCA due to the use of a pre-existing model of the national energy system (*i.e.* the TIME MIRET model, as a bottom-up model).

Concurrently, Jones and Gilbert, (2018) provide a consequential LCA example on a rooftop photovoltaic deployment, with a network perspective by considering aggregated installed PV capacity. Up and down zooming is thus implemented with network management trade-offs required to respond to PV network penetration, following three strategies (Reinforcing network, PV management and Voltage Control) resulting in varying greenhouse gas (GHG) emissions.

This case study also covers archetype 3 (reaching a level) as it considers PV devices with an aggregate/comprehensive approach. However, while archetype 3 focuses only on the technology, this paper explores interactions between fleets of PV panels and the electricity network made up of sub-systems (*e.g.* transformers, wires or on-load tap chargers).

Another example of up-and-down zooming is given by Baltazar *et al.*, (2022) environmentally assessing the technical requirements of implementing EVs in a highway. Based on data collection, optimization modelling and an attributional framework, the study demonstrates that to fulfil the same service as a thermic vehicle, the electrical battery properties and the charging design are strongly related. These design parameters offer trade-off strategies for reducing the environmental impacts of the whole service system.

In practice, adopting (or even discussing) these strategies would require bringing together designers and decision-makers, usually not collaborating and dealing with different natures of constraints. (*e.g.* a designer of Battery of EV and municipal officials in charge of implementing charging stations). At least, such models support the cause-to-consequence link with design constraints and the potential environmental impact generated.

Lastly, with regard to technical system examples, Quisbert-Trujillo *et al.*, (2020) reviewed LCA on the Internet of Things (IoT) to develop a sectorial eco-design framework. The method developed involves the interaction of three layers (sensing layers, edge layers and cloud layer), necessary to satisfy a given functional unit.

Interactions with the environment can also be considered with a spatialized approach, as in the study of the integration of a floating wind power farm on a particular site (Perez-Lopez *et al.*, 2020; Poujol *et al.*, 2020). In that study, the wind resource map is combined with the implemented technology location, deducing the environmental impacts generated. More broadly, territorial approaches are dedicated to identifying the interactions with the life cycle of a product and geographical regions (Loiseau *et al.*, 2018). These examples show that modelling choices are very dependent on what kind of complex system is studied and if a prospective approach is needed.

Addressing several complex systems modelling issues in LCA, Ventura (2022a) proposes the *transition LCA* framework, suitable for assessing ecological transition in a territory (*i.e.* a complex system) enabling to anticipate changes that would occur due to the implementation. The study provides several illustrations: concrete recycling at a regional scale, low-tech building materials in building work or shared electric scooters in a city. Additional case studies should emerge in the coming years based on this emerging framework to support its operability.

Thus, the modelling requirements and LCA specificities to carry out the environmental assessment of the integration of a technology into a complex system are compiled in Table 5, as follows:

| Upscaling archetype                                                  | Methodological requirements to model the archetype profiles                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                                                                                                                                                                                                                                                                                      |
|----------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Geographical and Temporality scopes                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | LCA specificities                                                                                                                                                                                                                                                                                                                                                                                                    |
| <b>Archetype 4</b><br>Integrating a complex (socio-technical) system | <ul style="list-style-type: none"> <li>Mobilize system dynamic engineering and systems thinking with an interoperability focus as tools to model the complex system to be integrated (Ceschin and Gaziulusoy, 2019; Jones and Gilbert, 2018; Onat <i>et al.</i>, 2017),</li> <li>adopt a culture of trade-offs from optimization modelling or socio-economic expertise on a territorial scale (Baltazar <i>et al.</i>, 2022; Ventura, 2022a),</li> <li>more broadly, develop a multidisciplinary approach (Riondet <i>et al.</i>, 2024).</li> </ul> | <ul style="list-style-type: none"> <li>Large geographical scales (the one of the complex system). Usually includes a worldwide perspective (Sacchi <i>et al.</i>, 2022b; Stadler <i>et al.</i>, 2018),</li> <li>Scope studied: the socio-technical complex system where the product or system developed is deployed (<i>e.g.</i> economic market, grid and network, urban metabolism),</li> <li>Spatial and geographical properties focus. Phenomenon's timescale is varying from real-time to decades.</li> </ul> | <ul style="list-style-type: none"> <li>Analysis perimeter challenges (<i>i.e.</i> which territory to consider?) (Ventura, 2022a),</li> <li>Causal model to choose (if consequential approach) and more broadly interaction modelling challenges (Weidema <i>et al.</i>, 2018),</li> <li>Data collection and management challenges (Cluzel, 2012; Cluzel <i>et al.</i>, 2010; Salehy <i>et al.</i>, 2020).</li> </ul> |

Table 5: Modelling recommendations for Archetype 4: confronting methodological requirements to model the archetype to the Modelling constraints given by the LCA mode(s) that would best fit this archetype profile.

### 3.2.5. Archetype 5 – down-limiting, downscaling the planetary boundaries to the technology level

The upscaling archetype 5 sets the question “*Are the environmental impacts of the studied object lower than environmental limits/sustainability levels normatively defined?*”. The AESA is therefore the suitable LCA approach for dealing with the environmental aspects of this archetype. In addition, depending on the time and region where the sustainability of the technology is studied, prospective and regionalized approach are recommended. The environmental assessment of the (absolute) sustainability of a technology can be based on:

- Absolute (attributional) LCA (or AESA)
- Prospective LCA
- Regionalized LCA

Absolute LCA or AESA intends to support the down-limiting of science-based global limits to a regional scale. As mentioned in the introduction, this approach relies on *sharing principles* applied to the SOS from the planetary boundary framework to build an *environmental space* (or limit) on the object's scale under study. Hjalsted *et al.*, (2021) structure the process of building the environmental space (also called SoSOS) by going through two stages: The first step consists of reporting the SOS at an individual level, based on *allocation principles*. These allocation principles can follow an egalitarian line, or consider compensations (for example depending on the historicity of the environmental impacts or the supposed capacity to reduce them over time). The second step consists of “*upscaling*” the individual environmental space to the scale of the object under study, such as an industry, a country or a product. To do so, the authors develop two *upscaling methods* titled *Final Consumption Expenditure* (FCE) and *Green Incentive-Based* (GIB). FCE follows an allocation principle based on the current consumer preference for existing companies and products, while the GIB allocation tends to reward initiatives aimed at sustainability. These two methods are mainly intended for the industrial sector level. Hjalsted *et al.*, (2021) applied both of them to a non-regionalized case study for the dairy sector. Ryberg *et al.*, (2020) in the article titled “*downscaling the planetary boundaries in absolute environmental sustainability assessments*” reviewed the case studies in the literature applying AESA and clarified seven associated distributive justice theories (*e.g.* egalitarianism, utilitarianism, prioritarianism). The authors then proposed recommendations to build an environmental space (or SoSOS) according to the study objective and following a distributive justice theory.

In addition to methodological developments, Bjorn *et al.* (2020) and Ryberg *et al.* (2018) offer practical case studies of such an approach. Authors shape a SOS at the scale of a product (washing machine) respectively with (Bjørn *et al.*, 2020b; Ryberg *et al.*, 2018a) and without (Bjørn *et al.*, 2020b; Ryberg *et al.*, 2018a) a regionalized attributional

LCA. The regionalization developed by Bjørn *et al.*, (2020b) enables LCA practitioners to attribute to each region covering a life cycle step of the studied product takes place, the corresponding use of the SoSOS (*i.e.* environmental impacts). It is a retrospective case study because the washing machine already exists in the case study nevertheless the method could a priori be implemented for a prospective or ex-ante perspective (*i.e.* integrated in design), provided sufficient and accurate data and an implementation following this framework (Bjørn *et al.*, 2020a; Ryberg *et al.*, 2020).

In the building sector, Bendahmane *et al.*, (2022) provide an example of a territorialisation approach in conjunction with AESA to define a carrying capacity specifically for abiotic material circularity concerning a specific territory. This method, untitled MIMOSA, defines normative thresholds for material circularity and therefore helps consider the sustainability of a building project.

Finally, as evoked in subsection 1, the AESA relies on allocation principles to be justified (and subject to discussion with the actors/population of a territory), as they are not imposed by physical laws or product operation. Therefore, AESA is today spontaneously used in connection with attributional LCA. Thus, for each attributional LCA applied (in each archetype), it could be possible to apply an AESA to compare the environmental impacts of a product or a service with a set SoSOS embodying absolute environmental sustainability objectives.

To conclude, the modelling requirements and LCA specificities to carry out the sustainability assessment of a technology are synthesised in Table 6, as follows:

| Upscaling archetype                                                                               | Methodological requirements to model the archetype profiles                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|---------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Geographical and Temporality scopes                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | LCA specificities                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| <b>Archetype 5</b><br>down-limiting, downscaling the planetary boundaries to the technology level | <ul style="list-style-type: none"> <li>Observe fair allocation methods (<i>i.e.</i> argue justice principles) and strictly define the service being studied. Multiple allocation methods are recommended (Hjalsted <i>et al.</i>, 2021; Ryberg <i>et al.</i>, 2020),</li> <li>Manage the data collection associated with the service (usually techno-economically based)(Hjalsted <i>et al.</i>, 2021; Kara <i>et al.</i>, 2023),</li> <li>Monitor methodological development (for product) from (AESA: impact indicators, weighting, allocation rules/justice principle).</li> </ul> | <ul style="list-style-type: none"> <li>The pollution space is based on an attributional LCA of the product or system lifecycle,</li> <li>Studied system scope: AESA implies adapting environmental phenomenon scale considerations to the scale of the functional system studied (Bendahmane <i>et al.</i>, 2022; Bjørn <i>et al.</i>, 2020b),</li> <li>Temporal and geographical scopes focus on the services provided to humans through the artefact developed. The lifecycle inventory should describe best the local or regional focus (national/sectorial) and time variability (Kara <i>et al.</i>, 2023; Ryberg <i>et al.</i>, 2018b).</li> </ul> | <ul style="list-style-type: none"> <li>Scope and analysis perimeter challenges (<i>i.e.</i> which human service/system to consider?),</li> <li>The functional unit is measured per unit of time (as an annual pressure on the environment) (Ryberg <i>et al.</i>, 2018b),</li> <li>Use multi-criteria assessment and specify characterization factors of the impact assessment (Bjørn <i>et al.</i>, 2020a; Sala <i>et al.</i>, 2020).</li> </ul> |

Table 6: Modelling recommendations for Archetype 5: confronting methodological requirements to model the archetype to the modelling constraints given by the LCA mode(s) that would best fit this archetype profile

### 3.3. Guidelines for LCA practices adapted to upscaling archetype assessment

The available LCA modes in the literature have been presented in section 3.1 and the LCA practices associated with each upscaling archetype in subsections 3.2.1 to 3.2.5. In this subsection, we propose synthetic guidelines for LCA practitioners and design teams to deal with the environmental aspects of the upscaling of a product. **Table 7** compiles in column 2 LCA methodological requirements depending on each upscaling archetype to assess or anticipate an upscaling. It refers to the identified necessary expertise (*e.g.* techno-economic) and management



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strategies that design teams must apply during the upscaling assessment. Column 3 suggests relevant or regularly used LCA modes in the literature with regard to an upscaling archetype, and illustrated on study cases reviewed in previous subsections. Thus, as each of the first four archetypes has a different temporality, scope and purpose, one or more LCA “modes” appear to be suitable to environmentally assess an upscaling.

Table 7 - Synthesis of environmental methods and guidelines for LCA practitioners according to upscaling archetypes.

| Upscaling archetype                                                                 | Methodological requirements to model the archetype profiles                                                                                                                                                                                                                                                                                                                                          | Main used environmental assessment modes adapted to the archetype (from literature study)                                                 | Additional compatible LCA modes                                                                                          | Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype                                                                                                                                                                                                                                                                                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | Additional resources For further development                                                                                                                                                                             |
|-------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                                                                           |                                                                                                                          | Geographical and Temporality scopes                                                                                                                                                                                                                                                                                                                                                                      | LCA specificities                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                                                                                                                                                                                                          |
| <b>Archetype 1</b><br>Scaling-up, from laboratory to industrial scale               | <ul style="list-style-type: none"> <li>Define the domain-technical expertise required to model the processes (Buyle <i>et al.</i>, 2019).</li> <li>Ensure strong interactions between researchers and engineers (<i>e.g.</i> technologist, chemist) (Tsoy <i>et al.</i>, 2020).</li> <li>Implement a future-oriented design (Arvidsson <i>et al.</i>, 2024, 2018)</li> </ul>                         | <ul style="list-style-type: none"> <li>Ex-ante LCA</li> <li>Simplified (attributional) LCA</li> <li>ETV</li> </ul>                        | <ul style="list-style-type: none"> <li>Regionalized</li> <li>Parametrized</li> </ul>                                     | <ul style="list-style-type: none"> <li>Mainly use phase-focused scopes units integrated in a life cycle scope.</li> <li>Object studied: a product.</li> <li>Expertise's timescale: over months.</li> <li>Geographical scale: from laboratory scale to an industrial site.</li> </ul>                                                                                                                     | <ul style="list-style-type: none"> <li>Foreground system caution and clear scenario of use phase in the comparative framework: “to which incumbent technology the prototype is compared?” (Cucurachi <i>et al.</i>, 2018; Thonemann <i>et al.</i>, 2020).</li> <li>Data production and collection challenges (Erakca <i>et al.</i>, 2024).</li> <li>Parametrization of the LCI with design parameters (Kamalakkannan and Kulatunga, 2021; Tan <i>et al.</i>, 2018; Tsoy <i>et al.</i>, 2020).</li> </ul> | Available means in literature for data collection: (Zargar <i>et al.</i> , 2022)                                                                                                                                         |
| <b>Archetype 2</b><br>Mass-producing, industrializing                               | <ul style="list-style-type: none"> <li>Follow an integrative and normative approach.</li> <li>Refer to techno-economic expertise.</li> <li>Identify the stakeholders of the value chain (life cycle engineering).</li> </ul>                                                                                                                                                                         | <ul style="list-style-type: none"> <li>ISO Standards-based LCA (attributional, consequential)</li> <li>Prospective dynamic LCA</li> </ul> | <ul style="list-style-type: none"> <li>Regionalized</li> <li>Dynamic</li> </ul>                                          | <ul style="list-style-type: none"> <li>Life cycle-based, regionalized approach over the value chain (Weidema <i>et al.</i>, 2018).</li> <li>Studied system: a product system included in an industrial context (Hauschild <i>et al.</i>, 2020).</li> <li>Expertise's timescale: over years.</li> <li>Geographical scope: adjusted to the mass production and worldwide industrialized system.</li> </ul> | <ul style="list-style-type: none"> <li>Industrial trend focus (<i>e.g.</i> favour dynamic LCI).</li> <li>End-of-life modelling challenges.</li> <li>data collection/extrapolation challenges (Zargar <i>et al.</i>, 2022).</li> </ul>                                                                                                                                                                                                                                                                    | Design for X (Manufacturing) LCA standards and European commission (“European Platform on LCA   EPLCA,” 2011)                                                                                                            |
| <b>Archetype 3</b><br>Reaching a level of cumulated service, deploying a technology | <ul style="list-style-type: none"> <li>Develop a market maturity and sectorial long-term expertise (Muñoz and Weidema, 2021).</li> <li>characterize a cumulative technology's performance (Hung <i>et al.</i>, 2022; Laratte <i>et al.</i>, 2014; Menten <i>et al.</i>, 2015).</li> <li>Set up scenario expertise and specific data uncertainty management (Langkau <i>et al.</i>, 2023).</li> </ul> | <ul style="list-style-type: none"> <li>Prospective, attributional and dynamic LCA</li> <li>Integrated LCA - dynamic modelling</li> </ul>  | <ul style="list-style-type: none"> <li>Attributional, consequential</li> <li>Regionalized</li> <li>Transition</li> </ul> | <ul style="list-style-type: none"> <li>Large spatial/social scale (regional, national - sectorial or group of technology).</li> <li>Scope studied: the industry sector where the products are deployed.</li> <li>The phenomenon's timescale is over decades.</li> </ul>                                                                                                                                  | <ul style="list-style-type: none"> <li>Background system accuracy challenges: rigorous scenario hypothesis is required (Langkau <i>et al.</i>, 2023).</li> <li>Avoidance of temporal mismatch (<i>i.e.</i> favour dynamic LCA) (Mendoza Beltran <i>et al.</i>, 2020).</li> <li>Natural resources focus, and more broadly cumulative properties of the environmental impacts (Charpentier Poncelet <i>et al.</i>, 2022).</li> </ul>                                                                       | Material indicator: mineral resource dissipation (Charpentier Poncelet <i>et al.</i> , 2022) Prospective scenario management : (Langkau <i>et al.</i> , 2023) Uncertainties and prospective (Maier <i>et al.</i> , 2016) |

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Table 7 (continuing)

| Upscaling archetype                                                                               | Methodological requirements to model the archetype profiles                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Main used environmental assessment modes adapted to the archetype (from literature study)                                                                                          | Additional compatible LCA modes                                                                                                              | Modelling recommendations about clauses and constraints of the LCA mode adapted for this archetype                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Additional resources For further development                                                                                                           |
|---------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                                                                                                                                                                                    |                                                                                                                                              | Geographical and Temporality scopes                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | LCA specificities                                                                                                                                                                                                                                                                                                                                                                                                                                 |                                                                                                                                                        |
| <b>Archetype 4</b><br>Integrating a complex (socio-technical) system                              | <ul style="list-style-type: none"> <li>Mobilize system dynamic engineering and systems thinking with an interoperability focus as tools to model the complex system to be integrated (Ceschin and Gaziulusoy, 2019; Jones and Gilbert, 2018; Onat <i>et al.</i>, 2017),</li> <li>adopt a culture of trade-offs from optimization modelling or socio-economic expertise on a territorial scale (Baltazar <i>et al.</i>, 2022; Ventura, 2022a),</li> <li>more broadly, develop a multidisciplinary approach (Riondet <i>et al.</i>, 2024).</li> </ul>                                    | <ul style="list-style-type: none"> <li>Regionalized/spatialized LCA</li> <li>Consequential LCA</li> <li>Transition LCA</li> <li>Integrated LCA - Optimization modelling</li> </ul> | <ul style="list-style-type: none"> <li>Attributional</li> <li>Consequential</li> <li>Hybrid</li> <li>Dynamic</li> <li>Prospective</li> </ul> | <ul style="list-style-type: none"> <li>Large geographical scales (the one of the complex system). Usually includes a worldwide perspective (Sacchi <i>et al.</i>, 2022b; Stadler <i>et al.</i>, 2018),</li> <li>Scope studied: the socio-technical complex system where the product or system developed is deployed (e.g. economic market, grid and network, urban metabolism),</li> <li>Spatial and geographical properties focus. Phenomenon's timescale is varying from real-time to decades.</li> </ul>                                                                                                                                              | <ul style="list-style-type: none"> <li>Analysis perimeter challenges (<i>i.e.</i> which territory to consider?) (Ventura, 2022a),</li> <li>Causal model to choose (if consequential approach) and more broadly interaction modelling challenges (Weidema <i>et al.</i>, 2018),</li> <li>Data collection and management challenges (Cluzel, 2012; Salehy <i>et al.</i>, 2020).</li> </ul>                                                          | Design for Sustainability (Ceschin and Gaziulusoy, 2019)                                                                                               |
| <b>Archetype 5</b><br>down-limiting, downscaling the planetary boundaries to the technology level | <ul style="list-style-type: none"> <li>Observe fair allocation methods (<i>i.e.</i> argue justice principles) and strictly define the service being studied. Multiple allocation methods are recommended (Hjalsted <i>et al.</i>, 2021; Ryberg <i>et al.</i>, 2020).</li> <li>Manage the data collection associated with the service (usually techno-economically based) (Hjalsted <i>et al.</i>, 2021; Kara <i>et al.</i>, 2023).</li> <li>Monitor methodological development (for product) from (AESA: impact indicators, weighting, allocation rules/justice principle).</li> </ul> | <ul style="list-style-type: none"> <li>Absolute (attributional) LCA</li> </ul>                                                                                                     | <ul style="list-style-type: none"> <li>Prospective</li> <li>Regionalized</li> <li>Dynamic</li> <li>Spatialized</li> </ul>                    | <ul style="list-style-type: none"> <li>The pollution space is based on an attributional LCA of the product or system lifecycle.</li> <li>Studied system scope: AESA implies adapting environmental phenomenon scale considerations to the scale of the functional system studied (Bendahmane <i>et al.</i>, 2022; Bjørn <i>et al.</i>, 2020b).</li> <li>Temporal and geographical scopes focus on the services provided to humans through the artefact developed. The lifecycle inventory should describe best the local or regional focus (national/sectorial) and time variability (Kara <i>et al.</i>, 2023; Ryberg <i>et al.</i>, 2018b).</li> </ul> | <ul style="list-style-type: none"> <li>Scope and analysis perimeter challenges (<i>i.e.</i> which human service/system to consider?);</li> <li>The functional unit is measured per unit of time (as an annual pressure on the environment) (Ryberg <i>et al.</i>, 2018b);</li> <li>Use multi-criteria assessment and specify characterization factors of the impact assessment (Bjørn <i>et al.</i>, 2020a; Sala <i>et al.</i>, 2020).</li> </ul> | Specific characterization factors (PB-LCA): (Ryberg <i>et al.</i> , 2020; Sala <i>et al.</i> , 2020; Winther, 2023) Ryberg <i>et al.</i> , 2020, 2018b |

The specificity of the upscaling archetype 5 (down-limiting) is that it does not have a predefined temporality and can therefore be applied at the same time as the others. We propose in column 4 “Additional LCA modes” that have to be considered as a possible enrichment of the recommended or current LCA practices. It might lead to further research into the interoperability of LCA modes and new guidelines for design teams including LCA practitioners. Columns 5 and 6 present recommendations and constraints to which LCA practitioners must pay attention. “Geographical/Temporality” (column 5) stands for aspects of the LCA scope related to spatial and time characteristics of the studied product or system and the implementation of its assessment (*e.g.* timescale of the assessment). “LCA specificities” (column 6) provide particular features to be conserved by LCA practitioners. It concerns challenges for the modelling approach (*e.g.* foreground and background systems considerations, choices of impact categories, model selection) and result interpretations (comparative analysis or not). Column 7 gives

additional methodological content or operational resources relevant for a specific upscaling archetype identified in the literature. This column aims to guide LCA practitioners toward available resources to facilitate or improve their practice of the upscaling assessment. Table 7 is intended to be completed and revised in the coming years by the interested communities, according to new methods, and case studies, demonstrating feasibility or incompatibility.

### 3.3.1. From generic recommendations to specific guidelines; An illustration of the literature review of engineering fields

In this research paper, and based on multiple examples and case studies from the LCA literature, the compatibility between LCA modes and upscaling archetypes has been illustrated. It clearly appears that “LCA modes” are not immovable and depend on the practices and identified needs for environmental assessments. Transition LCA is the best example of this trend. Many developments are coming concerning new interfaces or hybridizations between them, facilitated for instance by new practices. For instance, the Python-based LCA with open-source approaches supports new computational means and methodologies (Cardellini and Mutel, 2018; Mutel, 2017; Steubing *et al.*, 2020) dedicated to dynamic, regionalized and prospective LCA, respectively. Thus, new practices and then LCA modes could therefore arise supported by new resources, expertise, habits, laws and standards to meet the crucial stakes of environmental assessment for technology upscaling. To complete the generic guidelines of Table 7, a cartography of our accessed literature is proposed in Fig. 1. This matrix, called UA-EF for *Upscaling Archetypes (UA) by Engineering Fields (EF)*, has been designed to relate the upscaling archetypes (horizontally) to the engineering sectors in which LCA content and practices were identified during the literature review. It represents the references used to identify methodological invariants and structure the guidelines (large dots) and case studies to illustrate the LCA practices (small squares). The objective of this illustration is to present a snapshot at a given moment of an identified literature related to LCA practices to assess or anticipate the upscaling of a technology. It is not intended to be exhaustive but could be supplemented by further research with, for instance, a focus on a specific engineering field.

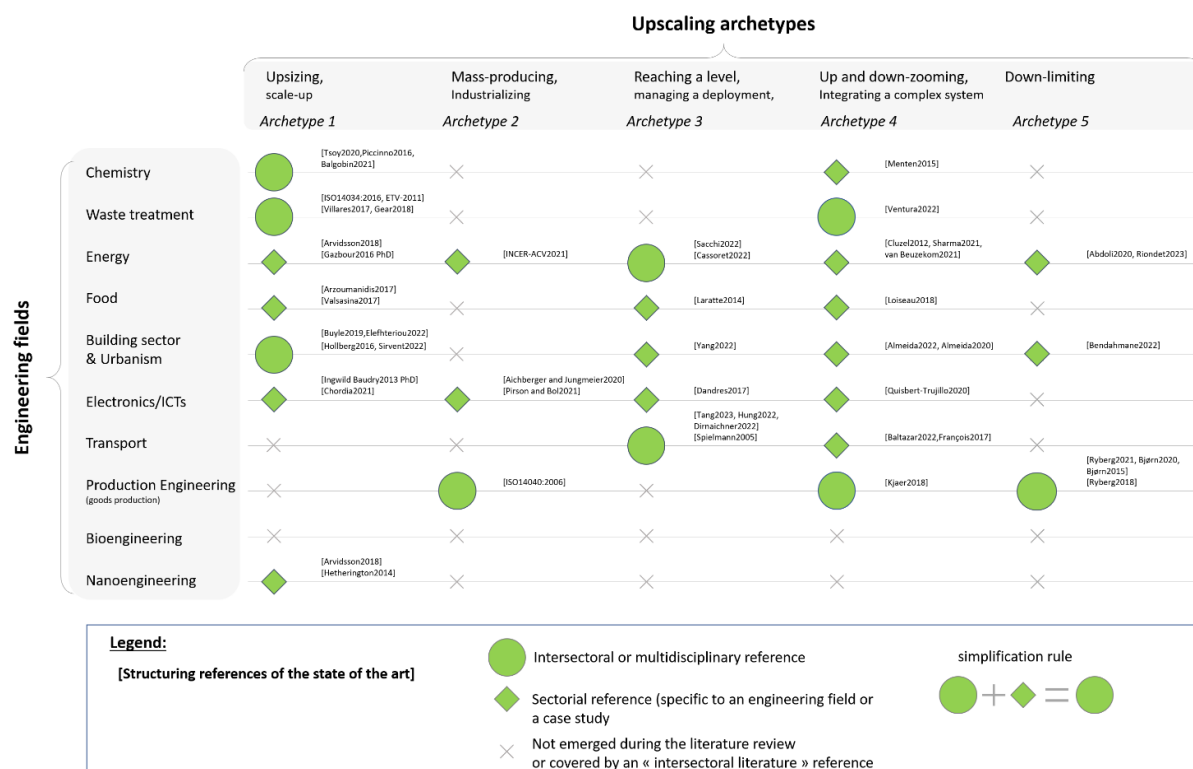


Fig. 1 - The Matrix UA-EF, presenting the selected LCA literature depending on the archetype of upscaling and the engineering field.

A few remarks can be made about this illustration:

- Archetype 1 (upsizing) is developed in multiple engineering fields and therefore benefits from a well-structured LCA approach, mainly based on ex-ante LCA.
- Archetype 2 (mass-producing) is evolving to a standard approach, not exhaustive in terms of case studies. Specific Product Environmental Footprint (PEF) could also enrich this column. As it stands, many examples may exist but are not specifically tagged as an assessment of “mass-produced” products.
- Archetype 3 (reaching a level) is mentioned in the energy and transport sectors, both related to energy transition scenarios (see large dots in column 3). As it is a relatively new topic of research in LCA, more case studies and structuring guidelines are forthcoming.
- Archetype 4 (integrating a complex system) presents many case studies. As there are no generic models for all possible interactions between a technology and the complex systems it integrates, there are few generic guidelines for LCA. The only identified generic framework is the description of the Transition LCA provided by (Ventura, 2022a) which is relatively recent and presents few associated case studies.
- Archetype 5 (down-limiting) hinges on two approaches structured in a few references (Bjorn *et al.*, 2016; Ryberg *et al.*, 2020) and applies theoretically to any engineering field. Like archetype 3, it is a relatively new topic of research in the LCA community, implying upcoming case studies and developments to solve methodological dilemmas (Guinee *et al.*, 2022). Currently, methodological results and case studies in various engineering fields are regularly arising (cf. researches of Center for Absolute Sustainability team, DTU).

Finally, The matrix UA-EF (*i.e.* Fig. 1) could help members of design teams, including LCA practitioners, to identify which engineering field is proactive on a certain vision of the upscaling (*i.e.* upscaling archetype). It also points to which groups of authors have been identified as contributing to the development and/or operationalization of methodologies through case studies.

## 3.4. Discussion: LCA, upscaling archetypes and ecodesign

To be clear, the upscaling archetypes must be understood as five analysis grids to study specific aspects of a technology upscaling. These aspects rely on each other, and their predominance and interactions depend on the industrial sector as evoked in subsection 0 and illustrated by Fig. 1. Moreover, each archetype hinges on a particular vision (supported by its goal, scope and subject), making an upscaling assessment ideally merging component vision, product vision, value chain or market vision, holistic vision, etc. The integration in the design process of these “visions” is variable. Those related to engineering are more integrated, while others are not yet (*e.g.* vision of long-term energy transition management or absolute sustainability). Consequently, our research work strives to be aligned to integrate environmental aspects of a technology upscaling in the design process. This objective can be included in the *Design for Sustainability* (DfS) framework of Ceschin and Gaziulusoy (2019). In this future-oriented paradigm, the integration of knowledge is a crucial stake which, on the one hand, may add a possible new designer’s levers by considering phenomena that are currently considered at best as externalities. In contrast, it could drastically modify the organization and design process, which is never an easy point. Each upscaling archetype has a specific timescale, from several months or years for the laboratory to industrial scale (archetypes 1 and 2), to decades for transitioning (archetype 3), through spatial varying focus (archetype 4), oscillating between real-time up to several decades. The efforts to environmentally assess them must be strengthened, especially as the time horizon is distant. The duration and precise steps in the process design to apply methods for each archetype are not covered by this paper, partly due to the specificities of engineering sectors and technology development timescales. Further research could be held to answer the question, “*What is the necessary maturity to carry out a specific archetype of upscaling?*”, in the wake of the work of Buyle *et al.*, (2019) for the first archetype and to complete the present guidelines (cf. Table 7).

More broadly, the issue of integration in design is part of the consideration of the consequences of choices that are increasingly outside the traditional scope of designers. Rae *et al.*, (2020) for instance define researchers, planners, designers and consumers as stakeholders of an upscaling. All of these actors take part in the upscaling process. Indeed, the literature reviewed usually involves only a few of them, *e.g.* technology experts and engineers, joined recently by LCA practitioners (Tsoy *et al.*, 2020). In that perspective, the upscaling archetypes could be mobilized throughout other types of literature to reflect the management of a technology upscaling in disciplines other than environmental assessment (*e.g.* engineering design, risk assessment, management or governance, etc.). Thus, a

review process similar to that presented in this article could be conducted in further research to complete the UA-EF matrix with complementary assessment methodologies. Hackenhaar *et al.*, (2024) provide a comprehensive framework, grouping environmental, social and economic indicators. This approach, mentioned as Life Cycle Sustainability Assessment (LCSA) could also be applied to the phenomenon of emerging technology upscaling. The present article would then only support the environmental part of a LCSA of the upscaling.

### 3.4.1. Literature review exhaustivity for LCA Modes and perspectives for LCA practices

This article is not intended to be exhaustive regarding LCA approaches and their specificities. For instance, matrix UA-EF (see Fig. 1) presents some lack of structuring references for the fields of Chemistry or Bioengineering. With a view to completeness, these engineering fields could be completed with additional literature review, and new engineering fields could be integrated into the UA-EF matrix. More broadly, this paper focuses on currently available approaches in LCA literature for environmentally assessing a technology upscaling. In that regard, it presents a partial picture of the LCA literature between 2022 and 2024 on this topic. The accessibility of methodologies, their nominations and associated practices will require updating as they evolve rapidly (see prospective LCA tools and practices). In addition, LCA modes have different levels of maturity and new approaches could emerge, challenging the LCA practices. However, a characterization process similar to the one presented in this paper could be applied to these future LCA modes to delve into their operability to assess a technology upscaling. A cross-disciplinary vision would then be crucial to identify the technical upscaling models and databases available from engineering fields.

### 3.4.2. Towards environmental assessment practices encompassing the five upscaling archetypes

As mentioned in section 2 “Formalism of upscaling archetypes”, ideally, as many of the five upscaling archetypes should be assessed during the development of a product or technology. However, very few engineers or LCA practitioners can fully master the five upscaling archetypes or all the LCA modes presented with associated databases and models. Moreover, as shown in this paper, the degree of maturity for LCA methods and practices varies depending on the upscaling archetype.

Nevertheless, following an integrative posture, the cogitation should rather focus on the level of detail that engineers and designers (including LCA practitioners) need to target, to properly model a product and the related potential upscaling. Thus, the interpretation of the results must be made in light of sustainability goals and, therefore, document “go/no-go” strategies regarding the upscaling of an emerging technology. To an extent, documenting an existing or underdevelopment upscaling process could be a requirement to clarify the designer’s decisions taken during the evolution process steps transparently, and justified by socio-technical and environmentally scientific-based assessment methods.

Finally, no structured methodology yet exists to aggregate several facets of the upscaling and help LCA practitioners in product design teams to orchestrate a LCA-based assessment concerning archetypes and identified prior upscaling goals. However, this research paper paves the way for such methodological outcomes, as well as tests of operational conditions to consolidate the development of emerging technology strategies from the environmental perspective.

## 4. Conclusions

In response to a *lack of clarity of available LCA modes for design team members* including LCA practitioners, this paper defines and characterises fifteen LCA “modes”, including attributional, consequential, prospective, spatialized, dynamic, and absolute LCA. These LCA “modes” are categorised into classic or historical modes, temporal or geographical-focused approaches and hybrid or combined approaches depending on the diversity of case studies over different engineering fields, the availability of practical tools, software and guidelines and the age of the structuring references. The analysis points out the lack of adoption by design teams of some of these available LCA modes that would best fit to model a technology upscaling.

Then a critical review has been carried out to investigate which LCA modes best fit the technology upscaling aspects design teams are confronted with. This review matched the modelling requirements of the fifteen LCA modes to the objectives of the five technology upscaling archetypes commonly faced by designers: *scaling-up, from laboratory to industrial scale* (archetype 1), *mass-producing or industrializing* (archetype 2), *reaching a level*

of cumulated service or deploying a technology (archetype 3), integrating a complex system (archetype 4), and down-limiting or downscaling the planetary boundaries to the technology level (archetype 5).

Multiple examples and case studies from various engineering fields (e.g. mobility, chemistry, energy, urbanism) are provided to illustrate the LCA practices associated with each archetype, together with synthetic guidelines for design team members about methodological requirements to model the archetype profiles, the main used LCA modes in literature and additional compatible ones, and LCA modelling recommendations. Available resources for specific LCA modes to go further on theoretical aspects, or for applications, are also provided.

This paper also reveals that LCA modes are not time-frozen categories. New frameworks and practices emerge depending on the needs for environmental assessments, that are particularly challenging in the case of the technology upscaling phenomenon (e.g. transition LCA or AESA). To extend the applicability conditions of the given recommendations, the paper proposes LCA practitioners a graphical tool, to support them in finding the best available method to assess their upscaling case, i.e. regarding their respective engineering field (EF) and the targeted upscaling archetype (UA). This tool, called matrix (UA-EF) is intended to be updated to follow the evolutions of LCA mode categorization.

This paper finally addresses several challenges to extend the present methodological recommendations and move toward a systematic eco-design practice integration when dealing with technological system upscaling in the coming years.

## Credit authorship contribution statement

Lucas Riondet: Conceptualization, Methodology, Investigation, Data curation, Writing - original draft. Maud Rio: Formal analysis, Supervision, Writing - review & editing. Véronique Perrot-Bernardet: Formal analysis, Supervision, Writing - review & editing. Peggy Zwolinski: Validation, Supervision, Writing - review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Chapitre 7 – Analyse environnementale du changement d'échelle (proposition 2)

L. Riondet, M. Rio, V. Perrot Bernardet, P. Zwolinski

SECTION 7.1 – ARTICLE 2

### Appendix

Appendix 1 - Selected characteristics of LCA modes potentially suitable for assessing one or several upscaling archetypes, adapted from (Guinée et al., 2018) and (Ventura, 2022a).

|                    | LCA mode              | Definition                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Addressed question                                                                                                                                                                                                                                                          | Scope                                                                                           |                                                      | ISO-standard covered | Considered expertise* and actors                                                                                                                                                                             | Databases or specific resources                                                                                                  | Associated references                                                                    |
|--------------------|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|------------------------------------------------------|----------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
|                    |                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                                                                                                                                                                                                                                                             | Reference flows or object in the foreground system                                              | Temporal                                             |                      |                                                                                                                                                                                                              |                                                                                                                                  |                                                                                          |
| Classic/historical | Attributional         | <ul style="list-style-type: none"> <li>“The attributional approach attempts to provide information on what portion of global burdens can be associated with a product (and its life cycle).” (Sonnemann et al., 2011).</li> <li>“Describe actual and/or forecasted specific and/or average life cycle of a studied object relatively to its functional unit into a static background system” (Ventura, 2022a).</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                         | <i>What portion of global environmental impacts can be attributed to the studied object?</i>                                                                                                                                                                                | A product system (including the product's life-cycle), usually product and value chain focused. | Future or past-oriented.                             | Yes                  | Product and industrial engineering. Allocation rules. One actor (in general).                                                                                                                                | Standard LCA data(bases), such asecoinvent, GaBi, ILCD, USDA or Idemat                                                           | “ISO 14040,” 2006; Schaubroeck et al., 2021; Sonnemann et al., 2011                      |
|                    | Consequential         | <ul style="list-style-type: none"> <li>“The consequential approach attempts to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product).” (Sonnemann et al., 2011).</li> <li>“Describe expected changes in response to possible decisions or to changes in demand for the functional unit into a dynamic background system” (Ventura, 2022a).</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                      | <i>How human activities (societies) react to an unusual event/request and what are the resulting environmental impacts?</i>                                                                                                                                                 | Product system as they change due to a decision. (Multiple value chains).                       | Future-oriented.                                     | Yes                  | Technical and/or economic causal modelling expertise. One actor (in general).                                                                                                                                | Standard LCA data(bases), such asecoinvent.                                                                                      | “ISO 14040,” 2006; Sonnemann et al., 2011; Weidema et al., 2018                          |
| Temporal focus     | Prospective           | “Prospective LCA deals with technologies in the future, whereas retrospective studies deal with products in the past, regardless of other modelling approaches.” It is a scenario-based approach and can be motivated by predictive, exploratory or normative perspective (Arvidsson et al., 2018).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | <i>What will/may or must be the environmental impacts of a studied object?</i>                                                                                                                                                                                              | A product system, already mature of not.                                                        | Future-oriented: predictive, exploratory, normative. | No                   | Scenario management expertise and socio-economic-technological expertise. If necessary, multiple actors (technical and technological experts, economists, social scientists, engineers, decision-makers...). | Software and computation resources: (Sacchi et al., 2023, 2022b; Steubing et al., 2020) Sensitivity analysis: (Kim et al., 2022) | Arvidsson et al., 2018                                                                   |
|                    | Ex-ante               | A particular case of prospective LCA. <ul style="list-style-type: none"> <li>Describe the “environmental profile of an emerging technology on an industrial scale and use this information to steer further research efforts or compare an emerging technology with an incumbent technology on an industrial scale”. (Buyle et al., 2019).</li> <li>“Ex-ante is defined as before a product or technology is commercially deployed at scale and information and insights on the topic under assessment are not (yet) readily available.” (Tecchio et al., 2016; van der Giesen et al., 2020).</li> </ul>                                                                                                                                                                                                                                                          | <i>What will/may be the life cycle impacts associated with early-stage technology after its industrialization/commercialization?</i>                                                                                                                                        | An emerging/early-stage/prototype technology or product system. Rarely including EoL.           | Future-oriented: predictive, exploratory.            | No                   | Technology and extrapolating expertise. Multiple actors: LCA practitioners and technical experts (R&D actors) (Tsoy et al., 2020).                                                                           | Sensitivity analysis (Lacirignola et al., 2017)                                                                                  | Tecchio et al., 2016; van der Giesen et al., 2020; Buyle et al., 2019; Tsoy et al., 2020 |
|                    | Parametrized          | A particular case of ex-ante LCA.           “The basic concept of the parametric life cycle assessment (PLCA) approach is combining the principles of parameterization with a general LCA method. [...] it helps to identify the eco-design as well as the effective parameters based on their effects on the entire life cycle through sensitivity analysis and scenario analysis.” (Kamalakkannan and Kulatunga, 2021)                                                                                                                                                                                                                                                                                                                                                                                                                                          | <i>What is the influence of design parameters on LCA results?</i>                                                                                                                                                                                                           | A future or current emerging/early-stage technology or product system.                          | Future-oriented: predictive, exploratory.            | No                   | Technology modelling, extrapolating and design expertise. Multiple actors: LCA practitioner and technical experts (R&D actors) (Tsoy et al., 2020).                                                          | /                                                                                                                                | Kamalakkannan and Kulatunga, 2021                                                        |
|                    | Anticipatory          | <ul style="list-style-type: none"> <li>Describe future developments and “states that stakeholders should be included in the process to obtain more valuable results”. (van der Giesen et al., 2020). Based on anticipatory governance, “takes a forward-looking (not retrospective assessment) and engages stakeholders to inform critical modelling decisions and increase the credibility and relevance of results.</li> <li>Anticipatory LCA can be defined as “non-predictive and inclusive of uncertainty, which can be used to explore both reasonable and extreme-case scenarios of future environmental burdens associated with an emerging technology”. The aim is to identify the most relevant uncertainties and engaging research and development decision-makers to guide research and development and innovation” (Wender et al., 2014).</li> </ul> | <i>What may be the life cycle impacts associated with early-stage technology after its industrialization and what are the levels to lower them?</i><br>OR<br><i>What must be the life cycle impacts associated with early-stage technology after its industrialization?</i> | An early-stage technology/ product system.                                                      | Future-oriented: exploratory, normative.             | No                   | Decision-sharing expertise. Multiple actors (LCA practitioner, technical experts, decision-makers).                                                                                                          | /                                                                                                                                | van der Giesen et al., 2020; Wender et al., 2014                                         |
|                    | Ex-post/retrospective | Describe the environmental profile of a product after it had been “Commercially in use for extended periods of time and information and data are available from empirical experience” (van der Giesen et al., 2020).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | <i>What was/is the environmental impacts of the studied object?</i>                                                                                                                                                                                                         | A commercially existing product system.                                                         | Past-oriented.                                       | Yes                  | Data collection and management expertise, one actor (in general).                                                                                                                                            | Standard LCA data(bases)                                                                                                         | van der Giesen et al., 2020                                                              |

\*added to usual LCA expertise

Appendix 1 (continued)

# Chapitre 7 – Analyse environnementale du changement d'échelle (proposition 2)

L. Riondet, M. Rio, V. Perrot Bernardet, P. Zwolinski

## SECTION 7.1 – ARTICLE 2

|                     | LCA mode                        | Definition                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Addressed question                                                                                                                                                                                                                                          | Scope                                                                                                                                                     |                          | ISO-standard covered | Considered expertise* and actors                                                                                                                        | Databases or specific resources                                                                         | Associated references                                                               |
|---------------------|---------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
|                     |                                 |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |                                                                                                                                                                                                                                                             | Reference flows or object in the foreground system                                                                                                        | Temporal                 |                      |                                                                                                                                                         |                                                                                                         |                                                                                     |
| Temporal focus      | Dynamic (Static)                | Dynamic LCA “assess the environmental impacts at different time steps, according to both different moments of emissions and kinetics of their effects inside the ecosphere.”; “The dynamic approach is justified by the fact that the environmental impact of a pulsed emission is certainly different from that of the same quantity emitted but spread over time” (Ventura, 2022b).<br>Static : “LCIA considers that all of the elementary flows in a product’s life cycle are emitted at the same time” (Ventura, 2022b).                                                                                                                                                                                                                                                                                                                                                     | <i>What are the effects of the time dependence of inventory and characterization on environmental impacts in LCA results? (Including cumulative effects)</i>                                                                                                | A group of systems (fleet of products).                                                                                                                   | Future or past-oriented. | No                   | Temporal variability expertise.<br>One actor (in general).                                                                                              | Brightway2 resources: (Cardellini et al., 2018; Cardellini and Mutel, 2018)                             | Cardellini et al., 2018; Ventura, 2022b                                             |
|                     | Regionalized (non-regionalized) | Regionalization:<br><ul style="list-style-type: none"> <li>Describe the environmental impacts with “assigned geographical location” (Frischknecht et al., 2019).</li> <li>A term used to describe the representativeness of the processes and phenomena of a given region (Patouillard et al., 2018).</li> </ul> Spatial differentiation = regionalization of characterizing factors : site generic, site dependent and site specific (Potting and Hauschild, 2006).<br><br>Non-regionalized: use aggregated/generic environmental impacts without spatial differentiation.                                                                                                                                                                                                                                                                                                      | <i>What are the environmental impacts of a studied object with regard to its geographical location?</i>                                                                                                                                                     | A product system (including the product’s life-cycle).                                                                                                    | Future or past-oriented. | Yes                  | Data collection and management expertise.<br>One actor (in general).                                                                                    | Brightway2 resources: (Mutel, 2014; Mutel and Louineau, 2021)                                           | Frischknecht et al., 2019; Patouillard et al., 2018                                 |
| Geographical focus  | Territorialized                 | A particular case of regionalized LCA. Territorial LCAs have been divided into two types: type A and type B (Loiseau et al., 2018).<br>Type A study a technology anchored in a known territory of which functions may vary according to that territory, and type B study one territory with all its functions and related activities. In both methods, the foreground system is inside the considered territory. [...] Territorial LCAs (type A) assess environmental impacts relatively to a unitary functional unit, but it may include several actors if these are located inside the considered territory.<br>Territorial LCAs (type B) assess environmental impacts relatively to the total numbers of products that are produced and consumed inside the considered territory and thus all concerned actors inside this territory.” (Loiseau et al., 2018; Ventura, 2022a) | <i>Type A: What are the environmental impacts of a studied object with regard to its interactions with a considered territory?</i><br><br><i>Type B: What are the environmental impacts associated with functions and services provided by a territory?</i> | Type A: One product system produced in a territory.<br><br>Type B: A territory (“several products produced or consumed in a territory” (Ventura, 2022a)). | Future or past-oriented. | No                   | Geographer's expertise.<br>Type A: Possibly involving “several actors in the territory”.<br>Type B: “several actors in the territory” (Ventura, 2022a). | /                                                                                                       | Loiseau et al., 2018                                                                |
|                     | Spatialized                     | Spatialization: act of assigning a location to something, e.g. a flow (Patouillard et al., 2018). A term used to describe the variability of processes and phenomena depending on geography.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | <i>What is the geographical distribution of environmental impacts associated with LCA results?</i>                                                                                                                                                          | A large area system.                                                                                                                                      | Past-oriented.           | No                   | Geographical variability expertise, geographical information system (GIS) data collection.<br>One actor (in general).                                   | Brightway2 resources: (Mutel, 2014)                                                                     | Patouillard et al., 2018                                                            |
| Hybrid/ combined    | Transition (Hybrid)             | A particular case of hybrid LCA, using consequential and spatialized attributional LCA frameworks. “Describe expected changes in response to possible decisions or to changes generated by transition solutions into a dynamic background system” (Ventura, 2022a).<br><br>Hybrid: use methodological elements of LCA (e.g. environmental indicators, models, characterization factors).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | <i>What are the expected changes in a given territory in response to the implementation of “transition solutions”?</i>                                                                                                                                      | Territory, including the human activities                                                                                                                 | Future-oriented.         | No                   | “Several actors, several products, all involved in existing and substitution territorial scenarios” (Ventura, 2022a).                                   | /                                                                                                       | Ventura, 2022a                                                                      |
|                     | Input Output (IO)               | A particular case of hybrid LCA: “Describe macroscale changes in response to possible decisions or changes in a given economic sector” (Ventura, 2022a).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | <i>What are the global life-cycle impacts associated with the evolution of an economic sector?</i>                                                                                                                                                          | An economic sector (multiple product systems or economic sectors).                                                                                        | Future or past-oriented. | No                   | Economic expertise, A Multiple actors (industrials, economists).                                                                                        | Examples of model/databases: EXIOBASE: (Agez, 2022; Agez and Majeau-Bettez, 2020; Stadler et al., 2018) | Ventura, 2022a                                                                      |
|                     | Absolute (AESAs)                | A particular case of hybrid LCA, using the attributional LCA framework and completes it by comparing resulting impacts with an external list of environmental carrying capacities. It implies that for a given functional unit, no technical solution may be environmentally sustainable (Bjorn et al., 2020a).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | <i>Are the environmental impacts of the studied object lower than environmental limits/ sustainability levels normatively defined?</i>                                                                                                                      | Product system, organization, industrial or economic sector, human activities.                                                                            | Future or past-oriented. | No                   | Allocative, economic, social expertise.<br>One actor (in general).                                                                                      | Specific characterization factors. Available from (Winther, 2023)                                       | Bjorn et al., 2016; Bjorn et al., 2020b; Heijungs et al., 2014; Ryberg et al., 2020 |
| Classic/ historical | Relative                        | Also identified as “classic” attributional LCA, meaning a relative assessment comparing products’ impacts between each other, and enabling to determine the “best technology” from the environmental point of view. (Bjorn et al., 2020a).<br>Use methodological elements of LCA (e.g. environmental indicators, models, characterization factors).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | <i>Are the environmental impacts of the studied object lower than similar objects/references?</i>                                                                                                                                                           | Product system.                                                                                                                                           | Future or past-oriented. | Yes                  | Benchmarking expertise.<br>One actor (in general).                                                                                                      | /                                                                                                       | Bjorn et al., 2020a                                                                 |

\*added to usual LCA expertise

## 7.2 Article 3 - Processus *Environmental Assessment for Upscaling (EAU)*

### Stratégie de publication pour l'Article 3

L'**Article 3** a été soumis une première fois à *International Journal of Life Cycle Assessment* le 31 Juillet 2023 et rejeté le 21 Avril 2024 après une première révision majeure. Ce journal avait été visé en tant que journal d'expert ACVistes (h-index 131, impact factor 4.8, Q1 sur sciences environnementales). Le démarche actuelle est de positionner le processus EAU comme une méthode destinée à des équipes de conception pratiquant des formes d'ACV mais sans être crédités d'experts ACVistes. Les journaux *International Journal of Sustainable Engineering* ou *Journal of Cleaner Production* sont envisagés pour une soumission en 2024 du manuscrit.

Cet article s'intitule « *Environmental Assessment for Upscaling : a LCA-based eco-design process for design teams* » et constitue les **pages 146 à 174** de la thèse.

### Abstract

*The upscaling of technology appears to be a socio-technical phenomenon covering the technology development and deployment in society to meet societal imperatives (e.g. sustainability). It has been characterized with five archetypes, each encompassing specific vocabulary, design practices, stakeholders, and methods referring to a great variety of consequences on industrial systems. These upscaling archetypes are not all considered in the current eco-design practices, and even less in a unified way, as it potentially involves modelling and LCA practices from varying scientific communities. This research paper, based on a literature review on LCA, upscaling, and eco-design, identifies six methodological requirements to propose upscaling environmental assessment guidelines for design teams. It results, based on the identified requirements, in the proposition of a new LCA-based design process, titled Environmental Assessment for Upscaling (EAU). Its originality is to propose a structure favouring the emergence of an accurate consideration of the environmental aspects of the upscaling with an aggregated approach of the upscaling archetypes. This methodology follows six necessary steps, and relies on original and interlinked categories of upscaling parameters, enabling design teams to consider the upscaling of a technology as a whole during the design process. An organization framework and four additional resources to guide the collaboration of design team stakeholders (e.g. technical expert, lifecycle expert, company manager) are also presented in parallel, with a focus on lifecycle engineering. The EAU process clarifies the main points of interest in the LCA practices related to upscaling assessment. It links ongoing work on the characterization of technology upscaling*

*with the various LCA communities. Using the LCA standard as a vector of integration contributes to making LCA approaches operational in companies. Finally, ongoing research, including case studies and expert interviews, is carried out to apply the EAU process in varying contexts. Reinforcing the EAU process' operationalization could help design teams manage sustainability consistently and support the necessary ecological shifts at the company level.*

## ARTICLE 3

# Environmental Assessment for Upscaling: a LCA-based eco-design process for design teams

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## Abstract

The upscaling of technology appears to be a socio-technical phenomenon covering the technology development and deployment in society to meet societal imperatives (e.g. sustainability). It has been characterized with five archetypes, each encompassing specific vocabulary, design practices, stakeholders, and methods referring to a great variety of consequences on industrial systems. These upscaling archetypes are not all considered in the current eco-design practices, and even less in a unified way, as it potentially involves modelling and LCA practices from varying scientific communities. This research paper, based on a literature review on LCA, upscaling, and eco-design, identifies six methodological requirements to propose upscaling environmental assessment guidelines for design teams. It results, based on the identified requirements, in the proposition of a new LCA-based design process, titled *Environmental Assessment for Upscaling* (EAU). Its originality is to propose a structure favouring the emergence of an accurate consideration of the environmental aspects of the upscaling with an aggregated approach of the upscaling archetypes. This methodology follows six necessary steps, and relies on original and interlinked categories of upscaling parameters, enabling design teams to consider the upscaling of a technology as a whole during the design process. An organization framework and four additional resources to guide the collaboration of design team stakeholders (e.g. technical expert, lifecycle expert, company manager) are also presented in parallel, with a focus on lifecycle engineering. The EAU process clarifies the main points of interest in the LCA practices related to upscaling assessment. It links ongoing work on the characterization of technology upscaling with the various LCA communities. Using the LCA standard as a vector of integration contributes to making LCA approaches operational in companies. Finally, ongoing research, including case studies and expert interviews, is carried out to apply the EAU process in varying contexts. Reinforcing the EAU process' operationalization could help design teams manage sustainability consistently and support the necessary ecological shifts at the company level.

**Keywords:** Environmental Assessment for Upscaling (EAU), Integrated Design for Sustainability, Upscaling, Eco-design, Life Cycle Assessment, Absolute sustainability

## Nomenclature

|              |                                                  |
|--------------|--------------------------------------------------|
| <b>AESA</b>  | Absolute Environmental Sustainability Assessment |
| <b>CLD</b>   | Causal Loop Diagram                              |
| <b>CS</b>    | (socio-technical) Context Scenario               |
| <b>DfS</b>   | Design for Sustainability                        |
| <b>DS</b>    | Deployment Scenario                              |
| <b>EAU</b>   | Environmental Assessment for Upscaling           |
| <b>ECD</b>   | Environmentally Conscious Design                 |
| <b>EEIOA</b> | Environmentally Extended Input-Output Analysis   |
| <b>EIME</b>  | Environmental Improvement Made Easy              |
| <b>LCA</b>   | Life Cycle Assessment                            |

|               |                                                                                |
|---------------|--------------------------------------------------------------------------------|
| <b>LCE</b>    | Life Cycle Engineering                                                         |
| <b>LCI</b>    | Life Cycle Inventory                                                           |
| <b>LCIA</b>   | Life Cycle Impact Assessment                                                   |
| <b>IAM</b>    | Integrated Assessment Modelling                                                |
| <b>MFA</b>    | Material Flow Analysis                                                         |
| <b>PSS</b>    | Product Service System                                                         |
| <b>PB</b>     | Planetary Boundaries                                                           |
| <b>PEFCR</b>  | Product Environmental Footprint                                                |
| <b>PESTEL</b> | Political, Economic, Socio-cultural and Technological, Environmental and Legal |
| <b>SIMPL</b>  | Scenario-based Inventory Modelling for Prospective LCA                         |
| <b>TEA</b>    | Techno-Economic Assessment                                                     |

## 1. Introduction

### Upscaling in engineering and design

In previous research, we proposed a framework to define the “upscaling of a technology” in a design and engineering paradigm (Riondet et al., 2024a, 2022a). Technology upscaling is “*a techno-economic phenomenon involving the development and deployment of a technology in society to meet societal imperatives (e.g. sustainability)*” (Riondet et al., 2024a). The literature review in engineering shows that this complex socio-technical phenomenon merges several perceptions from technologists and technology researchers, industrial and process engineers, forecasting experts and planners, socio-technical experts, and planetary boundary experts or environmental experts. Five facets, also referred to as “upscaling archetypes” have been characterized from the engineering and design literature. Archetypes represent visions of technology upscaling and document associated methods and approaches for designers and engineers to better assess it. Table 1 synthesizes, for each upscaling archetype, its name (column 1), its definition (column 2), the associated assessment actors (column 3) and generic goal according to the literature (column 4). For more details about the upscaling archetypes, please refer to (Riondet et al., 2024a).

Table 1 Definition, usual goal, and LCA modes usually applied for each upscaling archetype. Adapted from (Riondet et al., 2024a, 2024b)

| Upscaling archetype                                | Definition                                                                                                                                                | Typical assessment actor                 | Upscaling goal                                                         | Examples of associated LCA modes in literature                      |
|----------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------|------------------------------------------------------------------------|---------------------------------------------------------------------|
| <b>Archetype 1</b><br>Upsizing, scaling-up         | Design and engineering processes generating a “prototype” at an industrial/commercial scale, or to increase the existing characteristics of a technology. | Technologists and technology researchers | Maximise maturity and/or productivity.                                 | Ex-ante LCA, anticipatory, parametrized LCA                         |
| <b>Archetype 2</b><br>Mass-producing               | Design and engineering processes to adapt a technology to be mass-produced.                                                                               | Industrial and process engineers         | Maximise producibility.                                                | Prospective LCA, PEF (attributional retrospective LCA), dynamic LCA |
| <b>Archetype 3</b><br>Reaching a level, deploying  | Design and engineering processes to translate transition requirements into a technology sector perspective.                                               | Forecasting experts and planners         | Reaching a sufficient level of cumulated service.                      | Prospective LCA, dynamic LCA                                        |
| <b>Archetype 4</b><br>Integrating a complex system | Design and engineering processes to implement a technology as a part of a larger and complex system.                                                      | Socio-technical experts and planners     | Maximize the efficiency of a complex system.                           | PSS LCA, Territorialized LCA                                        |
| <b>Archetype 5</b><br>Down-limiting, downscaling   | Design and engineering processes tending to restrict technologies according to sustainability considerations.                                             | Earth’s system experts and designers     | Assess the sustainability of a technology, service, or human activity. | PB-LCA, AESA                                                        |

### Motivation: Eco-design and Life Cycle Assessment

The discrepancy between business-as-usual engineering practices and current and future environmental concerns has led historically to *eco-design* practices, *i.e.* the integration in the system or technology design process of environmental aspects to minimize negative impacts through the whole life cycle perspective (Standard IEC 62430: 2019). Dekoninck *et al.*, (2016) investigated the main challenges in the 2010s to implement eco-design in



companies. Based on interviews and literature review, management issues emerged as a bottleneck to eco-design practices: poor integration into management and corporate strategies, the need for multidisciplinary collaboration, and lack of environmental expertise to deal with trade-offs concerning environmental aspects. The upscaling of a technology and its resulting environmental impacts, as mentioned in the previous section, strongly depends on the corporate strategy. In addition, using Life Cycle Assessment (LCA) for eco-design purposes was considered difficult because of the resources involved (time, data, expertise). However, this situation seems to have changed in recent years: the design team management has evolved with the democratization of the “lifecycle engineer” profile to promote eco-design in design projects. Brambila-Macias and Sakao (2021) showed that such organization participates in implementing effective eco-design in companies. Companies progressively adopted a design team composed of at least a lifecycle engineer and a technology expert collaborating. In this research, this framework is operated explicitly in generic recommendations (Tsoy *et al.*, 2020) or indirectly, linking Techno-Economic Analysis (TEA) and LCA to deal with sustainability concerns in design (Ferdous *et al.*, 2023). As a third example, Kjaer *et al.*, (2018) propose guidelines for the eco-design of Product-Service System (PSS) addressed to the design team focused on LCA practice. This evolution of design teams in eco-design research and development contexts has motivated the present article to adopt a democratizing approach to LCA practices.

### LCA framework by upscaling archetype

Concomitantly to the evolution of design team management, the diversity of LCA approaches increased. Two main attempts to synthesize this diversity exist in the literature. Guinée *et al.*, (2018) gave a three-pages summary of height *LCA modes* in a commentary and discussion article. Ventura (2022) presented a characterization work of LCA modelling structures to bring out a new “transition” LCA approach. These two studies were not intended to be exhaustive on LCA modes. Nonetheless, they draw attention to the fact that lifecycle engineers must challenge modelling systems to better represent the phenomenon under study and properly assess the associated environmental aspects. A literature review was therefore carried out following this modelling requirements for technology upscaling. Riondet *et al.*, (2024c) show that the environmental assessment of emerging technology upscaling is, in literature, directly associated with *ex-ante*, *prospective*, *anticipative* or *early-stage* LCA. These LCA modes share in common the principle of practising LCA with a future-oriented perspective and are therefore linked to the eco-design practice. Although there are recent developments, many resources are available: Wender *et al.*, (2014) proposed the anticipatory posture, to pave the way to social and environmental assessments at the early stage of technology development, integrating stakeholders in the LCA operation. (Arvidsson *et al.*, 2024, 2018) and Cucurachi *et al.*, (2018) contributed to develop the conceptual framework (*e.g.* projection and scenario-based approach) of prospective and *ex-ante* LCA, respectively. Moni *et al.*, (2020) presented methodological challenges and recommendations to operate an *ex-ante* LCA regarding the maturity of the studied technology. Moreover, Buyle *et al.*, (2019) and van der Giesen *et al.*, (2020) reviewed practical recommendations and tools to deal with assessment uncertainties in the *ex-ante* context. Considering the upscaling archetypes, these previously cited research works in LCA and LCA integration into design contribute to form an LCA framework confined to the assessment of the upscaling archetype 1 (*scaling-up*) and to a lesser extent archetype 2 (*mass-producing*). On the contrary, and as highlighted by Guinée *et al.*, (2018) and Ventura (2022), many LCA-based methods have been developed to assess environmental aspects related to other upscaling archetypes. This statement and related methodological lacks for other archetypes drive the originality of Riondet *et al.*, (2024c): propose a LCA framework adapted to each upscaling archetype, and lifecycle engineers from different fields. Fifteen LCA modes have been firstly characterized in terms of goal, addressed question, modelling specificities, and structuring references or resources. For instance, in addition to the modes *prospective* and *ex-ante*, the modes *attributinal*, *consequential*, *regionalized*, *territorialized*, *Planetary-Boundaries (PB) LCA* and *Absolute Environmental Sustainability Assessment (AESAs)* were characterized. Secondly, using the treatment of archetype 1 as an example, LCA modes have been associated with upscaling archetypes according to their study object and modelling properties as illustrated in column 5 of Table 1.

This framework for matching LCA practices with upscaling archetypes constitutes a first guide for design teams and companies to consider the environmental aspects of a technology upscaling. This framework does not, however, enable design teams to apply the synthesis of recommended LCA approaches. For instance, if a user wishes to study two upscaling archetypes, and thus apply two recommended LCA approaches, Riondet et al., (2024c) do not allow coordination of practical implementation. This research background highlights the need for a harmonized environmental assessment process adapted to design teams to address technology upscaling as a whole and model it accordingly.

### **Originality and method description: for an aggregated Environmental Assessment for Upscaling (EAU) process**

As the upscaling of emerging technology results from the composition of the archetypes, design teams in an eco-design perspective need to articulate the LCA practices associated with each archetype at once. Riondet *et al.*, (2023) presented with a case study a combination of archetypes 1 (*scaling-up*), 2 (*mass-producing*), and 5 (*down-limiting*) using prospective LCA and AESA. This contribution points to the need for a better representation of what the upscaling entails in terms of models and LCA practices.

Kara *et al.*, (2023) proposed a step-by-step methodology using a generic model of cumulated impacts related to the deployment of a product from a Life Cycle Engineering (LCE) perspective. At least four upscaling archetypes are represented, more or less predominantly in this method: first, the focus on archetype 5 (*down-limiting*) with the operationalisation of the absolute sustainability paradigm in design. Second, archetype 3 (*reaching a level*) is covered with the choice of fixed scope since the studied product is assessed via its cumulated use by a population (*i.e.* its deployment). Third, LCE is historically attached to archetype 2 (*mass-producing*), guiding designers to integrate product system constraints into the design process. Fourth, archetype 1 (*scaling-up*) is considered in estimates of the technical improvements needed to observe the sustainability targets generated in the context of archetype 5. The genericity of the proposed methodology is double-edged: on the one hand, it provides a clear procedure to integrate AESA into the design process of a product. The absolute sustainability paradigm is then brought closer to design practices. The modelling work relies on the IPAT identity giving a comprehensive framework to deal with technology upscaling: the total environmental impact (I) is the impact of the technology developed (T), multiplied by the affluence (A), meaning its use per capita, multiplied by the number of people using it (P). The component (T) is assessed through the prism of systemic and value chain analysis, proper to LCA practice. On the other hand, the apparent simplicity of the model suggests that the components A, P, and T are independent and could be tuned regardless of their interactions. More precisely, component T is an extrapolation model of a product system, often in a controlled laboratory context where components A and P are presumed, to be real-world operations, with diversified and potentially unanticipated socio-technical interactions. Authors recognize this limitation and call for further research, including on “problem shifting” between life cycle stages as well as the foreground and background systems.

Concomitantly, LCA researchers claim an interest in using socio-technical models from a prospective perspective, in the direction of the upscaling archetype 4 (*integrating a complex system*) (van der Giesen *et al.*, 2020). In this lineage, Langkau *et al.*, (2023) proposed a methodology to generate scenarios for prospective Life Cycle Inventory. This methodology, instead of presenting a fixed prospective model of the socio-technical system to be modelled, details a structure favouring accurate practices to reflect the diversity of socio-technical possibilities. In this way, it guarantees genericity and leaves users, mainly LCA experts, to contribute the specific elements linked to their situation, in line with their needs and expertise. Notably, it is not intended for the design process context, preventing potentially the design team from appropriating it. Finally, this work underlines the importance of a systemic vision, crucial in LCA practice and exacerbated in prospective LCA. Thus, Kara *et al.*, (2023) and Langkau *et al.*, (2023) point respectively the imperatives of eco-design operationalization and the necessity to

correctly model phenomena to avoid possible burden-shifting, *i.e.* a representativeness requirement. Based on the idea of minimal modelling to be simultaneously operationalizable and representative of the technology upscaling environmental aspects, the present paper, therefore, intends to answer the following research question: “*How to orchestrate a Life Cycle Assessment within an upscaling archetype approach under an eco-design context?*”.

The originality of the paper's contribution is to propose a structured process favouring the emergence of an accurate consideration of the environmental aspects of the upscaling with an aggregated approach of the upscaling archetypes. In other terms, this paper presents a guide for design teams to ensure the completeness of the environmental modelling of the upscaling.

Section 2, based on a literature review and eco-design practices, identifies the methodological requirements that must underpin the proposed process, including being systemic, multi-stage and multi-criteria-based, representative, suitable for design teams, technical parameter-based, generic, and upgradable. Section 3 details the six steps of the proposed process to practice Environmental Assessment for Upscaling (EAU) and presents the use of additional resources developed to support its application. The core of the process relies on a framework of minimal modelling of the upscaling (see upscaling parameters) and its adaptability to the upscaling goal of the LCA practitioners. Section 4 discusses the compliance of the presented version of the process with the methodological requirements and its evolution in future research toward eco-design for upscaling technology.

### 2. Methods: methodological requirements for integrated upscaling environmental assessment

The proposed process was conducted based on a literature review on integration barriers in upscaling assessment within an eco-design framework. To anticipate and minimize the environmental impacts resulting from the life cycle of a product/technology (*i.e.* practice eco-design), the standard IEC 62430:2019 presents the life cycle thinking as crucial. It suggests using LCA as a multi-criteria and multi-stage method. It recommends deploying this integrative approach based on the ISO 14040:2006. This results in considering the following methodological requirement:

**# 1** The EAU process must hinge on the life cycle thinking, meaning to support multi-criteria environmental assessment, with a multi-stage and a systemic approach.

Additionally, as presented in the introduction, the five upscaling archetypes must be considered. Thus, the second requirement involves two properties related to the upscaling archetypes; to be anticipative and representative of the upscaling of a technology/product. These three groups of approaches (future-oriented, systemic, and absolute sustainability-focused), along with others, are required to be coupled to achieve a complete vision of the upscaling of a technology (Riondet *et al.*, 2023). This leads to the second requirement:

**# 2** The EAU process must be anticipative and representative of the upscaling. In other words, due to the eco-design context, the method should guide the anticipation of potential environmental impacts resulting from the upscaling of a technology, including based on prospective scenario management. It must facilitate the integration in the design process of the upscaling environmental specificities. This goes together with the question of the representativeness of the upscaling archetype: the method should therefore be designed to cover all five upscaling archetypes. For instance, it must give the possibility to enable reasoning in the absolute environmental sustainability paradigm.

Although most of the mentioned methods refer to the ISO standard 14040:2006 to position concerning LCA, they are at different levels of design integration as mentioned in the introduction: Brambila-Macias and Sakao (2021) investigated the levers of the effectiveness of the implementation of eco-design. In particular, they highlighted the

requirement of “organizational context of the eco-design implementation” and difficulties of accessing methods (“too much research effort on methods”). The authors proved that the design team paradigm with competencies profiles such as technical and lifecycle engineers is a fruitful organization. In that respect, the lifecycle engineer ensures the life cycle thinking in the design process. Its role is to collect literature and interact with technical experts and decision-makers to facilitate the integration of environmental aspects. This brings about the third methodological requirement:

**# 3** The EAU process must be addressed to the design team: it means to define the tasks, with a focus on environmental assessment (*i.e.* life cycle engineering), to consider the upscaling of a technology and therefore guide the collaboration of stakeholders (*e.g.* technical expert, life cycle expert, company manager) and the progress of the design process. It must be “user-friendly”, including be manageable for a design team familiar with the life cycle approach, or at least LCA. It must also adapt to the design team's goals. *i.e.* translate the need for environmental assessment regarding the main upscaling archetype mobilised while considering the others.

The practice of eco-design implies highlighting design levers, meaning linking the technical choices of the design team with their respective potential environmental consequences. As the upscaling of technology involves a wide range of stakeholders and expertise making up a design team, generic levers must be identified for each archetype. For instance, Hung *et al.* (2020) in the method LiSET, mentions “intrinsic” and “extrinsic” properties of the designed technology to be respectively understood as inner to the developed system/technology itself and relative to value chain development (*e.g.* provider choice) (Hung *et al.*, 2020). These two characteristics refer to archetype 1 (*upsizing*) and archetype 2 (*mass-producing*) properties and emphasis on different design levers, more or less close to the technical expertise of a design team. We presented a similar distinction in previous works with “designer's levers”, “industrial's levers, and “national and intersectoral evolution integration” (Riondet *et al.*, 2023). This evaluation grid leads to the following methodological requirements:

**# 4** The EAU process must be technical-parameters based: it should help design teams to manipulate parameters that influence the environmental impacts of the technology upscaling. Put differently, the method should interface the technical design with environmental aspects, meaning to propose minimal characteristics from every upscaling archetype, to parametrise the environmental aspects of the upscaling as a composition of interacting archetypes.

Moreover, and in line with existing guidelines related to upscaling assessment or eco-design practices (Kjaer *et al.*, 2018; Langkau *et al.*, 2023; Tsoy *et al.*, 2020), a certain level of genericity must be maintained, to ensure the application of the method in various disciplinary fields and on different types of technology. In other terms:

**# 5** The EAU process must be generic: it must apply to different kinds of technology and from different engineering fields.

Finally, and due to the rapid evolution of the literature relative to eco-design practices and upscaling assessment (*e.g.* risk analysis, industrial planification and scenarios, raw material criticality assessment), we decided to add the following last requirement:

**# 6** The EAU process must be evolutive: it must integrate updates and changes relative to the upscaling assessment literature.

These six methodological requirements, summarized in Table 2, were the cornerstone of the development of the proposed methodology. The proposed methodology is thus detailed in section 3.

Table 2 Methodological requirements based on key findings from literature review and previous work

| Requirement #                                        | Description                                                                                                                                                                                                                                                                                                   |
|------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| # 1 Multicriteria, multi-stage and systemic          | The EAU process should integrate environmental aspects via life cycle thinking.                                                                                                                                                                                                                               |
| # 2 Anticipative and representative of the upscaling | The EAU process should help to investigate the potential environmental relations of an emerging technology before its upscaling and therefore, during the process development of a product or system. It should also enable the consideration of upscaling archetypes, and eventually archetype combinations. |
| # 3 Suitable for a “design team”                     | The EAU process should be designer-friendly and operationalizable in an organization familiar with the product life cycle approach. It should be intended for a “design team”, and meant to guide the collaboration between members toward eco-designing the upscaling of a technology.                       |
| # 4 Technical-parameter-based                        | The EAU process should parametrise the environmental impacts with technical parameters associated with a configuration of the technology upscaling.                                                                                                                                                           |
| # 5 Generic                                          | The EAU process should be independent from the engineering field and non-specific to a technology or an organisation.                                                                                                                                                                                         |
| # 6 Evolutive                                        | The EAU process should allow updates and support modular adaptation with regard to other types of upscaling assessments (e.g. risk analysis, industrial planification).                                                                                                                                       |

For instance, methodological requirement #4 points to the identification of minimal necessary characteristics, which may not be sufficient to fully represent the upscaling of a technology. That case would lead to future complements after multiple iterations of the EAU process.

Finally, the design of the EAU process and its founding principles were strengthened by the experimental approach: two case studies on photovoltaic systems were set up, one to test the feasibility of taking several archetypes into account ((Riondet et al., 2023)), the other to test the completeness and validity of the modelling part of the process (Riondet et al., 2024c). Elements of these two case studies will be presented to illustrate the EAU process steps.

### 3. Results: proposition of the EAU process

As stated in section 2, the EAU process is intended to design teams in an eco-design perspective. This new method presents six steps that design teams must follow according to our research and literature review to meet the six methodological requirements relative to EAU.

Fig. 1 presents an overview of the proposed EAU process. The linear formalism is adapted from Kjaer *et al.*, (2018), providing a LCA framework adapted to the assessment of PSS. The blue column represents the six steps. Of the methodology Then, similarly to the way Kjaer *et al.* had to define elements specific to PSS, we present in the second column as *key elements* the specifics of upscaling. These key elements are what the design team need to determine to move on to the next step. They can be interpreted as sub-steps, even if as we will see some of them must be developed at the same time and not successively. The four LCA phases (see third column) were used as a common thread to guide readers into the methodology.

The novelty of this proposed method lies in the identification of key elements associated with upscaling and their positioning to each other. For instance, steps 2 and 3, as we shall see, were developed from scratch to fit the

upscaling assessment constraints. Furthermore, steps 4 and 5 are adaptations of pre-existing frameworks (e.g. LCA phases) to deal with upscaling specificities. The same goes for steps 1 and 6 with the addition of the eco-design paradigm.

Additionally, and to reinforce the common thread of the methodology, we decided to split the research question presented in the introduction into the following successive questions:

- *What is the goal of the environmental upscaling assessment, regarding the mobilised upscaling archetype(s)?*
- *Which solutions/design configurations/scenarios to compare and which upscaling parameters to consider?*
- *Which models can support the design team to assess a comparison of upscaling scenarios?*

These questions cover methodological steps (activities, inputs/processes, ...) that members of design teams must adopt to environmentally assess the upscaling of a technology. They reflect the six identified challenges extracted from the literature and practices of eco-design experts (see section 2).

Finally, additional resources are proposed, external to the EAU process, as they are deemed helpful to support stakeholders of design teams to manage one or several steps (Cf. requirement #3).

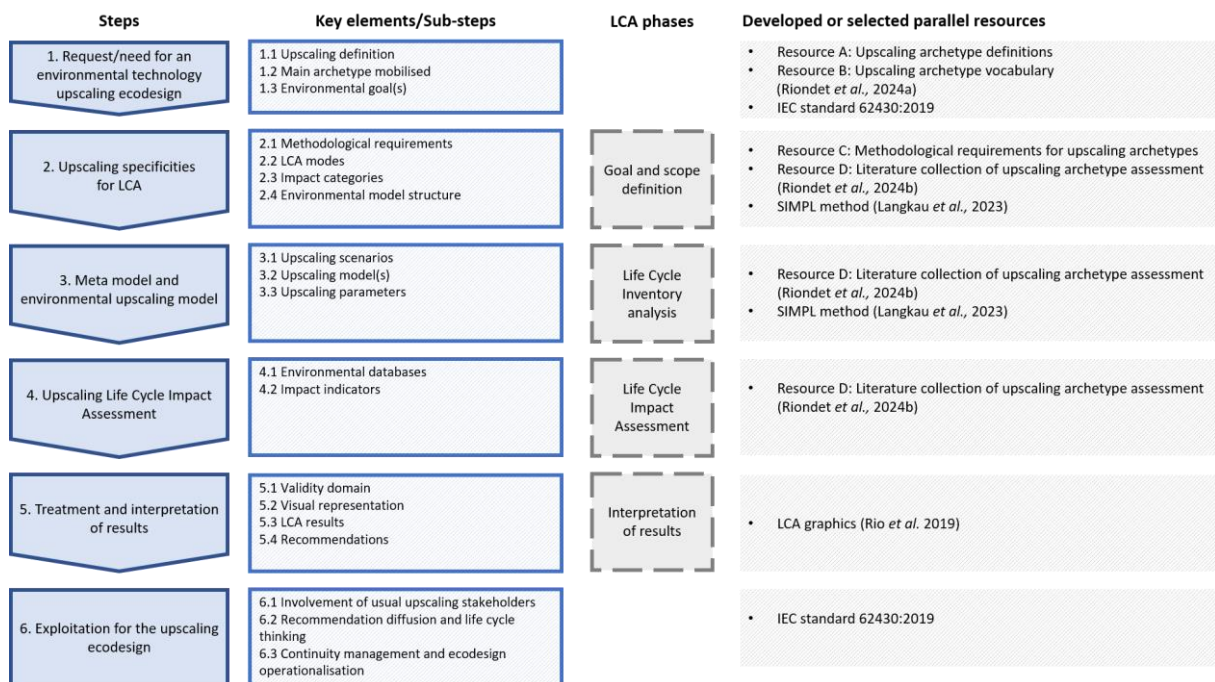


**Fig. 1** Overview of the EAU process, inspired by Kjaer *et al.*, (2018). The blue colour of the boxes means that the content comes under the method, while the grey colour means that the content is not exclusive to the method.

Four resources titled A, B, C and D have been developed in parallel with the methodology. They will be discussed during the related steps of the methodology. Resources A and B are available from (Riondet *et al.*, 2024a) and C and D from (Riondet *et al.*, 2024b). Others have been selected as examples of identified methods guiding LCA practices related to upscaling scenario management (SIMPL method from Langkau *et al.*, (2023)), visual representation of LCA results (LCA graphics from Rio *et al.*, (2019)) or eco-design practice (Standard IEC 62430: 2019). These resources will be discussed in their related sections. Again, there are not necessary to operate the

proposed methodology but found complementary and this list is not exhaustive. It could be completed in further research.

Thus, subsections 3.1 to 3.6 detail the six steps and present furthermore possible use of resources to complete them. The summary of the relationship between methodological requirements and the method's step-by-step structure will be detailed in the following sections and discussed in section 4.

### 3.1. Step 1: Definition of the need for technology upscaling

The objective of this stage is the characterization of the need regarding upscaling environmental assessment. In other words, the *environmental goal(s)* of the technology upscaling eco-design. As illustrated in Fig. 2, three steps are necessary for the design team to establish it: 1. Definition of the triplet (*goal, subject, scope*) regarding the technology upscaling to be studied, 2. identification of the upscaling archetypes mobilised and 3. clarification of the environmental goal(s). These three steps are respectively detailed in subsections 3.1.1, 3.1.2 and 3.1.3.

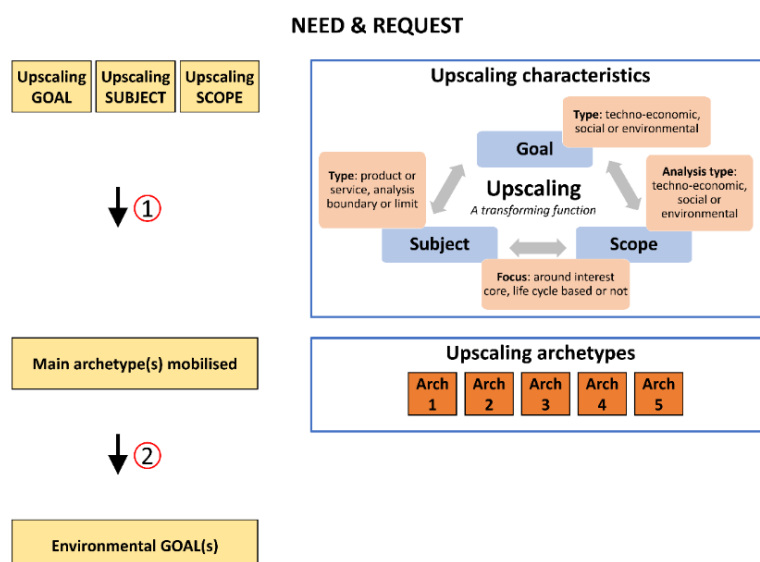


**Fig. 2** Step 1: request and need for an environmental upscaling eco-design. The parts coloured yellow highlight the new elements introduced by the EAU process.

#### 3.1.1. Upscaling goal, subject and scope

To define the environmental assessment need, a clarification on the meaning of upscaling for the design team is required. The identification of the upscaling has to be carried out based on the techno-economic characteristics of the desired technology upscaling, in order to clarify then the environmental methodological requirements. In that regard, the need for the upscaling assessment is defined according to the three characteristics: goal, subject and scope (see Riondet *et al.*, 2022).

- The upscaling goal is associated with techno-economic considerations and consequently determines the direction of the analysis and conditions of methodological requirements and models. It differs from the LCA step “goal definition” as it is centred on the user's objectives description for the upscaling assessment, to coincide with one or more of the upscaling goals identified in Table 1.

- The upscaling subject can be a component, a technology, a group of technology, or a complex system (composition of several types of interacting technologies). It is similar to the concept of “subject” in traditional LCA or TEA.
- The upscaling scope must be adapted to the upscaling subject, *i.e.* the studied technology, the fleet of technology that is intended to be industrialised or the upper system in which it will be integrated. This step is similar to the LCA step of the same name but is not limited to LCA sense alone. In addition to the system boundary of the study (common to LCA practice), the scope also specifies the type of approach to be developed. Material Flow Analysis (MFA) or TEA (*e.g.* risk analysis, industrial feasibility analysis) may therefore be considered. This paper focuses on LCA approaches.

Practically, Table 1 and Resource A titled “upscaling archetype definitions” (see (Riondet *et al.*, 2024a)) in which archetypes are already characterised, can be taken as an example source to support this clarification work. As the upscaling archetypes were created for design teams and are not specific to a technology or an engineering sector, this clarification step meets requirements #3 and #5. Furthermore, the design team as a collective is free to involve as many stakeholders as necessary to position the practice of the design team or the company within the framework of the upscaling archetypes. This collaborative work will then be re-used during the step of exploitation for the upscaling eco-design (see step 6 in section 3.6).

### 3.1.2. Main archetype(s) mobilised

In this second sub-step, the way to proceed is guided by the question “*Which archetype(s) the assessment need refer(s) to, are goal/subject and scope fully defined?*”. If several goals/subjects and scopes emerge from this process or if the triplet is incomplete, the vocabulary used can also point towards one or more upscaling archetypes as documented in the resource B, untitled “Upscaling archetype vocabulary” (see (Riondet *et al.*, 2024a)). It groups the vocabulary used in the literature depending on the upscaling archetype. This resource could help to carry out a literature review based on vocabulary related to an upscaling archetype that was not initially considered. Moreover, Resource A can also support the clarification of the mobilised archetype. Finally, a triplet that does not correspond to a specific archetype could be reduced to a composition of known archetypes. This step deals with the requirement #2 as it follows an archetype-selective approach.

### 3.1.3. Environmental GOAL(s)

In this third sub-step, when the main archetype(s) to mobilise in the assessment is determined, this last step consists of answering the question: “*What is the environmental goal(s)/requirements associated with?*”. As depicted in the eco-design standard, the environmental goal implies defining an environmental indicator dataset and possible targets for these indicators. These metrics can be defined based on variable sources: upscaling archetypes are dedicated to helping the user clarify its need regarding technology upscaling, however, environmental requirements can also be fed by the technical practices of the upscaling design standards (*i.e.* usually related to *mass-producing* related to the upscaling archetype 2). In other words, this step can also be managed with the literature and experience of the design team members. Finally, engagements (*e.g.* ecolabel specifications), a roadmap of the organism that wants to assess the technology upscaling (*e.g.* carbon neutrality targets) or respect of standards (*e.g.* RoHS Directive) can be other supports to complete this step.

## 3.2. Step 2: Definition of upscaling specificities of goal and scope

This stage follows the “Goal and Scope” phase of the ISO standard but specifies the objective to define the *methodological requirements* and the *environmental model structure* implied by the environmental goal.



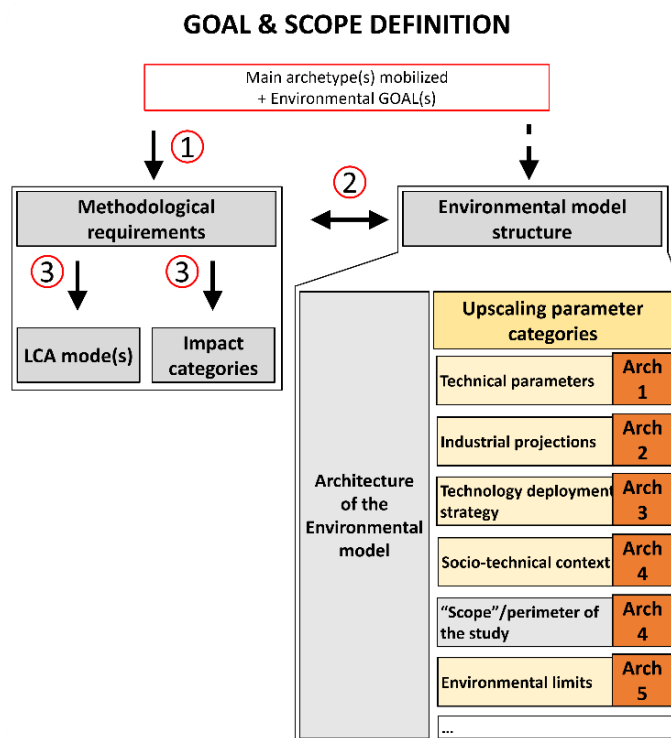


**Fig. 3** Step 2: Definition of upscaling specificities, associated with the GOAL & SCOPE phase of the ISO 14040:2006. “Arch” means upscaling archetype. The parts coloured yellow highlight the new elements introduced by the EAU process.

The following two subsections therefore only present the specifics relating to the consideration of the upscaling assessment, included in the broader stage “goal and scope definition” of the standard. It also focuses on the activities of the life cycle engineer, in interaction with other parts of the design team. These details are presented in Fig. 3.

### 3.2.1. Methodological requirements for upscaling assessment

The methodological elements that structure the environmental assessment are the following:

- The phenomena to be observed, *i.e.* the interaction between technology upscaling and the environment (*e.g.* local or global pollution, resource uses),
- The geographical/temporal scope (*e.g.* dynamic and/or scale, cause and consequences of the phenomena),
- The clauses and constraints (*e.g.* methods and expertise required to deal with the phenomena).

These elements, to be set in this step, depend on the archetype(s) mobilised and the environmental goal(s) (see red boxes in Fig. 3) and possibly to the specificities of the study case. They have to be added to the classic “Goal and Scope” definition as stated by the standard. This participates in the consideration of requirement #2 of the proposed methodology by clarifying the upscaling definition of the design team into methodological requirements. These elements condition the *LCA mode* mobilised and the metric selection, leading finally to *impact category* identifications:

- The *LCA modes* (*e.g.* attributional, consequential, hybrid, dynamic, regionalised) are listed and defined in (Riondet et al., 2024b). Every *LCA mode* follows a multi-criterion, multistage and systemic approach,

this step and all steps mirroring the four LCA phases strengthen the anchoring of the proposed methodology into requirement #1.

- The impact categories are linked with the chosen LCA mode and they include the environmental indicator dataset defined in the previous stage with the *environmental goal(s)*. It is completed with upscaling archetype specificities (*e.g.* resource depletion focus or spatialised metrics). They may not only be classic LCA indicators but may tend towards other types of metrics (*e.g.* criticality or circularity).

So that the design team can make these decisions, resource C can be mobilised. Resource C, titled “Methodological requirements for upscaling archetypes” (see (Riondet et al., 2024b)) points to methodological requirements according to the upscaling archetype. It guides the lifecycle engineer to suitable methodological guidelines, and then to LCA modes based on a literature review. As this support is meant to be as generic as possible (aligned with requirement #5), it can be completed with another resource: resource D, called “literature collection of archetype upscaling assessments”. An illustration of the use of resource D is presented in sub-section 0. It paves the way to use this resource as a collaborative tool for the operational members of the design team, *i.e.* technical engineers and lifecycle engineers.

Resources C and D are not exhaustive supports, additional research in the literature on upscaling and user experience must also feed the elaboration of the methodological requirements, and consequently the LCA mode selection as well as the impact categories.

Additionally, if the design team wants to explore results on the absolute sustainability paradigm as one of the methodological requirements, particular attention should be paid to the related impact categories (see step 4 in section 3.4).

### 3.2.2. Environmental model structure definition

The proposed methodology is structured as the *environmental model structure* must be developed in parallel with the definition of methodological requirements, including phenomena to be observed. This structure has to be linked to the objectives of the study, *i.e.* which interaction between the design choices of a technology and the environment the user wants to highlight?

This should result in a structure that reflects both the architecture of the technical system and its life cycle (mentioned as “architecture of the environmental model” in Fig. 3) and the elements that can influence the environmental upscaling assessment. Five categories of upscaling parameters are proposed to embody, for each archetype, such elements.

- Technical parameters; those are the technology expert levers, meaning the most related to the upscaling archetype 1 (*upsizing*).
- Industrial projections, archetype 2 (*mass-producing*). Temporal alignment of industrial dynamics.
- Technology deployment strategy; this is the elicitation of the mean to reach the targeted cumulated service at an upper level that the product associated with the upscaling archetype 3 (reaching a level). It requires possibly more than technology expertise and specific planification models external to the design team (see section 3.3 “Meta model”). Contribute to adding design levers and precise also the aim of the upscaling from the industrial sector perspective.
- “Scope” (refers to the ISO definition); it is the expression of the extension of the perimeter, it must be aligned with the functional unit and potentially to the system complex/technical structure required to do so (geographical consideration related to archetype 4).
- Socio-technical context; (time consideration related to archetype 4). IPCC scenarios for instance.

- Allocation principles; Allocation rules to carry an environmental space (e.g. carbon budget) for the studied object, based on the planetary boundary framework.

These upscaling parameter categories are deemed necessary but potentially not sufficient to cover all configurations of possible upscaling assessments. They contribute to the final result and link the classic life cycle model to upscaling models and possibly external expertise to the design team (see step 3). It is, therefore, necessary to think about the architecture that will enable the team to identify as soon as possible the required data and expertise to build the environmental model (see step 3), identify the available and corresponding environmental databases and analysis (see step 4) and point to hotspots and design levers (see step 5 and 6). It can potentially provide other levers depending on other stakeholders of the upscaling management. In this view, the model structure can be value-chain oriented, with a classic “background” and “foreground” systems as in Kara *et al.*, (2023) to operate a life cycle engineering. The model can also capture non-technical aspects. In that respect, we propose as a resource the publication of Langkau *et al.* (2023), describing a stepwise method, called SIMPL for *Scenario-based Inventory Modelling for Prospective LCA*, to integrate socio-technical modelling expertise at this stage. This method consists of four steps operated during the standard LCA “goal and scope definition” and “LCI” stages. The aim is to develop a representation of interactions, a so-called *Causal Loop Diagram (CLD)* between phenomena (*parameters*) classified as inventory foreground parameters, inventory background parameters or external parameters. In other words, it is a procedure to help users model a part of the complex socio-technical system in which they want to integrate their product. The parameters of this system are identified based on the PESTEL approach, helping to explore Political, Economic, Sociological, Technical, Environmental and Legal factors (Fahey and Narayanan, 1986; Narayanan and Fahey, 2006). The SIMPL method helps designers to build consistent scenarios to parameterize the LCI (see step 3). For the present step 2, the environmental model structure through the upscaling parameters categories is consequently influenced by the CLD. For instance, the upscaling parameter category “socio-technical context” is strongly dependent on the PESTEL analysis results and on the stakeholder expertise gathered to operate it. It is therefore crucial in such analysis to diversify the roles of the design team’ members. Additional examples taken from the literature can also help users clarify the model or variables to be placed behind the upscaling parameter categories.

## Illustration of use of resource D: Literature collection of archetype upscaling assessments

**Fig. 4** presents the matrix archetypes/engineering fields developed in previous research to wrap up fruitful examples and resources from academic literature in the upscaling eco-design context (Riondet *et al.*, 2024a, 2024b). This two-entry table can be consulted through the upscaling archetype, the engineering field, or both. Blue elements represent collected literature associated to TEA (technical expertise-oriented) and green elements for LCA (lifecycle-engineering oriented) related to upscaling archetypes. This framework is meant to be evolutive, and adapted for members of the design team, easing the literature research of methodological requirements (large dots) or case studies (small squares) for them. Large dot references in the table are rather oriented toward generic methodological framework and conceptualisation, while the small square references are providing operationalization elements of methods on a particular engineering/design/sectorial problem. A version of pre-filled resource D according to an interdisciplinary literature review is available in Riondet *et al.*, (2024c) for LCA literature and in Riondet *et al.*, (2024a) for engineering and design literature. Fig. 4 illustrates the use of this framework, by a lifecycle engineer in a design team specialised in the photovoltaic sector.

First, user is invited to look for the nearest identified engineering sector, here the energy sector. On that line, blue and green elements are represented, as they are related respectively to technical engineering literature and lifecycle engineering literature. In this example, the user is assumed to be a lifecycle engineer, so the emphasis is on the green dots. The same could have been done with blue dots, *i.e.* from the technical engineering perspective.

Second, the selected line must be completed with references from other engineering sector. For the step 2 of the proposed methodology, it may be worthwhile to focus first on the literature reviews (large dots), to explore the type of analysis possibly from other engineering fields and eventually to broaden the consideration of environmental aspects, leading then to environmental indicator categories selection.

Finally, additional literature reference specific to the photovoltaic sector can be added to complete the upscaling archetype assessment representativity.

The application of these three steps by at least the lifecycle engineer and technical engineer could induce the design team to take ownership of this framework, to generate a common vocabulary and a shared representation. It could thus strengthen collaboration and general knowledge on the technology upscaling assessment and could lead to greater compliance with the proposed methodology requirements #2 and #3.

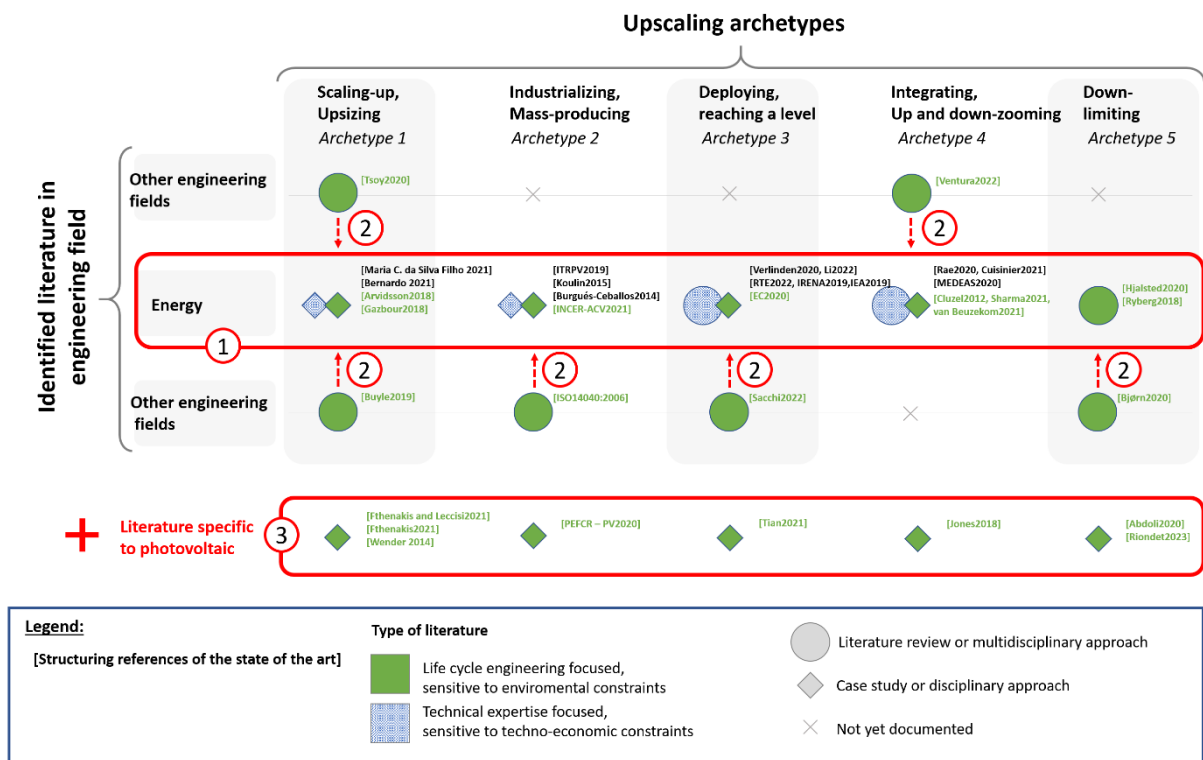


**Fig. 4** Application to the photovoltaic engineering regarding the lifecycle engineering perspective (i.e. green dots and squares) and with Resource D reference collection. in three steps: 1) identification of the general field, 2) transposition of literature from other fields, 3) specific research on the engineering field.

### 3.3. Step 3: Meta-model and environmental model

The aim of this step is to help users to create their own *meta-model*, meaning to interface the architecture developed in the previous step with the diversity of upscaling models. It results in proposing a structure to parametrize the LCI illustrated in Fig. 5. This interfacing is called *meta-model* due to the potential involvement of multiple upscaling models and therefore deals in depth with the requirement #2, i.e. to be anticipative and representative of the study technology upscaling. This section addresses therefore specifically the sub-research questions “which

*solutions/design configurations/scenarios to compare and which upscaling parameters to consider?” and “which models can support the design team to assess a comparison of upscaling scenarios?”.*

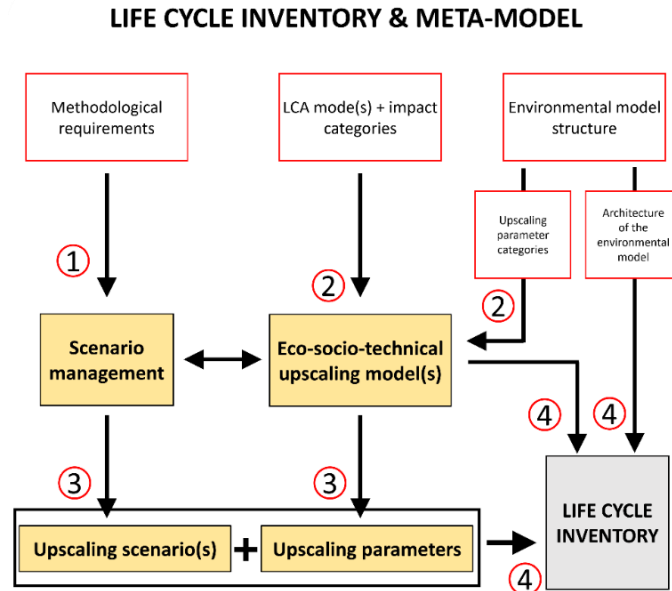


**Fig. 5** Step 3: Meta-model implementation, encompassing the life cycle inventory step of the ISO 14040:2006. The parts coloured yellow highlight the new elements introduced by the EAU process.

It must be kept in mind that this interface is made in relation to the initial environmental goal though the *methodological requirements* (including *LCA modes* and *impact categories*), ultimately oriented toward eco-designing the technology to be upscaled. It results that scenarios are also necessary to compare distinct solutions between each other. It led to consider first a scenario management, interconnected with specific upscaling models. Four steps are suggested to deal with the elaboration of the meta model.

### 3.3.1. Scenario management for upscaling modelling

The first sub-step consists in turning the methodological requirements established in step 2 (red box in Fig. 5) into scenarios to be modelled. The two questions, *which solutions/design configuration to compare?* and *what models enable the team to apply this comparison?* Can help to structure this first step. This introduces to the focus of *upscaling models*. Attention must be paid to the inherent assumptions of modelling and their alignment with the methodological requirements. This caution is necessary to use adapted models regarding the initial objective and it feeds the treatment of the assumptions of modelling as sources of uncertainties in step 5 (see section 3.5).

With regard to scenario management, Cluzel *et al.*, (2014) proposed a framework to deal with LCA modelling of complex systems, to be understood as “generic industrial systems”. Authors suggest extending the classic LCA modelling with additional categories (*e.g.* transport failures, corrective maintenance) and associated parameters (*e.g.* number of rectifier batches lost during transport due to transport failures). This proposition is included in the sensitivity analysis approach to identify the relevant parts needed to be carefully modelled and iteratively complete the LCI. This scenario-based approach targets the robustness of the LCI model with a vision rooted in engineering focusing on the studied technical (complex) system. The scenario-based approach developed in Steubing *et al.*, (2016) and more recently in (Steubing and de Koning, 2021) are complementary: these researches intend to support

modular practices and develop computational means to automate scenario generation. It becomes easier to multiply the scenarios, for instance for uncertainty treatment purposes. Such approach also gives the possibility, in the prospective approach, to assess the range of possible of product's environmental impacts depending on socio-technical considerations. In that regard, the SIMPL method, mentioned in sub-section 3.2.2 (*Environmental model structure definition*), helps to build consistent scenarios to parameterize the LCI. Thus, the need range and complexity of scenarios will be based on the goal and scope definitions. In that way, the corresponding scenario expertise will be related to the applied upscaling models.

### 3.3.2. Upscaling model(s) for LCI

The second sub-step to build the meta-model is driven by the selection of upscaling models. As no generic upscaling model exists, this article cannot provide such a one. The selection of a model depends on the scenario to be simulated and the set LCA modes and impact categories. Thus, the upscaling model must provide data for the “upscaling parameters”, to be considered as parts of the foreground and background systems that will form the LCI. Depending on the aspects of the upscaling to be modelled, it may imply economic and technical but also social approaches. As in the previous stage, Resource D, “literature collection of archetype upscaling assessments” (see **Fig. 4**) can support and gives examples of the application of methods and models with regard to upscaling archetypes. Thus, in this step, case studies (small squares) may be preferred to reviews (large circles) because they are more oriented towards the operability of methods and models. The scale factor for prototype development anticipation, MFA model for deployment strategy or Integrated Assessment Modelling (IAM) for prospective interaction assessment between activity sectors are three examples of upscaling models. They can possibly be compiled together if scenarios to be tested require it. This implies a dialectic process between scenario management (reflecting methodological requirements) and models' selection and/or development (reflecting what can be simulated) and finally trade-offs in the design of the meta-model (*Cf.* double arrow in Fig. 5). Additional research in the literature on upscaling and user experience naturally contributes to the modelling. The resulting trade-offs thus depend on the choice of eco-socio-technical upscaling models, itself influenced by the design team composition.

Another example of upscaling model is given by the AESA methodology associated with the upscaling archetype 5 (*down-limiting*): It generates an environmental absolute limit is calculated to assess the sustainability of the studied object. In this latest example, AESA directly affects the LCI by imposing a vision by flow, matching a pressure on the environment depending on time. The time consideration in the system boundary is consequently changed and the inventory data is measured in mass per time spent (“kg/year”) instead of only mass (“kg”) (Ryberg *et al.*, 2018b).

### 3.3.3. Upscaling scenarios and upscaling parameters for parametrized LCI

The third and four sub-steps manage the computation of the scenarios and the supply of data, to the set of *upscaling parameters* of the environmental model and/or directly to the environmental model (*i.e.* the LCI) observing its architecture defined in step 2. *Upscaling scenarios* refer therefore to combination of sets of *upscaling parameters* that are deemed interesting by the design team to compare design solutions toward the eco-design of the studied technology. In other words, these two steps consist of parameterising with upscaling parameter values the LCI to complete the step 2 of the ISO standard regarding upscaling specificities, *i.e.* dealing with requirement #4 (see Table 2). Fig. 6 presents a distinction between three groups of scenarios that contribute to define the upscaling scenarios with regard to upscaling parameters:

- The *Technology Scenario* (TS): it is characterised by a range of values for the technical parameters, possibly supplied with industrial projections, it concerns mainly the technology expert part of the design team.
- The *Deployment Scenario* (DS): it is defined by one or several deployment strategies, which involves first managers and/or company decision-maker parts of the design team.
- The *socio-technical Context Scenario* (CS): what society context is considered in the upscaling assessed. It implies for instance to set hypotheses concerning global warming which affects human activities, including environmental industrial performances. This type of scenario is not yet standardised and requires diverse knowledge. It must therefore involve all the design team.

These three types of scenarios, TS, DS and CS mobilize different areas of expertise within the design team: the left part of Fig. 6 break down the upscaling parameter management regarding three groups of expertise, the technical engineering, the lifecycle engineering and the company management. A filled box represents the mobilisation of the corresponding expertise for the horizontally aligned upscaling parameter. An empty box means that, a priori, the corresponding expertise is not required, but does not rule it out. The three scenarios (TS, DS and CS) all contribute to the final upscaling scenarios, supplemented with *absolute paradigm* and the specification of the perimeter of the study (defined in step 2). Each scenario hinges on assumptions, including from the different expertises, to be specified as much as possible to further deal with associated uncertainties during the step 5 in subsection 3.5.

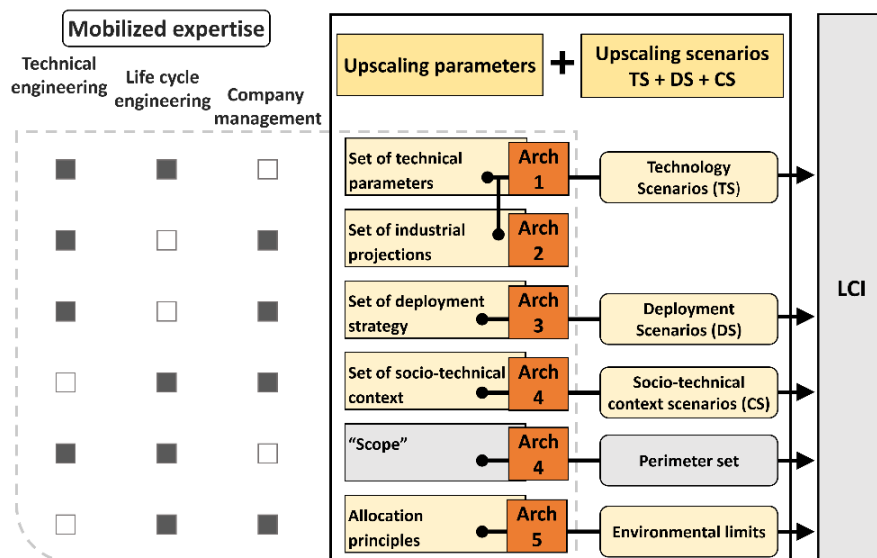


**Fig. 6** Zoom on step 3: Mobilised expertises in the design team to develop sets of upscaling parameters that constitute upscaling scenarios and parametrize the life cycle inventory. The parts coloured yellow highlight the new elements introduced by the EAU process.

Finally, this process leads to variations of LCI formatted by the *environmental model structure*, reflecting the potential design team's choices to be environmentally assessed. For an example of this step, please refer to (Riondet et al., 2024c). The EAU process is illustrated using the case of photovoltaic upscaling in France. The study combines the modelling of technology improvements, a deployment strategy between 2021 and 2050 and a carbon budget defined by allocation principles to stay within the Paris Agreement.

### 3.4. Step 4: Upscaling Life Cycle Impact Assessment

In the same way as for step 2, step 4 is integrated into the LCA phase called *Life Cycle Impact Assessment* (LCIA). The usual procedure defined by the LCA standard is valid for the upscaling assessment case. This section therefore only gives examples of upscaling specificities regarding and link these practices with the other steps of the EAU proposed methodology. This step is mainly associated with the activities of the lifecycle engineer, *i.e.* strongly related to requirement #1 (see Table 2). It may although involve occasionally other members of the design team.

#### 3.4.1. Environmental databases for upscaling assessment

Once the environmental model is defined (see step 3), the impact assessment remains to be applied. To do so, the LCI has to be interfaced with *environmental databases* with regard to *methodological requirements*, including the *LCA mode* selected. For instance, for a consequential approach, EXIOBASE is a global economic database based on input-output modelling (Stadler *et al.*, 2018). It enables non-linear modelling and can be updated or modified for specific sectors if necessary. It is available in open access but must be computed with Python (compatible with open-source LCA software (*e.g.* Open LCA or Brightway2)). It can be considered as Environmentally Extended Input Output Analysis (EEIO), to differentiate from LCA (Steubing *et al.*, 2022). However, the Ecoinvent database also provides a generic consequential database, implemented with a linear model and accessible via classic LCA software (*e.g.* Simapro, EIME or Gabi). Finally, Ben Maes *et al.* in 2023 presented the use of IAM models for prospective consequential LCA (Maes *et al.*, 2023).

Either could suit the methodological requirements of the assessment, considering theoretical or conversely very practical necessity. Recent work in the literature compares LCA results from different databases as Steubing *et al.* with CO<sub>2</sub> equivalent emissions resulting from the EXIOBASE hybrid version and ecoinvent 3.4 (Steubing *et al.*, 2022). Its aim is to better control uncertainties associated with the chosen databases. Criteria supporting the environmental database selection include therefore availability, compatibility with current practices and level of accuracy required. Resource D can provide examples to guide the database choices, as well as the literature or experience of the design team. Depending on the engineering field, groups of experts may have been formed to propose updated environmental databases (*e.g.* TASK 12 or EIME for environmental databases relative to photovoltaic devices).

#### 3.4.2. Impact indicators for upscaling assessment

Simultaneously, the impact indicators have to be selected regarding *methodological requirements* and *environmental databases*. Indeed, characterisation factors, embedded in impact indicators, must be questioned from a dynamic or static perspective in relation to the characteristics phenomenon to be observed.

For instance, the upscaling archetype 3 (*i.e. deploying a technology to reach a level*) must be considered from the material resources perspective. A further step must concern the identification of the most relevant indicators in relation to the initial objective (*e.g.* Abiotic depletion potential, material footprint (Čuček *et al.*, 2015) or mineral dissipation (Charpentier Poncelet *et al.*, 2022, 2021)). Documentation on such methods is often necessary to understand their purpose and scope. Similarly, although criticality indicators rarely integrate environmental aspects, they can also provide fruitful insights into the upscaling archetype 3.

Another example of impact indicator selection is related to archetype 5 (*i.e. down-limiting*), implying comparing the LCIA with planetary boundary values or at least with an absolute sustainability reference. In simple terms, the LCIA outputs and the absolute environmental reference have to be in the same unit to be compared. It brings to possibilities: selecting characterisation factors directly computing results into planetary boundary indicators



(Ryberg *et al.*, 2021, 2020, 2018a) or using an adapted absolute reference, in “classic” LCA indicators, linked to absolute sustainability limits as proposed by Bjørn and Hauschild, (2015) with “carrying capacities”. For the second option, however, updating work may be involved (*e.g.* update of the global population).

Finally, the eco-design practice encourages the use of mid-point indicators, due to their less aggregated nature reducing the uncertainties and promoting the multi-criteria vision for the design team. However, after several iterations of the method, groups of indicators may emerge from the environmental characteristics of the system studied (correlation, relative low importance, etc.) and simplify the complexity of the result treatments.

### 3.5. Step 5: Interpretation of results

In this section, as stated by Fig. 8 and the ISO standard, the interpretation of results is in relation to all the other stages of the method. Fig. 7 shows the relation between key elements of stage 2 (methodological requirements and environmental structure), stage 3 (upscaling models, life cycle inventory) and stage 4 (life cycle impact assessment) on the pre-analysis process made up of *visual representation* selection, identification of *validity domain* of results. This step, like step 4 is mainly associated with the activities of the lifecycle engineer. It however involves the operational part of the design team and puts the spotlight on the set hypothesis (see step 3) and the structure of the environmental model collaboratively built with the technical engineer during step 2. This involvement assures the development of practices and results based on the collaboration of the design team which is aligned with requirement #3 (see Table 2).

#### 3.5.1. Visual representation selection

First, methodological requirements, traducing the environmental goal of the study sponsor, impose visual figures or merit (comparison, life cycle stage focus). These representations are built based on the environmental model structure and adapted according to the life cycle impact assessment. Rio *et al.*, (2019) presented a guide for interpretations of results according to the function that LCA practitioners want the graphs to respect (numerical comparison, ranges of variation, relationships hierarchy, proportions or flows). For instance, considering the proportion regarding the distribution of impacts on one indicator from a system perspective, pie charts are usually applied. However, circle packing can enhance them due to their better visual information compactness. Visualisation of LCA results in the literature associated with upscaling archetype can also be taken as an example. What is important is to understand that a graph carries a message, which is not obvious in itself, especially with many indicators. It is therefore preferable to keep the LCA representation as simple as possible (Rio *et al.*, 2019).

#### 3.5.2. Validity domain associated with LCA results

The validity domain, *i.e.* the uncertainties and the variability of the LCA results, should be studied as much as possible, alongside the representation results themselves. The influence of modelling hypothesis from the foreground system must be analysed thanks to sensitivity analysis and when accurate, uncertainty assessment (Jolivet *et al.*, 2021). These supplementary assessments may modify or change pre-set visual representations due to supplementary information revealed. For instance, a discrete numerical comparison between two scenarios may no longer make sense when represented as “bars”, once the uncertainties associated with each have been highlighted. Assessing the background system is also crucial due to its proven influence on results (Mendoza Beltran *et al.*, 2020).

Remark that the validity domain assessment and data management to apply may depend on the LCA mode: for instance, in the prospective LCA framework, uncertainty may not be the point, because scenarios do not necessarily aim to reflect likelihood behaviour (*e.g.* worst/best case scenario). In this case, sensitivity analysis is preferred.

The accuracy of the final LCA results benefits from iterative feedback between the selection of visual representation (*i.e.* figures of merit) and the identification of the validity domain (double arrow in Fig. 7). Moreover, the structure of the environmental model, including the upscaling parameters, must ideally be reflected in these analyses.

### 3.5.3. LCA results

LCA results are considered as the synthesis of the LCIA. They must be formatted according to the *environmental model structure* and corresponding *upscaling parameters*, with a complementary validity analysis, clarifying for instance the main controversial assumptions of modelling. Elicitation of results must be privileged to avoid misinterpretations by readers of the study. If the AESA paradigm is selected in steps 2 and 3 (respectively in sections 3.2 and 3.3), the values of share of safe operating space are added to the LCA results definition.

### 3.5.4. LCA recommendations

Finally, and as specified in the LCA standard, the fourth step consists of the exploitation of results to identify the hotspots, *i.e.* the main contributor to environmental impacts (*e.g.* life cycle stage, impact category, upscaling parameters or technical architecture part of the studied system). This multi-perspective exploitation leads to recommendations to minimise, among considered scenarios, the environmental impacts and propose rules for the management of the upscaling of a technology/product regarding its environmental aspects.

Fig. 7 depicts step 5, with multiple downward arrows towards a unit element, as an aggregation process of the key elements (red boxes) from the other stage to the interpretations of results and recommendations to the LCA sponsors.

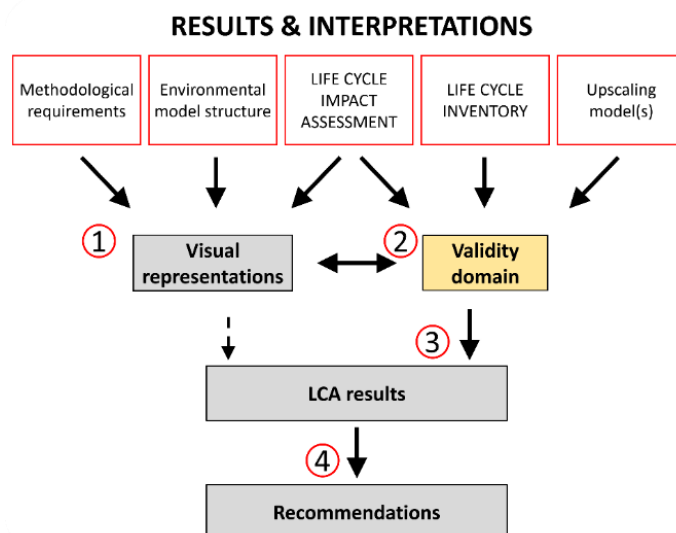


**Fig. 7** Step 5: Treatment & interpretation of the life cycle impact assessment (included in the life cycle impact assessment step of the ISO 14040:2006). The parts coloured yellow highlight the new elements introduced by the EAU process.

It must however be kept in mind that LCA assessment is an iterative process, meaning that each element is related to a previous stage. Back and forth between stages are then necessary to maximise the improvement of the assessment accuracy and be aligned with requirement #1 (see Table 2). This may require (for the first iteration for

instance) to short-cut some third step to return feedback to other previous stages of the methodology (represented by the dashed arrow in Fig. 7).

### 3.6. Step 6: Exploitation for the upscaling eco-design

LCA results are by definition brought about by LCA practices and therefore require specific expertise to be fully understood and construed. Moreover, as illustrated in Fig. 8, the LCA practice is a part of eco-design which is broader and responds therefore to longer timeframes and different constraints. The environmental upscaling assessment may therefore be completed with other types of assessment such as risk, criticality (related to archetype 3: *deploying a technology*) (Hackenhaar *et al.*, 2022) or industrial capacity analysis. Indeed, if the material or component supply of the current or future value chain is not sufficient to supply the studied technology at the required level, the eco-design will not be aligned with the real use phase of the technology. These additional analyses can therefore help to qualify the quality or likelihood of the anticipation of the technology upscaling, on which the LCA results are based.

#### 3.6.1. Widening and involvement of usual upscaling stakeholders

LCA results diffusion in an integrated design approach deals with two elements, intelligibility and consistency.

On the one hand, design LCA results, to be integrated into design, must be translated into intelligible messages and guidelines to every stakeholder, to be considered as a designer in a large sense but with varying relation with the studied technology. Reinterpreting the *Causal Loop Diagram* of the SIMPL method (Langkau *et al.*, 2023) could also help to identify the stakeholder levers on the environmental impacts of the studied technology.

In a case study applied to the electronics field, UNEP provided in 2022 a framework presenting four categories of stakeholders: with professional interests, with personal interests, supply chain stakeholders and customers. It results from this representation of sub-groups (*e.g.* technology experts, software developers, investors, re-sellers, local residents) more or less close to the electronics production (at the centre) and representing the relative sphere of influence of every affiliated stakeholder (Valdivia *et al.*, 2022). In a way, combining these two kinds of illustration paves the way to disaggregate LCA results and guidelines regarding the proximity of the stakeholders with the study object, inside and outside the company, to reach their associated design levers, *i.e.* dealing with requirements #3 and #4 (see Table 2).

#### 3.6.2. Diffusion of recommendations and life cycle thinking

A systemic and lifecycle-based vision must be maintained to correctly manage environmental aspects (requirement #1, Table 2). Neglecting these prerequisites is hazardous and can threaten the accuracy of potential *interpretations of results and recommendations to stakeholders*. Two interesting examples of attempts to integrate environmental or systemic analysis into design practices. First, the “sustainability” indicator in process selection for additive manufacturing may consider “sustainability” or “environment” as one aggregated indicator among technical ones (Thiede *et al.*, 2021). Second, the integration of the criticality indicator may be included in the material selection method (*i.e.* Ashby method) (Ferro and Bonollo, 2019). As criticality is a technical-economic property, it can vary over time, bringing about a time-sensitive selection of material, which is not the case when only physical properties are considered. These two examples illustrate practices of design integration of new indicators without clarification of their construction and methodological basements. It leads thus, additionally to explain the assumptions on which the results hinge in a language adapted to the audience, first for the sponsor of the study and then other upscaling stakeholders out of the design team. This should not prevent the design team from conveying, for instance through

illustrations, the systemic and multicriteria nature inherent to anticipative assessment, including environmental upscaling assessment.

### 3.6.3. Continuity management and eco-design operationalization

Alongside the LCA results and direct interpretation, *data continuity* and *model continuity* are crucial for every stage of the method, including step 3 (see section 3.3 “meta model”) to improve the speed, fluidity and accuracy of the eco-design process.

The data continuity implies data collection and curation to be regularly updated. It concerns data for upscaling models, and also management data (*e.g.* difficulties of access to data, communications, changes in the organisation). In other words, data on how the operationalization of the method changes the design process. This could reduce uncertainties and increase representativeness for the purpose specified in the *environmental goal* (see subsection 3.1.3).

The model continuity implies updated inputs and updates if necessary. Some *upscaling models* also require significant computational means to operate. As mentioned in the introduction of step 6, supplementary upscaling analysis or stakeholders' proposition may complete or modify the model assumptions.

These elements (data and upscaling model continuity) must be considered as they are necessary to maintain eco-design over the timescale of companies and enable them to capitalise on the resources (and organisation) that would have been implemented. Resource D (upscaling archetype/ engineering field matrix) can be updated and used as an organisation tool to collect and save data sources, methods and tools out of the organisation.

Upscaling eco-design guidelines, aligned with the eco-design standard, are thus composed of the clarification of stakeholder levers enabling the iterative improvement of LCA results, the resulting guidelines addressed to strategic stakeholders and the recommendations on data and model continuity used by the design team.

## 4. Discussion

### 4.1. LCA standard as a vector of eco-design integration

To make the six steps of the proposed methodology easier to operationalize for design team, we decided to use the four steps of the LCA standards as a common thread for the method (see requirement #1). To be clear, the objective was not to point to hypothetical lacks or limitations of these standards but rather to compose with them for an LCA-based environmental upscaling assessment and toward eco-design practices. As illustrated in Fig. 8 with the formalism of the LCA ISO standard (yellow boxes), the six steps of the proposed methodology blend in the four LCA phases, except for the first and last steps which are in keeping with the broader framework of the eco-design practice (Cf requirement #2). This brought about adaptations to the standard in the form of additions or precisions to consider the upscaling assessment specificities, *i.e.* *key elements* in Fig. 1. These adaptations were divided into two types: precisions (white boxes) and additions (*i.e.* novelties) to consider upscaling assessment specificities (yellow boxes). Like in the standard, steps are linked to each other with bidirectional arrows, stating the iterative nature of the processes and by extension the method itself.

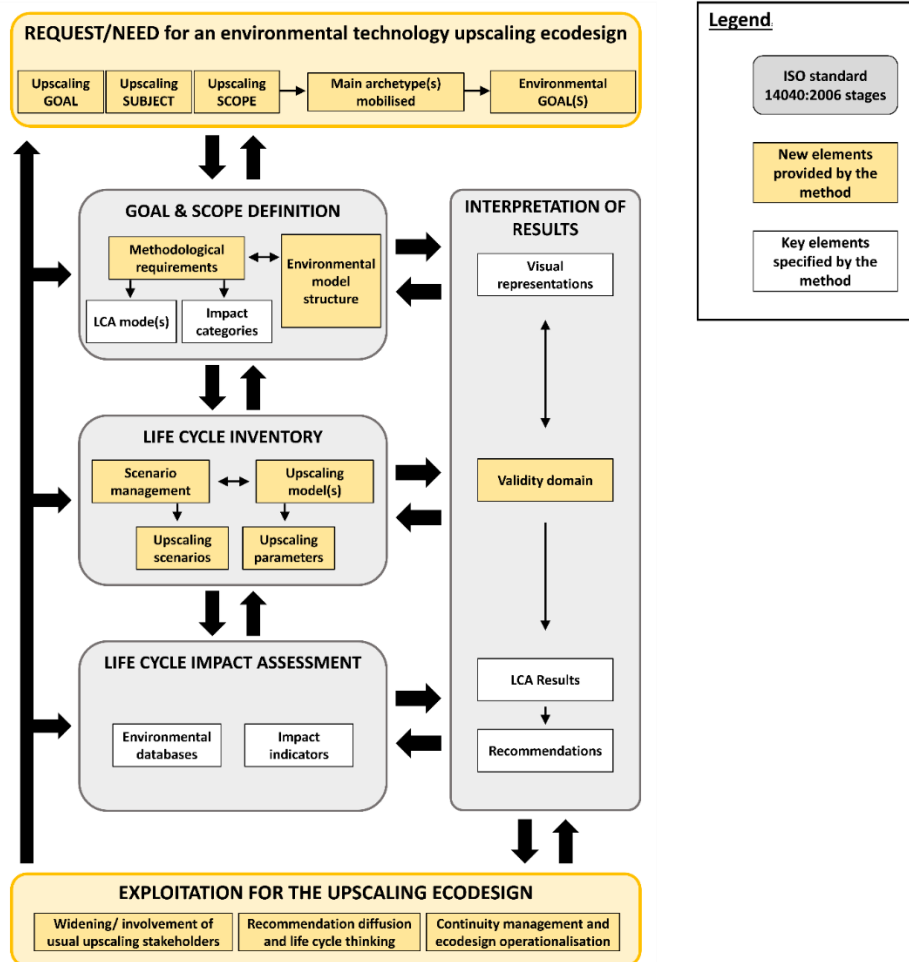


**Fig. 8** Overview of the proposed methodology in the formalism of the ISO 14040:2006 (grey elements). White boxes are precisions of elements of the ISO 14040 standard and yellow boxes are added elements related to upscaling specificities or eco-design practice.

The proposed methodology is an iterative procedure, and although it is not visible in Fig. 1, it implies that the end of step 6 “exploitation for the upscaling eco-design” can initiate an additional iteration of the whole or a part of the methodology.

#### 4.2. Synthesis and perspectives of the contributions of the proposed methodology with respect to methodological requirements

As mentioned along the description of the proposed methodology, each step aims to satisfy at least one methodological requirement summarized in Table 2. Recalling Fig. 1 structure (steps/requirements), Fig. 9 is an attempt to synthesize all remarks gathered during the development of this method, and qualitatively assess each step regarding the six main requirements, namely #1: Multicriteria, multi-stage and systemic, #2: Anticipative and representative of the upscaling, #3: Suitable for design teams, #4: Technical parameter-based, #5: Generic, #6: Evolutive. This qualitative assessment shows that step 2 and 3 are building the core of the method, addressing all six requirements together. It also appears that requirements #3 (suitable for design teams), #5 (generic) and #6 (evolutive) are shared by all steps, which comfort the proposed method in its generic structure, versatile regarding the engineering fields and supportive for the design community.

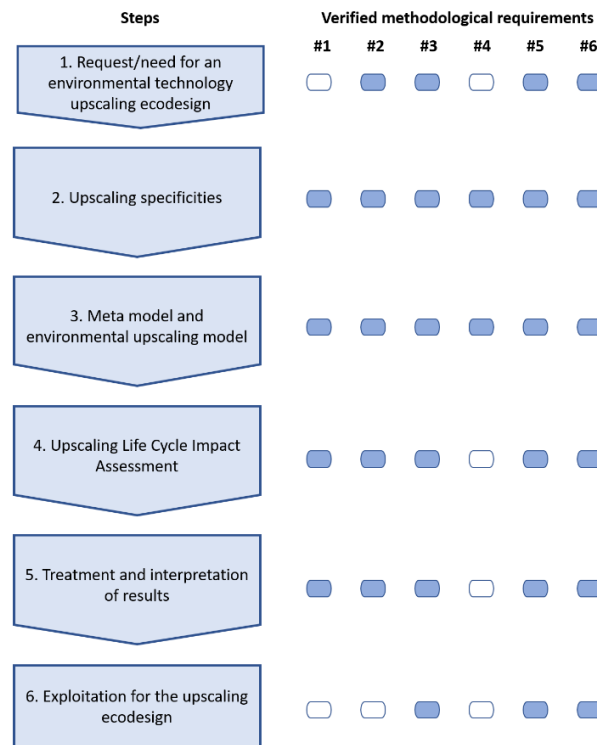


**Fig. 9** Proposed methodology steps with regard to methodological requirements, #1: Multicriteria, multi-stage and systemic; #2: Anticipative and representative of the upscaling; #3: Suitable for design teams; #4: Technical parameter-based; #5: Generic; #6: Evolutive.

As intended from the beginning of this development, the proposed EAU process fits the LCA-based standard and structure (requirement #1). The requirement assessment summarized in Fig. 9 also traduces some reserves regarding the capacity of the guidelines presented in this article to be handled by the design team to achieve an environmental upscaling assessment. For instance, requirements #3 (suitable for design teams) #5 (Generic) and #6 (Evolutive) involve real conditions to be testified, and much depends on the design team (skills, organisation, collaboration, support, etc.). Moreover, testing requirement #2 (Anticipative of the upscaling) raises the same issue as any future-oriented tool, *i.e.* to be *predictive* regarding future events or *prospective*, providing information about the field of future possibilities to support current decisions (Riondet *et al.*, 2022b), in this case for design team stakeholders.

Thus, and for further validation, the proposed method is meant to be confronted with a variety of design process conditions in ongoing research, in an empirical way. Ongoing research are currently partly dedicated to strengthening the accuracy of the proposed methodology in two complementary ways:

- case studies, carried out by fictive design teams or industrial partners will test the robustness of the method to requirements #1, #2 #3 and #4. They will exemplify generic parts of the method steps, reinforce its robustness and highlight potential operability/practical issues such as time requirements, expertise and data availability in an eco-design context.
- semi-directive interviews are intended to act on the adoption/suitability of the proposed methodology for varying design teams and technology (requirements #3 and #5) and canvass its upgradeability (requirement #6).

Additional resources were provided in the references (Riondet et al., 2024a, 2024b) to support the use of the EAU process. They constitute a review of the literature on upscaling, and if the literature evolves, they may eventually integrate it. An open-access version would help users to deal with this evolution. It can be particularly fruitful for the engineering field specificities to share case studies, tools and methods related to upscaling archetypes for additional engineering fields or applications.

The second part of ongoing research currently conducted concerns the applications of this methodology to multiple case studies, to assess the potential environmental impact assessment of the system being upscaled, for instance to photovoltaic systems, in an extension of work Riondet et al., (2024c).

### 5. Conclusion

This paper is the achievement of recent research works conducted on the topic of environmental assessment for upscaling. The lack of technical, generic and necessarily evolutive, process to support design teams in assessing the potential environmental impacts of an upscaling system, appeared crucial. The methodology proposed in this paper is meant to structure the upscaling approach in Life Cycle Assessment.

The emerging technology upscaling is defined in this research as a socio-technical phenomenon composed of five different facets interacting together. Literature review in engineering showed that these facets, also called "archetypes", are not explicitly linked to environmental approaches. Considering this factual heterogeneity, and difference in environmental treatment, or maturity, the LCA-based framework proposed in this article treats each archetype separately. The framework is based on a review of the LCA's existing literature. Fifteen "LCA modes" are technically and efficaciously matching with the upscaling archetypes on the basis of common modelling characteristics. But as upscaling is a composition of archetypes, these fifteen LCA approaches require to be combined in an ecodesign-process intended for design teams. Considering a minimal modelling is required for the designer teams to be simultaneously operationalizable and representative of the technology upscaling environmental aspects, the methodology developed in this paper sleeked to "orchestrate a Life Cycle Assessment within an upscaling archetype approach under an eco-design context".

The originality of the paper's contribution is therefore to propose a structure favouring the emergence of an accurate consideration of the environmental aspects of the upscaling with an aggregated approach of the upscaling archetypes. To help design teams manage an LCA-based environmental assessment of the upscaling of a technology, a new methodology has been developed based on six methodological requirements identified in the literature and eco-design expertise:

- # 1: Multicriteria, multi-stage and systemic
- # 2: Anticipative and representative of the upscaling
- # 3: Suitable for design teams
- # 4: Technical parameter-based
- # 5: Generic
- # 6: Evolutive

The proposed process, titled *Environmental Assessment for Upscaling* (EAU), intends therefore to guide design teams to structure and merge different groups of upscaling analysis at once in an eco-design context. It is a step-by-step and iterative process composed of six steps:

- 1) Request and need for an environmental technology upscaling eco-design

- 2) Definition of upscaling specificities of goal and scope
- 3) Meta-model and environmental upscaling model
- 4) Life cycle Impact Assessment
- 5) Interpretation of results
- 6) Exploitation for the upscaling eco-design

This step-to-step process starts with the clarifying of attempts of the users (*i.e. environmental goal(s)*) in step 1) and uses the classic LCA phases (steps 2 to 5) as a vector for integration within the design team and for improving upscaling eco-design practices (step 6). New elements are added to the classic LCA framework (*e.g.* Meta-model definition) and key elements are clarified with regard to upscaling specificities (*e.g.* impact indicator selection). Additional resources (A, B, C and D) have been also developed to help design teams make the proposed methodology their own. Finally, the use of LCA ISO standards as an integration vector in companies was discussed to strengthen the operationalization of the EAU process.

A synthesis of the contributions and research orientations to reinforce the validation of the methodology was discussed in the last section. The qualitative assessment conducted showed great potential given to the design teams to process each step of this methodology. Steps 2 and 3 are the backbone of the methodology and are carefully addressing each requirement. Ongoing research is currently partly dedicated to strengthening the accuracy of the proposed methodology according to two complementary ways: interviews of LCA practitioners, and designers from different engineering and technical fields, as well as case studies, to gather direct feedback from concrete situations. The second part of the ongoing research is currently carried out to apply the EAU process with several technologies, notably photovoltaic systems, to investigate its genericity and upgradability and ultimately support its operationalization.

Lastly, the objective of this publication is to provide key guidance to designers confronted with the environmental assessment of an upscaling. The EAU process is meant to support them in systematically considering the potential environmental impacts generated by the system under study, which is regrettably not always the case. Open to integrating upcoming evolutions in research, researchers and designers are invited to use this methodology to strengthen the capacity to assess the future of technological systems in their wide diversity.

### Data Availability Statement

Data will be available on request.

### Credit authorship contribution statement

Lucas Riondet: Conceptualisation, methodology, original draft. Maud Rio: Conceptualisation, methodology, supervision. Véronique Perrot-Bernardet: Conceptualisation, supervision. Peggy Zwolinski: Supervision.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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# 8

## Opérationnalisation de l'analyse du changement d'échelle intégrée en conception (proposition 3)

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## 8.1 Conférence 2 - Cas d'illustration d'une ACV prospective et absolue sur le photovoltaïque

### Stratégie de communication scientifique pour la Conférence 2

L'**Article de Conférence 2** a été présenté à la conférence *CIRP LCE* le 16 Mai 2023 dans la session *Life Cycle Assessment* pour présenter une première application de l'ACV prospective couplée à l'AESA aux communautés de concepteurs et d'ACVistes.

Cet article s'intitule « *Assessing energy technologies sustainability : upscaling photovoltaics using absolute LCA* » et constitue les **pages 177 à 183** de la thèse.

### Abstract

*The upscaling of a technology has different facets that should be considered with anticipatory environmental assessment to deem its sustainability before industrialization. The Life Cycle Assessment (LCA) methodology is widely used to assess a product sustainability based on technologies. LCA is however usually applied after technology deployment, as a comparative approach validating the efficiency of the previous technology usage. Anticipatory LCA developments are therefore needed to help designers and engineers to investigate the sustainability of future technology implementations. This article paves the way to enhance ex-ante (or prospective) studies with an absolute sustainability framework, thus demonstrating the incompleteness of current developments on the upscaling from the designer's perspective. This is achieved through a case study applied on two photovoltaic technologies, silicon mono-crystalline and silicon/perovskite tandem in France, and in the current and the 2050 perspectives. Results show that assigning absolute sustainability targets at the technology level provides a new design framework, resulting in a go/no-go strategy. The minimal environmental performance requirements associated to technology deployment conditions through scenarios are identified. During this process, however, questioning the temporal and spatial scope of the study remains crucial to design a sustainable technology and the corresponding service it provides.*

## Assessing energy technologies sustainability: upscaling photovoltaics using absolute LCA

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### Abstract

The upscaling of a technology has different facets that should be considered with anticipatory environmental assessment to deem its sustainability before industrialization. The Life Cycle Assessment (LCA) methodology is widely used to assess a product sustainability based on technologies. LCA is however usually applied after technology deployment, as a comparative approach validating the efficiency of the previous technology usage. Anticipatory LCA developments are therefore needed to help designers and engineers to investigate the sustainability of future technology implementations. This article paves the way to enhance ex-ante (or prospective) studies with an absolute sustainability framework, thus demonstrating the incompleteness of current developments on the upscaling from the designer's perspective. This is achieved through a case study applied on two photovoltaic technologies, silicon mono-crystalline and silicon/perovskite tandem in France, and in the current and the 2050 perspectives. Results show that assigning absolute sustainability targets at the technology level provides a new design framework, resulting in a go/no-go strategy. The minimal environmental performance requirements associated to technology deployment conditions through scenarios are identified. During this process, however, questioning the temporal and spatial scope of the study remains crucial to design a sustainable technology and the corresponding service it provides.

**Keywords:** Upscaling; Product and technology integrated design; Absolute Sustainability; Energy transition;

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### 1. Introduction

Energy production is the sector of human activity that contributes most to climate change [1]. In an energy transition framework, the production of low-carbon energy is a major objective, which pushes energy technology developers in a singular position. Life Cycle Assessments (LCA), following ISO standards [2], are carried out often retrospectively (*i.e.* post-ante assessment), which implies that results are not integrated in the design process. Referring to the sustainability framework for upscaling as a phenomenon with different facets to be considered defined in previous research [3], this paper focuses on the difficulties faced by designers to deal with these multiple facets of the upscaling of technology. In particular, there is a multiplicity of stakeholders and expertise to integrate in the environmental impact assessment. The purpose of this paper is to provide designers with an illustration of the benefit of implementing these archetypes perspectives in design, and consequently demonstrate the incompleteness of current upscaling assessments.

#### 1.1. Context: Sustainability Assessment of Technologies

To reach sustainable targets, technology designers need to anticipate the sustainability of a technology they intend to be mass-produced. A full application of the LCA ISO standards is however not well adapted to early design stage, and rather suits to a post-ante assessment. Several methodological supports for future-oriented perspectives (*i.e.* ex-ante or prospective LCA) are provided by the literature, dealing with the common issues faced by designers such as data collection, modelling, interpretation and uncertainties. One of the main issues regarding the uncertainties strongly relates to the technology maturity, that is usually evolving during the design process [4]. LCA method for emerging technologies therefore requires to be integrated at each stage of the design process, and can be the fruit of collaboration between the technology expert and a LCA practitioner [5].

#### 1.2. Research background and problem statement

Referring to the upscaling assessment framework published in [3], upscaling is defined in this research as a phenomenon (conferring several facets) presented through the following

*Archetypes*: upsizing from laboratory to industrial scale (Archetype 1), mass producing related to industrial engineering (Archetype 2), reaching a level of cumulated service (Archetype 3), integrating a complex system (Archetype 4) and down-limiting related to absolute sustainability (Archetype 5, see section 2). These archetypes correspond to different viewpoints of the upscaling of a technology or a service and hence draw on the expertise of numerous stakeholders. Scientific and economic actors, such as researchers, companies, public agencies and governments, produce studies and data required to feed these archetypes but not necessarily produced for direct use by designers. Data collection for assessing the technology upscaling can therefore result in a complex investigation, crossing multi-expertise. For instance, national policies, strategies and feasibility studies of energy transition (*e.g.* carbon neutrality targets), are partly driven by the upscaling of low-carbon energy technologies (*e.g.* photovoltaic and wind power). But the upscaling guidelines [4, 5], as complete as they are, do not integrate such data and studies and correspond to upscaling archetypes 1 and 2 only. Designers are therefore not equipped to deal with the multiple facets of technology upscaling, and are therefore limited in their environmental assessment. This research hypothesis considers this issue through the integrated design vision: the multiplicity of stakeholders and expertise to integrate in design to cover the multiple facets of upscaling requires additional support. There is a benefit of implementing these archetypes completeness perspectives during the design process associated to technology-based products. This research paper intends consequently to demonstrate the incompleteness of current upscaling assessments methodologies accessible to designers through a case study (sections 2 and 3), and formulate a method proposition to complete the upscaling assessment (section 4).

### 2. Application: Upscaling Technology Design in an Absolute Sustainability Perspective for Energy Transition

#### 2.1. Introduction to the case study

This study case investigates a practical way to implement absolute sustainability principle in an energy system design perspective based on data and prospective studies in literature. It results in the illustration of a down-limiting method (as Archetype 5 of upscaling [3]), applied to the process design development of photovoltaic systems. Referring to the methodology for addressing absolute sustainability in engineering, one of the key tasks is to delimit a *safe operating space* (SOS) to identify *how good is a technology, versus how best is a technology* [6]. In other words, moving from relative to absolute environmental assessment and promoting a design under (environmental) constraints. Literature provides a generic methodology to define these environmental constraints limits and chose the allocating rules and on justice principle [7, 8]. Energy provision is however a service, and its country

disparities in terms of availability and use complexifies the applicability of such methods, as energy system designers are used to “tangible” products. This study therefore builds on existing research and brings up a necessary discussion on what analyses are required to study the resulting service rather than the energy device only, *e.g.* a photovoltaic (PV) panel, and on how this might improve the completeness of its upscaling assessment (*cf.* section 4).

#### 2.2. Defining a French energy production SOS

This section outlines the methodology used to define a local share of the global SOS (SoSOS) over time for the climate change indicator in carbon dioxide equivalent (CO<sub>2</sub>eq). Abdoli *et al.* (2020) published a similar methodology with a different perspective [9]. This contribution leads to the characterization of sustainable photovoltaic technology mixes in 2050, while we focus on the characterization of the potential improvement margin over time for two PV technologies from an eco-design framework. The goal is to build a SoSOS with regard to a unit of electricity production (1kWh) and comparable with classic energy system LCA results based on a functional unit of 1kWh from 2020 to 2050. This method is divided in two steps, one requiring to collect data from the French government and the second involving scenarios of national electricity production.

First, the National Low Carbon Strategy, voted in 2015 by the French government [10] defines annual carbon budgets from 2015 to 2050 to ultimately reach carbon neutrality in 2050. As shown is Fig. 1 (to be read with the right y-axis in grey), the yearly carbon budget attributed to the French energy sector in 2020 accounts for 52 Mega tons (Mt) of CO<sub>2</sub>eq. Then, the curve (in gray) follows a decreasing slope from 2020 to 2025, a shallower trend between 2025 and 2031 and a constant slope between 2032 and 2050 until it reaches the value of 2 Mt CO<sub>2</sub>eq. This brings France to neutrality in 2050 considering the other activity sectors that will absorb the remaining emissions, so-called greenhouse gas (GHG) sinks [10]. This corresponds to the application of a sharing principle to allocate a part of the “global carbon budget” (*i.e.* the SOS in terms of GHG emissions) to the French energy sector (*i.e.* electricity production). The hypothesis set to create this first SoSOS will not be questioned in this paper. The second step to define a SoSOS over time consists of redistributing the previous SoSOS with regard to electricity production over time. To do so, it is necessary to collect prospective scenarios on electricity production until 2050. The *Réseau de Transport d'Electricité* (RTE), the electricity transmission system operator in France published in 2021 different power production pathways to reach carbon neutrality by 2050 [11]. These scenarios are represented by blue curves in Fig. 1 (to be read with the left y-axis).

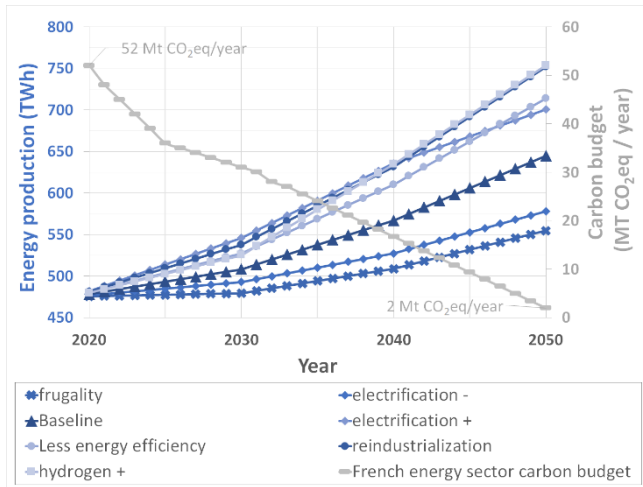


Fig. 1 - Energy production of France from 2020 to 2050 following 7 prospective scenarios (in blue) from RTE adapted from [11] and corresponding French carbon budget associated to the energy sector adapted from [10].

This results in the following seven scenarios with specific narrative, ranked from least to most productive in terms of energy produced in 2050: (i) *Frugality* (or sufficiency): implies the reduction of energy consumption per capita over time, (ii) *Electrification* “-”: corresponds to partial and slow electrification of other activity sectors including transport, (iii) *Baseline* scenario: implies a gradual electrification and strong energy efficiency improvement, (iv) *Electrification* “+”: corresponds to total and rapid electrification of activity sectors with decarbonized hydrogen production, (v) *Less energy efficiency*: represents a scenario with less energy efficiency implementation than the baseline scenario, including in the heating of building sector. (vi) *Reindustrialization*: models a re-localization of manufacturing industries, (vii) *Hydrogen*: production and used of decarbonized hydrogen as a vector of energy transition more than in the baseline scenario [11]. These scenarios are consistent with the objective of carbon neutrality for France in 2050, which allows for a single carbon budget curve. Even in the frugality scenario, the electricity production, according to RTE, is meant to increase based on population growth compensation and a more or less sustained and fast electrification of other activity sectors. The SoSOS allocated to the production in France of 1kWh is therefore defined as follows:

$$SoSOS_{\{1kWh\}i}(t) = \frac{\text{French Energy sector carbon budget (t)}}{\text{Energy production following the RTE scenario i (t)}}$$

with “i” the chosen RTE scenario (frugality, baseline, reindustrialization, etc.). For one selected RTE scenario, the resulting SoSOS, like the carbon budget and the energy production, evolve annually (see Fig. 1). It means that the constraint on energy production (i.e. on energy system

designers) is gradually increasing over time until 2050. The result of this approach is thus seven time-dependent SoSOS from 2020 to 2050 in terms of climate change indicator for the production of 1kWh of electricity. These dynamic SoSOS are considered independent of the technology mix. It defines a threshold not to overtake for the production of 1 kWh of energy to be considered as sustainable relatively to the climate change indicator.

## 2.3. Study case of photovoltaics in France

This section is dedicated to present attributional LCA results for energy production from PV systems in France in 2020 to be confronted with the SoSOS defined in section 2.2. A photovoltaic system, as shown in Fig. 2 is composed of an active part, the module, transforming more or less efficiently the solar energy into electricity according to the technology. In our case, the mono-crystalline silicon (c-Si) technology for the most mature and the tandem c-Si/perovskite technology as emerging and potentially more productive. Then, *balance of system* (BOS) components (e.g. structure, cables, inverter, transformer, etc) are integrated to manage mechanical and electrical constraints, including to adapt the energy supplied to the grid (i.e. DC/AC current conversion).

Concerning the scope of the LCA, Fig. 2 presents five generic life cycle stages considered in a LCA following the standards [2]: 1. raw material mining and purification (e.g. metallurgical grade silicon production), 2. conversion of raw material into material (e.g. solar grade silicon production), 3. component production and assembly (e.g. wafer production and cell assembly into modules), 4. installation use and maintenance and 5. End of Life (EoL) treatment (e.g. energy recovery or partial recycling of copper/aluminium). The grey arrow represents the transport of components between and into stages. The electricity network and energy storage interactions are usually neglected (cf. discussion in section 4.3).

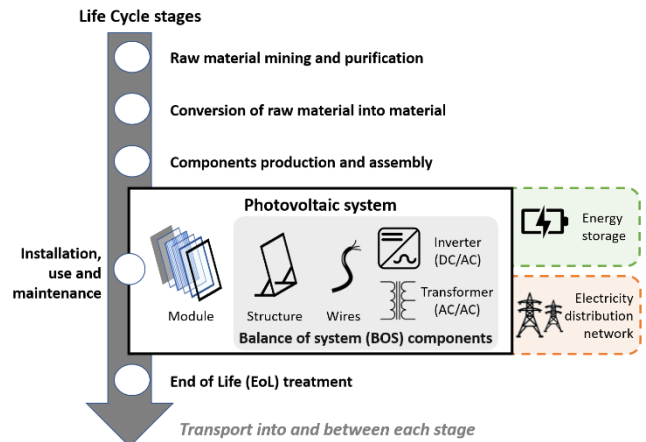


Fig. 2 - Elements composing a PV system (in black box) and associated generic life cycle stages. Energy storage (dash boxed in green) and grid (dash boxed in orange) interactions are usually excluded from the perimeter.



## 2.4. LCA of PV system (goal and scope)

The objective of the study is to compare the potential environmental impacts (only GHG emissions in our case) for the year 2020, with a view to the year 2050 for the two technologies: c-Si and tandem c-Si/perovskite. To do so, three studies have been compiled to use representative results from 2020 and the near future: the “INCER-ACV” (2020) [12] study, the study of Fthenakis and Leccisi (2021a) [13] for c-Si technology, and Fthenakis *et al.* (2021b) for the tandem technology [14]. Each study considers the first four life cycle stages and include the BOS in their perimeter, as depicted in Fig. 2. Publications [13] and [14] neglect the EoL stage due to lack of data. The functional unit in PV systems, is usually presented for designers in unit of capacity installed (kWp). This prevents designers from studying performance results depending on the location. The study being, however, carried out in France, the unit of energy instead of power capacity is preferred in this paper. The functional unit chosen is therefore 1kWh of energy delivered to the French electricity grid. The variation in the location of the studies is reflected in the uncertainties in the result graphs. Concerning the tandem system module and as an emerging technology at a laboratory scale, hypotheses have been set to assess its upscaling to industrial scale (*i.e.* implementation of archetype 1, upsizing). The time horizon of this technology upscaling is not specified, which is an issue for designers addressed in the results and discussion section. The lifetime and the energy efficiency of the module being key parameters in PV environmental assessments, several values of a lifetime (from 10 to 30 years) have been documented for this emerging technology to assess the variability of results (see section 3.1). The tandem system is assumed to reach 28% energy efficiency. The lifetime for c-Si system is considered by default equal to 30 years and its energy efficiency is 20.5%. To deepen the hypothesis of the LCA results used in this paper, please consult [12–14].

## 3. Results

The point of absolute sustainability is to set environmental constraints not to be overtaken for a sustainable potential technology. In the goal of reaching French carbon neutrality, Fig. 3 presents the CO<sub>2</sub>eq emissions c-Si PV technology, on average associated with the production of 1hWh generated in 2020 and the corresponding SoSOS in accordance with the French carbon neutrality goal following the baseline scenario.

Uncertainties bars show the sensibility analysis of key parameters in the LCA (energy efficiency, solar irradiation, raw material composition, manufacturing processes, EoL treatment, etc) for [12] and variation of location and solar irradiation (from 1000 to 2000 kWh/m<sup>2</sup>/year) for [13]. From these two retrospective studies on the incumbent PV technology that is the c-Si-technology and relatively to the SoSOS in 2020, the energy production can be estimated sustainable for 2020. Remark that

the EoL stage is not negligible, which is the only prospective (*i.e.* future-oriented) aspect of the study.

### 3.1. Go/no-go strategy in design

In the design framework, it is necessary to anticipate the environmental impacts of the designed/upscaled technology. The comparison of classic results of prospective LCA with the SoSOS as presented in the previous section, provides elements

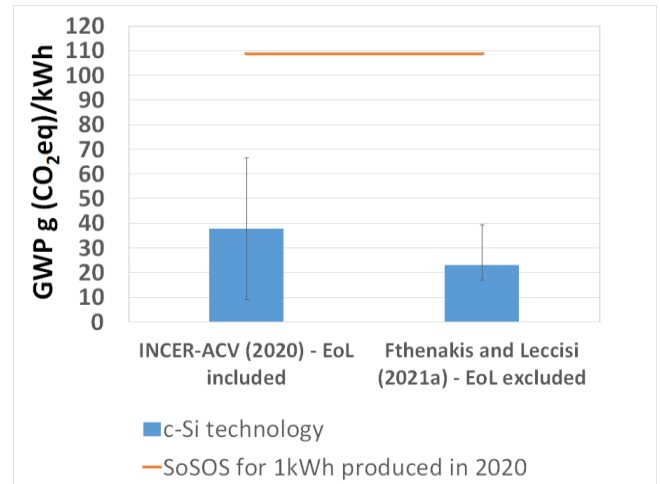


Fig. 3 - CO<sub>2</sub>eq emissions attributed to the production of 1kWh of electricity from c-Si PV technology in France in 2020 adapted from [12] and [13] compared to the SoSOS (in orange) in accordance with the French carbon neutrality goal.

to develop a go/no-go strategy in a prospective perspective. As an example of emerging PV technology, the tandem PV technology is not yet existing in 2020 at industrial scale. Moreover, at first order, the *Global Warming Potential* (GWP)

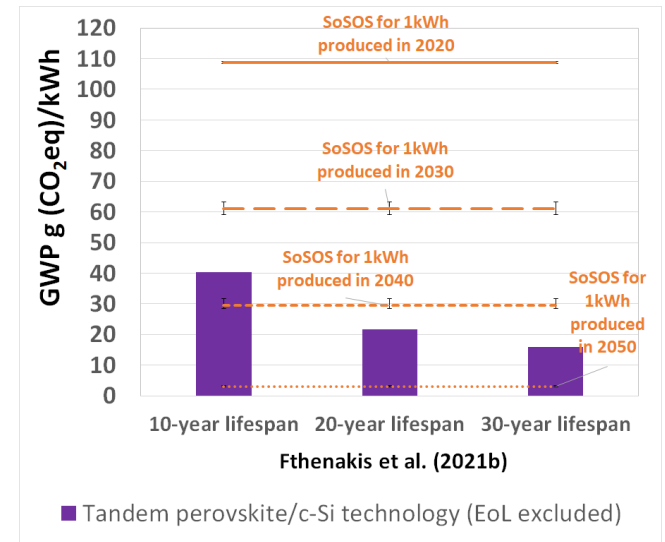


Fig. 4 - CO<sub>2</sub>eq emissions estimation for the production of 1kWh of electricity from upscaled tandem perovskite/c-Si PV technology adapted from [14] compared to the SoSOS in 2020, 2030, 2040 and 2050 in accordance with the French carbon neutrality goal.

of a panel is influenced by its lifetime and its efficiency. Their improvements are thus crucial and well identified levers for designers. Fig. 4 presents the prospective estimation of GWP for the perovskite/c-Si tandem technology, depending on its lifespan, provided by Fthenakis *et al.* (2021b) [14]. Note that for an equivalent lifetime (30 years), the impacts of tandem PV are lower, notably because its energy efficiency is higher than that of c-Si PV (28 instead of 20.5 for c-Si). Authors do not give a timeframe for these improvements. This study is therefore compared to the SoSOS for one unit of energy produced in 2020, 2030, 2040 and 2050 following the baseline scenario. Uncertainties bars represents the variation of these limits depending on the chosen RTE scenario. This graph shows that PV system designers need to improve the lifetime of tandem PV technology by up to 10 years before 2030 and, in the worst case, by up to 20 years before 2040 for the resulting energy production to be sustainable for 2030 and 2040, respectively, and from the GWP perspective. If PV system designers consider satisfying these constraints unachievable or unrealistic, a "no-go" strategy will be applied to redirect research to other more promising technologies. Note that, the EoL stage being excluded from the scope of the study, a more drastic deadline should be considered. Fig. 3 and Fig. 4 shows the completion of the usual analysis charts from PV LCA studies and therefore used by designers to consider environmental impacts. This work should be taken as a proof of concept of integration in the design process of the absolute environmental sustainability framework.

## 4. Discussion

### 4.1. Averaged GWP and dynamic SoSOS comparison issue

Results show the feasibility of integrating a SoSOS in a retrospective or a prospective vision for a specific year, assuming a constant ratio of GWP per kWh produced. In other words, the device sustainability has been estimated at a precise date of time, current or future, based on static environmental impacts. This study is focused on the estimation of the timescale for technology improvement requirements in France to fulfil the Paris agreement. The main issue of comparing SoSOS depending in time (*i.e.* dynamic) with averaged environmental impact over the whole life cycle of a device is illustrated in Fig. 5. Considering a c-Si panel installed in 2020 (in dashed blue) and a tandem panel installed in 2030 (in dashed purple) with a lifetime of 30 years, with an averaged GWP over time (*i.e.* static), the same level of environmental performance is maintained over time (23 g and 16 g of CO<sub>2</sub>eq/kWh respectively). The sustainability threshold is crossed in 2042 for c-Si technology, and at the horizon of 2045 for tandem technology. In other words, all things being equal, the energy provided by a panel installed in 2020, can be considered sustainable until 2042 for c-Si technology and until 2045 for the tandem technology. Given this artefact at the system level, no technology will be sustainable over its lifetime, disregarding the

possible variations of its impacts over time as exposed in [15] with the terminology "temporal issue 3". A robust go/no-go strategy therefore requires additional phenomena than usual ones to be considered, including the distribution over time of the environmental impacts (*e.g.* up to 75% of PV devices GWP is attributed to its manufacturing phase, within the year of the installation of the PV system [13, 14]). The following section discusses several research tracks focusing on the prospective study scope required to define this go/no-go strategy for designers of PV technology in an upscaling perspective.

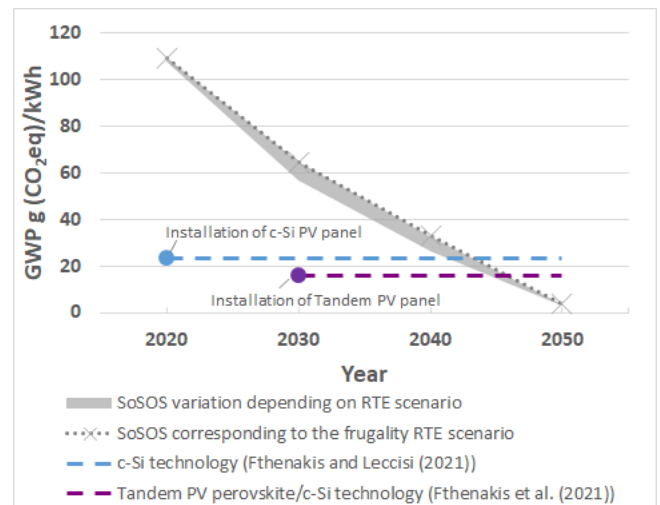


Fig. 5 - Comparison between averaged GWP associated to c-Si (blue) and tandem (purple) PV systems over their lifetime and a dynamic SoSOS (grey dashed line).

### 4.2. The temporal scope of the study

This study, as a proof of concept calls for complementary assessments with regard to the prospective LCA framework. In an eco-design context is commonly distinguished the foreground system, depending on the design and industrial parameters (*i.e.* foreground system) to the background system, as an imposed techno-economic context. This context leads to characterize the margin of improvement of a given technology regarding several influence perimeters, namely in terms of temporal evolution.

#### The PV designer's levers integration

This system corresponds to the usual design parameters: energy efficiency, lifetime, and raw material composition. As stated in section 3.1, energy efficiency and lifetime are the main improvement contributor to the reduction of PV environmental impacts. However, these improvements only have effect from one panel generation to another and not on a specific installed PV panel as studied in the results section.

#### The PV industrial's levers integration

This system consists of manufacturing process efficiency, relying on industrial trend of improvement (*e.g.* silicon wafer

slicing process, tandem process scalability, or EoL treatment maturation). These evolutions can be implemented following learning curves and scaling laws provided by PV sectorial experts [14, 16]. These variations are also carried out from a panel generation to another.

### ***The national and intersectoral's evolution integration***

The background system is by definition out of the expertise and levers of a technology designer. However literature demonstrated that variability of prospective LCA results are strongly affected by background system data [15]. As an example, the EoL stage is simultaneously a part of the foreground system (*e.g.* selection of components by the designer and the choice of technology for the recycling process), and the background system generally presented as an energy-intensive activity involving dynamic effects consideration. Thus, recycling could be overestimated in an energy transition context, because it is assumed to occur 30 years before the actual time in a static study (*i.e.* EoL allocation in 2020 instead of 2050 as in [13]), when energy consumption is more carbon intensive. There is still no consensus on modeling EoL, which leads designers to neglect it, in addition to the lack of data. The energy transition implementation (and resulting carbon intensity decrease) in data can be supported by the PREMISE framework [17]. This tool returns prospective inventory database considering different scenario of climate pathways (*e.g.* IPCC pathways [1]). This enables for instance to estimate the decarbonation of energy consumed in manufacturing and recycling processes over time.

### ***4.3. The spatial scope (or Energy providing is a service)***

As stated in the introduction, energy providing is a service, meaning that the scope of the study must integrate the Life Cycle of all systems required to provide the service, and this depends on time: the intermittency of PV systems is manageable today without energy storage. It is, however, meant, according to RTE, to be compensated with a grid management and energy storage system. This implies, for the same service, expanding the scope of the evaluation due to the evolution of the complex system (*i.e.* the national power grid) in which PV systems are increasingly integrated. Literature provides some examples of renewable energy intermittency management studies adding within the study perimeter required storage energy systems (*e.g.* battery integration in the perimeter [18], see green part in Fig. 2) and modification of the grid in reaction to cumulated PV installed capacity (*e.g.* [19], see orange part in Fig. 2). Ideally, these two types of analysis should have been carried out to consider the upscaling of energy production from PV technologies.

### ***4.4. Regarding the upscaling framework***

As the proof of concept, this assessment of PV technologies upscaling is not intended to be exhaustive. Several upscaling archetypes however have been fully or partially carried out or evoked to tend towards exhaustiveness.

- Archetype 1 is considered for the tandem PV technology based on [14].
- Archetype 2 is indirectly taken into account from the methodology and data used in [2, 12, 13] and could be assessed with parametrized modelling to integrate learning curves provided by the literature [16].
- Archetype 3 is partially considered due to the use of deployment RTE scenarios to define the SoSOS [11]. Cumulated phenomena linked to the PV deployment are, however, not explicitly in the scope of the paper.
- Archetype 4 is out of the scope of this paper. Energy storage systems, and additional infrastructures required to assure grid stability could be included in further work as presented in [13, 18, 19].
- Archetype 5 has been implemented with the definition of an energy production SoSOS based on external expertise for one environmental indicator [10]. A generalization must be implemented.

## **5. Conclusion**

This article presents a study case of assessment of the upscaling of a photovoltaic technology based on prospective and absolute LCA framework. It proves the incompleteness of current LCA methodologies, providing sustainability time constraints for upscaling designers to develop a go/no-go strategy. To enforce such strategy consistently, supplementary methods must be developed, including time-dependent LCA result representation. Two research tracks were evoked in the discussion: prospective methodology clarification for designers and an assessment of the scope consistency with respect to the technology upscaled and the related service provided.

## **Acknowledgements**

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## Chapitre 8 – Opérationnalisation de l'analyse du changement d'échelle intégrée en conception (proposition 3)

L. Riondet, M. Rio, V. Perrot Bernardet, P. Zwolinski

SECTION 8.1 – CONFERENCE 2

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## 8.2 Conférence 3 - Cas d'illustration du processus EAU sur le photovoltaïque

### Stratégie de communication scientifique pour la Conférence 3

L'**Article de Conférence 3** a été présenté à la conférence *CIRP LCE* le 20 Juin 2024 dans la session *Design for Sustainability* pour présenter une illustration de l'étape de modélisation du processus EAU aux communautés de concepteurs et d'ACVistes.

Cet article s'intitule « *Towards ecodesign for upscaling : An illustrative case study on photovoltaic technology in France* » et constitue les **pages 185 à 191** de la thèse.

### Abstract

*The upscaling of a technology encompasses many facets, which a designer concerned with reducing environmental impacts must manage. Recent developments show that prospective Life Cycle Assessment (LCA) and absolute sustainability considerations present great potential to assess product environmental sustainability. But such methods remain hardly adopted by designers facing technology upscaling in an operational process. This research therefore deals with ecodesign practices for technology upscaling using LCA-based approaches. The originality of this paper is to illustrate with a case study on photovoltaic systems the upscaling environmental assessment (UEA) methodology elaborated in previous research. The focus is made on the modelling practices (step 3 of the method) using upscaling design levers and create parametrized scenarios interpretable for a design team. Examples of data collection and upscaling modelling are provided for the upscaling of silicon-based photovoltaic technologies in France, from 2021 to 2050. This case study presents therefore a proof of concept for the integration of elements in the design process (e.g. industrial evolution, deployment strategy, socio-technical context) on which design teams have no a priori influence but to which final LCA results are sensitive. It brings, as a result for design teams, recommendations to assess the environmental implications of their decisions during design.*

# Towards ecodesign for upscaling: an illustrative case study on photovoltaic technology in France

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## Abstract

The upscaling of technology encompasses many facets a designer concerned with reducing environmental impacts must manage. Therefore, previous research proposed an environmental assessment for upscaling (EAU) methodology. This method hinges on Life Cycle Assessment (LCA) approaches (*e.g.*, prospective, absolute) and coordinates the environmental modelling from an ecodesign perspective. The originality of this paper is to present an illustrative application on photovoltaic systems. The focus is on the modelling practices (step 3 of the method) using upscaling design levers and generating parametrized scenarios meant to be interpretable for a design team. Examples of data collection and upscaling modelling are provided for the upscaling of silicon-based photovoltaic technology in France from 2021 to 2050. This case study shows that integrating upscaling parameters, such as industrial process evolutions, the technology deployment strategy, and the socio-technical context associated with the technology upscaling phenomenon influence LCA results significantly. The paper, therefore, discusses recommendations for design teams to support them in assessing the environmental implications of their technology choices.

**Keywords:** Upscaling; Ecodesign; Prospective LCA; AESA; proof-of-concept; photovoltaic case study.

## 1. Introduction

Ecodesigning, *i.e.*, integrating environmental aspects during the design process, should be based on a Life Cycle Assessment (LCA) methodology [1]. Various LCA approaches (*e.g.*, prospective and dynamic) are developed to model a product or a service lifecycle's environmental impacts. For instance, The Absolute Environmental Sustainability Assessment (AESA), considers some environmental limits a product lifecycle must not exceed to be considered sustainable. It is opposed to a "relative" approach comparing products with each other and is based on the planetary boundary framework [2]. With this absolute vision in mind, the operationalization of life cycle engineering has been challenged. Recent publications address design mitigation options and design guidelines [3] that could be associated with specific modelling practices [4,5]. However, with case-based reasoning, previous research has shown the incompleteness of LCA guidelines about environmental assessment for upscaling (EAU) for designers [6]. It leads in previous work to the proposal of a methodology (see Fig. 1) enabling design teams to anticipate the environmental impacts associated with the upscaling of a technology, by combining different LCA approaches, *e.g.*, prospective LCA with the AESA paradigm. Practically, the EAU method hinges on the identification of five designated necessary groups of parameters reflecting facets, also called "archetypes", of the upscaling of technology, *i.e.*, scaling-up, mass-producing,

deploying a technology, integrating into a complex system and down-limiting [7]. In other words, these five upscaling parameters refer to different models to be combined to reflect the socio-technical reality of a technology upscaling and its

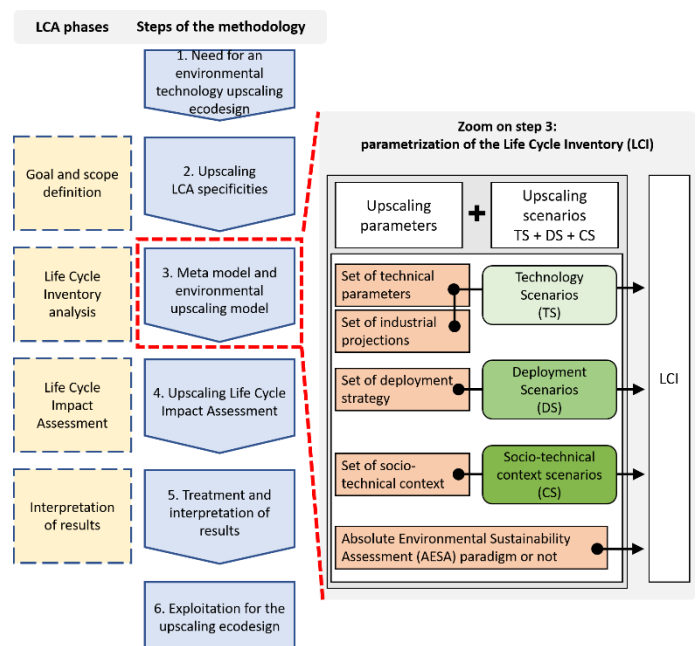


Fig. 1 – Overview of the EAU methodology (blue boxes) mirrored with the classic LCA phases (yellow boxes), focusing on step 3, dedicated to parametrize the Life Cycle Inventory (LCI) based on upscaling scenarios (right part).



potential environmental consequences. They are depicted in orange boxes in Fig. 1 and can briefly be defined as follows before being fully implemented in subsection 2.2.:

- technical parameters proper to the engineering studied object (e.g., material consumption, energy yield, choice of a component or structure);
- industrial projections of the technical parameters due to industry improvements (e.g., learning curves);
- deployment strategy of the studied object (e.g., production target over several years or decades);
- socio-technical context of the deployment strategy (e.g., climate change consequences on society);
- AESA or relative approach.

This paper focuses on the application of the EAU method step 3 to provide answers to the research question, “How to environmentally model the upscaling of a technology into an LCA framework within an ecodesign perspective?”. Based on a concrete case study, it therefore details the composition of sets of the upscaling parameters leading to *upscaling scenarios*, composed of 1) a technology configuration, 2) a *deployment strategy*, and 3) a *socio-technical context* (green boxes in Fig. 1), to reflect the design choices and their implications on environmental (e.g., damage) aspects. To do so, we propose a simplified case study on the upscaling of photovoltaic (PV) systems in France. Thus, to contextualize the focus on the 3<sup>rd</sup> step of the methodology, subsection 3.1 briefly reviews all the six steps presented in Fig. 1. Then subsection 2.2 details an example of the modelling practice associated with step 3 and the necessary development of a “meta model” related to environmental upscaling assessment. The result analysis is conducted in subsection 2.3. Lastly, section 3 provides

guidelines for design teams about EAU and absolute sustainability based on the results obtained. This methodology is meant to be iterative. The paper illustration could, therefore, be taken as the first run of several iterations along the PV system design process handled by designers to converge to a suitable LCI.

## 2. Research investigation and results

### 2.1. EAU application to the PV system deployment in France

**Step 1: definition of the need for an environmental technology upscaling ecodesign.** In this study case, the objective is to ecodesign the deployment of a PV technology in France, assuming to be part of a design team in charge of the PV system’s components “cell” and “module”. The planned PV deployment follows the strategy of the French electricity transmission system operator (named RTE) [8]. It must respect the carbon budgets defined by the French government in relation to the Paris Agreement. By extension, this technology deployment can be addressed within the AESA paradigm: target carbon neutral ambition by 2050 to keep our societies inside the Earth’s safe operating space (SOS). Fig. 2 presents the proposed framework to carry this environmental upscaling assessment, adapted from [2], assuming groups of PV system lifecycles installed successively over the years, all starting at the beginning of a given year, having the same duration and accruing depending on annual installed capacity demand. It formalizes the environmental aspects of the total cumulated installed capacity (i.e., the PV panel park) studied on a given date (red zones), confronted with a share of the global SOS, i.e., an absolute environmental limit (green line). As we shall

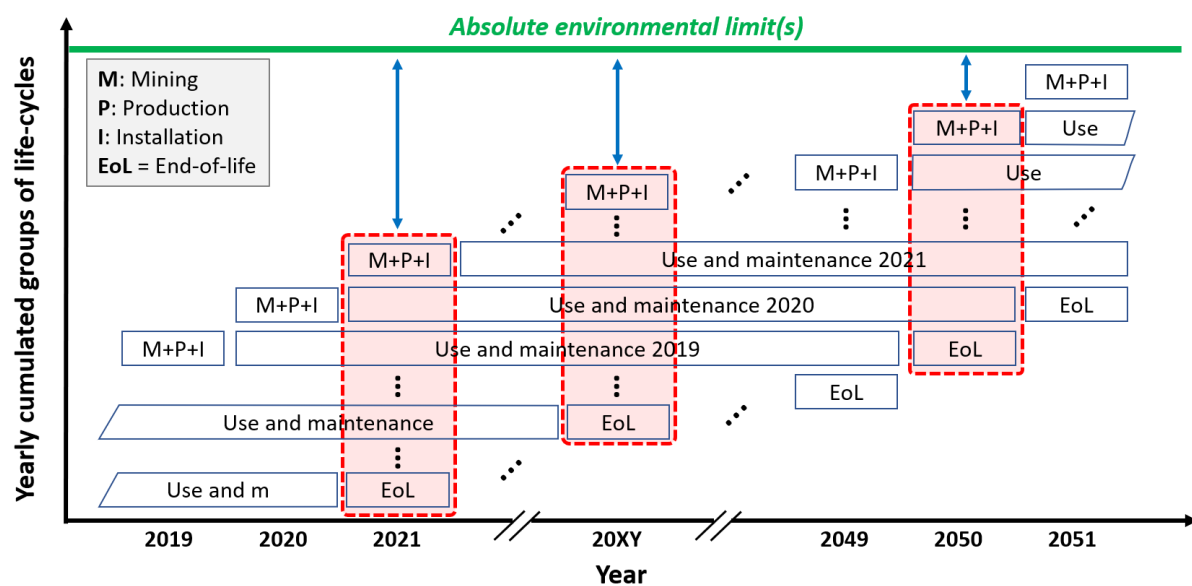


Fig. 2 – Framework of absolute sustainability proposed for PV panel deployment from 2021 to 2055, assuming a lifespan of 30 years. The analysis characterizes the difference (blue arrows) between the sum of every participation of the cumulated groups of PV system lifecycle in a particular year (red dashed boxes) and the defined absolute limit with regard to a specific environmental indicator (upper green line). Adapted from [10].

see, such a framework enables the representation of the temporal evolution integration consideration (*e.g.*, technological improvements and evolution of the background system) and prompts design teams to consider the End-of-Life (EoL) of past and present installed systems while designing future systems. **Step 2: upscaling specificities** concerning LCA approaches, invites to consider the LCA-based modelling needs accordingly to upscaling assessment needs defined in step 1. In our case study, this step drives us to choose an “anticipative” (*i.e.*, prospective) and absolute (*i.e.*, PB-LCA) approach of LCA. Available databases and means of computation involve an attributional approach. Moreover, and as detailed in subsection 2.2.1, industrial trends have been modeled over time, enabling to integrate a partial time dependency of the Life Cycle Inventory (*i.e.*, dynamic LCI). Thus, we selected an LCA approach (attributional) that is prospective absolute with a dynamic LCI. As the deployment strategy is defined at the national scale, a focus will be made on cumulative effects, including total material consumption. The Functional Unit (FU) corresponds to the need for installed energy capacity between 2020 and 2050 following an RTE scenario. For FU based on unit of produced energy, see previous work [6]. The studied systems include the photovoltaic modules and exclude the Balance of System (BOS), which is composed of inverters and AC-DC devices. No storage or panel support is considered. The perimeter encompasses all the stages from cradle to grave with the PV panels' End-of-Life (EoL) stage as illustrated in Fig. 2. **Step 3: meta model and environmental upscaling models.** This step involves a combination of technology scenarios, deployment scenarios and socio-technical context modelling to produce a parametrized LCI for PV system upscaling in France. It is illustrated in subsection 2.2. **Step 4: Upscaling Life Cycle Impact Assessment (LCIA).** This stage refers to database selection for LCI computation (defined in step 3) and characterization factors of environmental impact indicators:

- prospective inventory data were computed with Brightway2 V2.4.4 and a superstructure generated from PREMISE [9] in February 2023 withecoinvent database V3.8 through Activity Browser V2.9.1.
- usual characterization factors were selected to fit with the environmental limits (*i.e.*, carrying capacity) proposed by [10]. A focus is made on climate change indicator (“GWP100”).

**Step 5: treatment and interpretation of results.** Illustrated in subsection 2.3. **Step 6: exploitation for the upscaling ecodesign.** This step involves turning LCA results into comprehensive guidelines for stakeholders of the studied upscaling. It is excluded from the scope of this paper.

## 2.2. Focus on step 3: meta model and upscaling environmental upscaling model

As no generic model exists to deal with the multiple facets of the upscaling of a technology, design teams have to coordinate several models from variable sources and potentially from different scientific disciplines (*i.e.*, to operate a “meta model”) to finally parametrize the LCI and explore summations of technology scenarios, deployment scenarios and socio-technical context scenarios as depicted in Fig. 1.

### 2.2.1. Technology scenarios

As the introduction mentions, a technology scenario hinges on a set of selected design parameters and industrial projections. From a technical perspective, the proposed PV module model depends on two identified design parameters:

- the cell size (called G1, M6, M10, M12),
- the cell structure (whole cell or half-cell).

The literature identifies these selected design parameters as influencing the technical performances (*e.g.*, power) and the material consumption (*e.g.*, silicon, aluminum or silver) per system. Additionally, PV panels are assumed to be monofacial, 1.7m<sup>2</sup> large, weigh 17 kg, and be p-type doped. Fig. 3 displays the influence of the cell size on the power capacity for four PV module configurations in 2021, according to [11] (see colored triangles). It shows that the larger the cells, the more powerful the module is. Moreover, based on learning curves and trend projections for the coming decade from the yearly reports “International Technology Roadmap for Photovoltaic” (ITRPV) [14,15], we extrapolated industrial projections between 2020 and 2032 for each technology. This extrapolation transposes the projected improvement trend for G1 cells to other sizes of cells (M6, M10, M12) based on polynomial regression model (green formula in the top part of Fig. 3. Again, in this case study, the objective is not to model a complete PV system properly but to illustrate with a simplified model the modelling practices and to manage the influence of design parameters on the environmental impacts resulting from the upscaling of a technology. Finally, ITPV reports provide projections for unframed PV module material consumption for silver, silicon, and aluminium, as exemplified in the bottom part of Fig. 3 for a panel composed of 120 M6 half-cells. After 2032, since there is no source offering any projection, a prospective exercise would consist of scriptwriting continuing improvement trends or anticipating new configurations. We adopted a conservative approach in this case study, assuming that these physicochemical improvements will reach a final value in 2032 and stagnate until 2050. Thus, the two characteristics, power capacity and material consumption (*cf.* Fig. 3) contribute to parametrize the LCI, in this case, a part of the foreground system, based on set technical parameters and industrial projections constituting technology scenarios. Regarding the rest of the inventory, the three considered life



cycle stages, Mining, Production and Installation (MPI), Use and maintenance, and EoL, are not directly parametrized, and

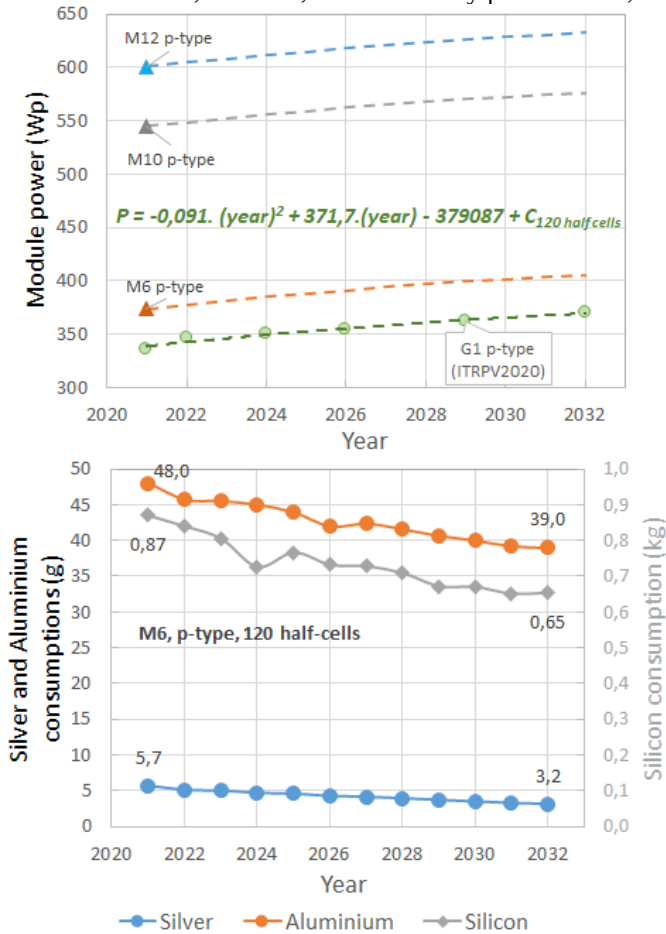


Fig. 3 – For a module of 120 half-cells: (Top) rebuilt data for module installed capacity depending on the cell size and time (Down) corresponding material consumption for an unframed module composed of M6 p-type cells.

data were collected from [14]. This includes a set rate for material recycling, but not the use of recycled materials.

### 2.2.2. Deployment scenarios

With respect to Fig. 2, the deployment strategy corresponds to the number of panels installed per year over a period of time. This can be likened to the company's planning for future production. In this paper, a long-term vision on a national scale was chosen by selecting two mid-range of the six RTE scenarios, differing in installed photovoltaic capacity. RTE details the scenarios in greater detail (see [8]). The aim is to exemplify the diversity of possible strategies to reach carbon neutrality in 2050. The two selected scenarios are as follows:

- Scenario **N03**: 13% of the French electricity production from PV; 70 GW of installed capacity in 2050.

- Scenario **M23**: 22% of the French electricity production from PV; 125 GW of installed capacity in 2050.

Considering that all PV panels have a lifespan of 30 years, Fig. 4 shows the resulting annual needs for PV capacity installation between 2020 and 2051 by following these two scenarios. It will be divided by the unitary power capacity (cf. Fig. 3) to define the number of needed modules and parametrize the LCI for both scenarios. Regarding the EoL stage, RTE does not provide specific assumptions; we therefore considered quantities of broken PV systems from 2020 to 2030 from [15] and extrapolated with RTE scenarios until 2050.

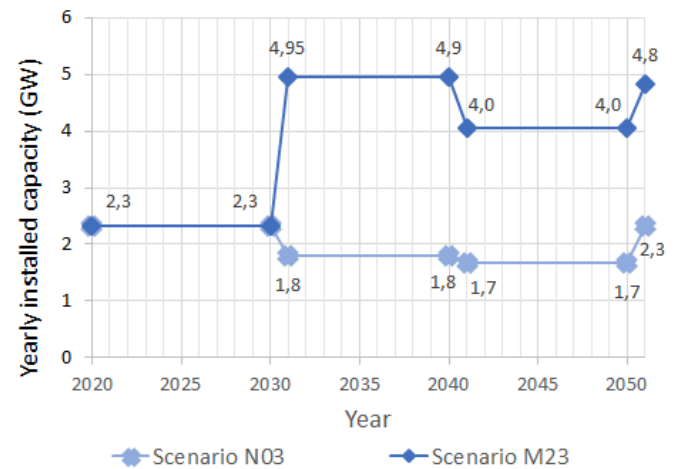


Fig. 4 – Yearly installed capacity of PV systems in France following two RTE scenarios, N03 and M23, assuming a constant lifetime of 30 years for PV panels.

### 2.2.3. Socio-technical context

The socio-technical context refers to all the required hypotheses to be specified to consider the evolutions of the background system of the study. It includes both technical aspects (*e.g.*, improvement of techniques, energy decarbonization) and socio-economic aspects (*e.g.*, habits and customs, markets and substitutions of uses, investments) that ultimately influence the results of the LCIA. This significant number of assumptions can be a barrier to developing a forward-looking (*i.e.*, prospective) approach from scratch. It is also possible to draw hypotheses on existing scenarios. In our case, we will use the scenarios “Shared Socioeconomic Pathways” (SSP), notably used by the IPCC in IAM models, and integrated into PREMISE to provide prospective LCIs [9]. These scenarios are parametrized considering two elements:

- the type of policies at the global scale regarding socio-economic challenges for mitigation and adaptation to climate change. Five types of SSP are identified. The SSP5, called “fossil fueled development” implies intense mitigation challenges. Conversely, the SSP4, titled

“inequality”, mainly sets challenges for adaptation as it considers no particular compensation mechanisms for the fact that different populations are not affected equally. The SSP3 (“regional rivalry”) can be seen as the worst case, implying significant socio-economic challenges for mitigation and adaptation. SSP1 (“sustainability”) implies low socio-technical challenges as human societies structure themselves efficiently to deal with mitigation and adaptation to climate change. Finally, SSP2 (“middle of the road”) is a trade-off of the other scenarios.

- Global warming mitigation targets, *e.g.*, 1.9, 2.6, 3.5, 6.0° C. Given that some of these targets might be unlikely to reach according to the type of SSP (*e.g.*, SSP3-1.9°C), in this paper, results are presented taking the scenario SSP2-base, equivalent to 3.5°C of global warming.

#### 2.2.4. Absolute environmental sustainability paradigm

As can be deduced from previous temporal representations and recommended in [2], the life cycle inventory must be identified as a flow per unit of time to be compared with environmental limits. Similarly, the absolute limits must be computed in a unit comparable to the life cycle impact assessment. Lastly, it is necessary to define a Share of the global SOS (SoSOS) for the studied system, here, the entire PV deployment in France. In our case, this local environmental limit is partly based on the “national low carbon strategy” voted in 2015 by the French government to respect the Paris Agreements and reach carbon neutrality in 2050. Consequently, it plans to decrease carbon budgets between 2015 and 2050 for France, divided by the industrial sector, including the energy sector. This corresponds to the factors “%<sub>A</sub>” and “%<sub>B</sub>” of the definition of SoSOS, as follows:

$$\text{SoSOS}^i(t) = \text{SOS} \cdot \%_A \cdot \underbrace{\%_B(t)}_{\downarrow} \cdot \underbrace{\%_C^i(t)}_{\uparrow} \quad (1)$$

with %<sub>A</sub> the ratio of the French population to the global population, assumed constant, %<sub>B</sub>(*t*) the ratio of the energy sector to the French industry, “*i*” the chosen deployment scenario (M23 or N03), and %<sub>C</sub><sup>*i*</sup>(*t*) the ratio of the PV installed capacity to the total French power capacity for a set of deployment scenarios. Two SoSOS are obtained based on the two deployment scenarios considered. Additionally, since the coefficients evolve over time, so does the resulting SoSOS (*cf.* subsection 2.3). The definition principle is based on climate change policies but can be transposed onto other environmental indicators, provided a global carrying capacity is defined. Attention should be paid to “compensation” assumptions in climate policies and potentially with “material depletion” and recycling but are not allowed for other indicators such as freshwater eutrophication.

#### 2.2.5. Upscaling scenarios

As illustrated in Fig. 1, the environmental upscaling assessment relies on designing one or several upscaling scenarios, combining sets of design parameters (*i.e.*, technology configuration), a deployment strategy, a socio-technical context modelling and a corresponding SoSOS. It brings about upscaling scenarios to be tested. Only one scenario is presented in this paper among the 16 possible with the considered technology and deployment scenarios: the one corresponding to PV panels upscaling, including cell-size M6 with half-cells, following a M23 RTE scenario in a SSP2-Base context scenario. Once again, this research paper focuses on the feasibility of the method and less on the exhaustivity of the analysis. An exploratory approach would instead use more scenario management methodology such as [16] to group assumptions and diminish accurately the possibilities. Explore extreme cases of socio-technical context (SSP1-1.5°C versus SSP3-7°C) can be accurate options. Similarly, it may be fruitful to custom directly into PREMISE the preregistered scenarios with additional data or different assumptions and implement the interaction between the upscaling with the background data modelling (*e.g.*, French electricity mix changes). However, it implies extra expertise on the part of the design team.

#### 2.3. Step 5: treatment and interpretations of results

This step of the EAU methodology consists of confronting a technology configuration’s environmental aspects with a corresponding SoSOS and comparing the scenarios to identify one or more that are environmentally sustainable. As an illustration, Fig. 5 represents results associated with the formalism of Fig. 2 applied to climate change indicator. As a reminder, this represents the potential environmental impacts, here CO<sub>2</sub> equivalent emissions, for the yearly cumulated lifecycle stage for the necessary quantity of PV panels to supply the need defined in an RTE scenario between 2020 and 2050. In that scenario, using a simplified model, the upscaling of PV systems can be considered environmentally sustainable until 2045 as the sum of the cumulated greenhouse gas emissions (bars) is below the SoSOS curve (M23 blue curve). Emissions are predominant in the MPI stage (purple) all over the run, increasing proportionally to the number of installed PV systems for the “Use and maintenance” (orange) phase and are progressively negligible compared to other stages for the EoL stage until 2050. This latest point is consistent before 2050 but potentially underestimated because it is assumed that the first installed panels have not yet reached the end of their lifecycle in 2050. The effect of continuous technology improvement modelling (in the foreground and background systems) is hardly visible until 2030, when the simulated installed capacity rises sharply, consequently increasing CO<sub>2</sub> eq emissions after 2030, but not directly proportionally to the installed capacity increase.

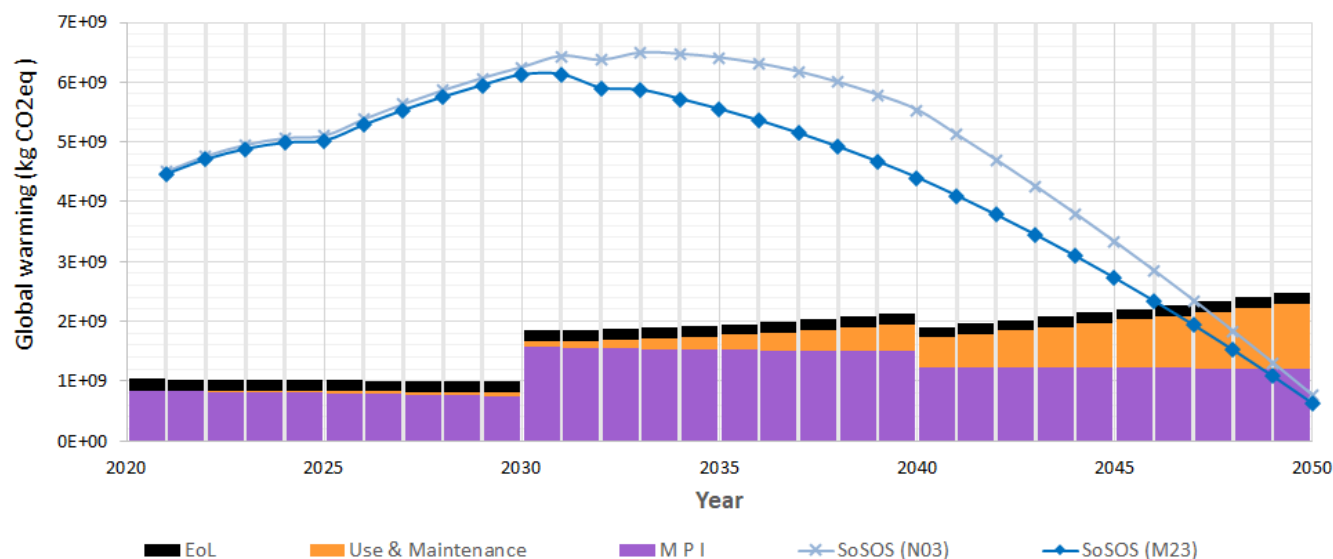


Fig. 5 – SoSOS/Carbon budgets (blue curves) and results of LCIA for the upscaling scenario M6/half cells - M23-SSP2-base.

### 3. Discussion: PV modelling limits and ecodesign practice

This paper provides a proof of concept for the data collection and modelling practices relative to the upscaling environmental assessment, to support the design teams for decision making. A PV designer aiming at the same “upscaling goal” as presented in step 1 in subsection 2.1, would have refined the technical assumptions to turn it into a robust case study. It is accessible through PV specialist expertises with industrial trends [17] and updated LCA models (*e.g.*, [18]). However, it is crucial to adopt a systemic approach: the technical considerations of the studied system interact with other industrial phenomena that ultimately influence the environmental impacts. That is why “deployment strategy” has to be defined with the technical design as they interact via the study perimeter. For the PV case, BOS designs, including power conversion systems, strongly depend on the type of installation. Typical designer concerns will be: precisising these characteristics would imply defining the targeted market and therefore the deployment strategy (*e.g.*, 10% of RTE scenario). Same reasoning goes for energy storage, and adaptation to the distribution network depends on local technical conditions and type of installations. Furthermore, increasing power capacity for PV panels would entail adapting the associated power devices and potentially worsening the resulting environmental impacts. This may illustrate a classic burden-shifting due to design optimization without a systemic and multi-criteria approach [19]. Thus, trade-off stands on a multi-stage analysis, as presented in Fig. 5, but also on a multicriteria assessment, and following sensitivity analysis in regard to the parameters chosen. Integrating at least material consumption and

freshwater eutrophication indicators is necessary in this study, due to the electronics involved. More broadly, environmentally assessing an upscaling in a design context supposes challenging different expertise from the design teams (technical and lifecycle engineering, company management, temporal risk analysis, standards, design guidelines) about the environmental benefits and burden of any technical improvement suggestion.

### 4. Conclusion

This paper illustrates the Environmental Assessment for Upscaling (EAU) methodology developed in previous research, through a comprehensive case study based on the photovoltaic sector. The six steps are applied with a focus on the third step, detailing the modelling approach dealing with the upscaling of a technology, that constitute a challenging step for the design team. Several modelling assumptions for photovoltaic product design and data have been chosen as examples. This case study exemplifies the EAU method output on a simplified model, given for an attributional prospective, absolute LCA with a partial dynamic inventory, computed to assess the environmental sustainability of the upscaling of a photovoltaic technology regarding climate change. This illustration highlights the existing difficulties designers face in such a process, the type of data computing required to provide practicable results, and the opportunity to strengthen the EAU models in research.

### Acknowledgements

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### 8.3 Article A - Apport 7 - Recommandations pour les non-experts pour le choix d'indicateurs de criticité (approfondissement de l'archétype 3)

#### Stratégie de publication pour l'Article A

L'**Article A** a été soumis une première fois au Journal *Resources* le 31 Aout 2023 et rejeté le 21 Mars 2024 après deux révisions majeures. Ce journal avait été visé en tant que journal d'expert en criticité des matières premières (h-index 54, impact factor 3.3, Q1 sur la discipline *Nature and Landscape Conservation*). Le démarche actuelle est de positionner la grille d'analyse proposée pour des équipes de conception débutants sur la criticité des matières premières, comme recommandé par Hofmann et al. (2018) [73]. Le journal *Sustainable Materials and Technologies* ou la conférence internationale *Smart Materials and Nanotechnology in Engineering* sont ainsi envisagés pour la soumission prochaine du manuscrit.

L'**Article A** s'intitule « *A review of the application of the European Commission Raw Material Criticality Assessment Methodology : Towards a comprehensive framework for criticality assessments decision-making* » et constitue les **pages 194 à 221** de la thèse.

#### Abstract

*In the context of the energy transition, the demand for strategic raw materials is expected to escalate. Consequently, an upsurge in literature about material criticality management has emerged in recent years. Various assessment methodologies, including those defined by the scientific community or governmental institutions like the European Commission (EC), have been devised for this purpose. However, these methods are usually developed and applied by material criticality experts. This paper examines therefore the application of criticality assessment methodologies by non-experts such as researchers, engineers, and designers with a specific focus on the EC's approach. A state of the art on this methodology is provided to clarify its goal, scope and evolution since 2014. To quantify the adoption of criticality assessment by non-expert researchers, citation patterns and case studies applying the EC's methodology have been compiled. Six case studies have emerged from the literature review process. Then, to qualify the adoption of the EC's approach, a framework is proposed with key characteristics from the criticality literature to help non-expert researchers in clarifying the alignment between the methodology's goal and their own. This framework was applied to the*

*EC's methodology. It shows that researchers often adjust the EC's methodology to correspond to their specific constraints. Finally, the proposed framework is discussed as a mean to help non-expert researchers in selecting the most appropriate criticality assessment method for their specific needs.*

## ARTICLE A - A review of the application of the European Commission Raw Material Criticality Assessment Methodology: Towards a comprehensive framework for criticality assessments decision-making.

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### Abstract

In the context of the energy transition, the demand for strategic raw materials is expected to escalate. Consequently, an upsurge in literature about material criticality management has emerged in recent years. Various assessment methodologies, including those defined by the scientific community or governmental institutions like the European Commission (EC), have been devised for this purpose. However, these methods are usually developed and applied by material criticality experts. This paper examines therefore the application of criticality assessment methodologies by non-experts such as researchers, engineers, and designers with a specific focus on the EC's approach. A state of the art on this methodology is provided to clarify its goal, scope and evolution since 2014. To quantify the adoption of criticality assessment by non-expert researchers, citation patterns and case studies applying the EC's methodology have been compiled. Six case studies have emerged from the literature review process. Then, to qualify the adoption of the EC's approach, a framework is proposed with key characteristics from the criticality literature to help non-expert researchers in clarifying the alignment between the methodology's goal and their own. This framework was applied to the EC's methodology. It shows that researchers often adjust the EC's methodology to correspond to their specific constraints. Finally, the proposed framework is discussed as a mean to help non-expert researchers in selecting the most appropriate criticality assessment method for their specific needs.

Keywords: Criticality assessment methodology, European Commission Raw Material Criticality, Decision-aid methodology

## Introduction

### 0.1 Criticality definitions and assessment methodologies

The increasing need for raw materials for the industrial and the economic development of countries has piqued their interest in the physical aspect of economic activities, mainly the economical use of materials, recognized as an essential component of an organization's sustainable development strategy [1]. Changes in technology, becoming outdated or replaced by alternatives, can also have a similar impact on how important certain materials are perceived to be, which in turn affects their level of criticality [2]. Among the materials that have become increasingly critical are raw materials, which are essential to the manufacturing of a range of products, from electronics to construction materials. As the demand for these critical raw materials increases, their scarcity and vulnerability to supply chain disruptions have become pressing issues. Raw material criticality has numerous definitions in the literature. Graedel and Nuss (2014) suggest a definition of criticality as being 'the quality, state or degree of being of the highest importance' [3], D. Schrijvers *et al.*, (2020) define it as "the field of study that evaluates the economic and technical dependency on a certain material, as well as the probability of supply disruptions, for a defined stakeholder group within a certain time frame." [4]. While Gleich *et al.*, (2013), characterize criticality as 'the extent of current and future risks associated with a certain metal [5]. Graedel *et al.*, (2012) define it as a measure of the economic risk arising from its utilization (incl. production, use, and end-of-life) for a specific consumer over a certain period. A consumer can be anything from a single company or technology, to a national or multinational economy [6]. Mancini *et al.*, (2015) argue that criticality cannot be



measured at a global level, because it is rather related to an economic or political system or entity [7]. According to M. Frenzel (2017), this variability in definitions makes it difficult to give one standard definition to the concept of raw material criticality [8], paired with the different assessment methods utilized in addition to the ambiguity of the definitions. Regardless of the terminology or measurement metrics used, two factors are usually viewed as critical for identifying CRMs: supply risk potential (probability) and a system's vulnerability (consequence) to a prospective supply shortfall [6], [9]. In 2021, McNulti and Jowitt state that the diversity of definitions regarding the criticality of certain materials is evident in the many reports that evaluate their criticality from the perspective or as they named it "the viewpoint" of different organizations. They gave an example of the European Commission (EC) that considers certain elements like boron and phosphorus as critical, but other governments and organizations do not share the same view [10]. Klinglmair *et al.* (2013) suggests that the notion of criticality is relative, and the approaches used to evaluate CRMs must address the underlying question: critical from whose perspective? ([11, 12]).

For example, the materials that are critical to one company which requires them to make its products are not necessarily the same as those critical to a certain region or country [13]. There are many criticality methods and indicators emerging from different disciplines (Yale [6], ESSENZ [14], EC [15], GeopolRisk [16]...) in addition, new ones are created regularly.

## 0.2 Criticality assessment adoption by non-expert researchers

Taking criticality into account in design communities is a major challenge. From the point of view of product or material designers, criticality is considered outside their field of expertise. It is seen as a geopolitical, economic and environmental analysis [17]. Phenomena over which designers believe they have no control. As a result, little attention is paid to criticality. The application of an analysis method is rare in a design context, as we shall see in this article [18]. Instead, criticality is identified by designers as a list of elements, mainly produced by governmental institutions such as the European Commission. In other words, the process involved in producing this list is not accessible to non-experts. This results in method choices that are often inadequate to the needs of criticality characterization. Non-experts lack the tools to identify whether a method corresponds to their needs in terms of study scope, for example. Additionally, choosing the appropriate method for criticality assessment may become a challenge, as it needs to have characteristics that align with the study's requirements. The wide range of methodologies for criticality assessment, primarily devised by scientific communities as outlined above, engenders a conundrum for non-experts/practitioners. Designers, in particular, may find themselves grappling with the selection of an appropriate method tailored to their specific objectives, given the absence of structured guidance in this domain. This lacuna underscores a significant gap in extant literature. Our study endeavors to address this gap by proffering a decision support tool designed to aid stakeholders, including non-experts in criticality assessment, in navigating the array of available methodologies effectively.

To deal with this gap, we decided to focus on one specific methodology, namely, the European Commission's criticality assessment methodology (EC RMC). This method was developed for assessing the critical raw materials to the European Union in 2010, particularly critical metals, and updated in 2017 to address methodological issues (e.g. economic allocation for industrial sectors or EU raw material sourcing). The appropriation of this major update and more broadly of the EC RMC methodology by designers and engineers raises questions as the EC reports applying it are published every three years and widely cited. In the 2023 report, the concept of strategic minerals is introduced, it is assessed based on the importance of a raw material for the digital and green transition in addition to space and defence applications [19]. Therefore, energy or material researchers and green technology designers are prompted to appropriate the criticality methodologies. Most papers studying critical raw materials or material criticality reference the EC's raw material criticality work [8], [20],[21], [22], but its methodology can sometimes be used in a different context than intended. This can lead to readjusting the original method to better answer the question asked.

The focus on the EC RMC is justified by its widespread recognition in engineering and design communities, establishing itself as one of the most cited approaches for criticality assessment. Its open-source nature, comprehensive data sources, and well-explained calculation examples make it an accessible and transparent



method for researchers and engineers alike [23, 24]. By delving into this well-established method, our study aims to provide valuable insights and comparisons, facilitating informed decision-making and advancing the discourse on raw material criticality assessment.

This paper intends therefore to address two research questions: *"How is the EC RMC used/adopted in the scientific literature?"* (RQ1) and *"To what extent does the current method meet the different needs of decision-makers (e.g., researchers/states/industry) for estimating criticality?"* (RQ2). Our work aims to identify the applications of EC RMC in the literature as case studies to characterise the criticality assessment needs of non-expert researchers. The investigation of these applications reveals key characteristics to enable decision-makers, such as researchers and designers, to know whether or not to use the EC RMC methodology. Through our research, we aim to offer a practical tool tailored for non-experts to navigate the landscape of existing methods for assessing material criticality. Drawing insights from diverse sources, we have developed a framework designed to simplify the evaluation process. While our analysis predominantly focuses on the EC RMC method, the framework we propose is designed to be adaptable to various criticality assessment methods.

Section 2 presents an overview of the EC RMC methodology and provide the basics for understanding both its versions (2010 and 2017) and then analyze its application and interpretation in the literature. Section 3 details the literature review process carried out to identify references referring to the EC RMC methodology. Section 4, to answer the two research questions presents the results in two parts: subsection 4.1 presents a quantification of the authors applying the EC RMC methodology to answer RQ1. Subsection 4.2 characterizes the adoption of the EC RMC methodology. In other words, this is a qualification of the adoption of the EC RMC method. It includes 1) the proposition of a framework to study the consistency of the EC methodology application with each stated objective, and 2) the application of the proposed framework to the papers identified in section 4.1. It brought about some recommendations for non-expert researchers. Section 5 discusses the defined characteristics of criticality methods and paves the way for the designer's appropriation of criticality assessment methods. Finally, section 6 concludes on the importance of considering method appropriateness and compatibility for effective and relevant criticality assessments.

## 1 the EC RMC assessment methodology in a nutshell

This section presents the key features and evolutions of the EC RMC assessment methodology. The EC RMC assessment methodology has been presented in three main versions since 2010: the original version was published in 2010 and applied in 2011 in an EC report [25]. Then, an updated version was delivered in 2014 [26] and finally, a revised version was published and applied in 2017 [27], then 2020 [28] and 2023 [19]. In the following subsection, we propose to clarify the latest version of the EC-RMC assessment methodology. A retrospective of the three previous versions (2010, 2014 and 2017) and a description for each indicators in detail is available in the appendix 4.2.

### 1.1 Criticality criteria

The EC-RMC assessment hinges on two indicators primary indicators: the Economic Importance (EI) and the Supply Risk (SR) for the European economy. A major point is that the way criticality was characterized in the 2010 version did not allow for sectorialization. This means that criticality was not considered dependent on the industrial sector, but aggregated at the highest economic level. Put another way, the 2017 update enables users to consider criticality at the scale of industrial sectors. The 2010 version also included an environmental dimension, in the sense of limits on access to mineral resources. This dimension was incorporated into the other parameters in 2017 (see detail in appendix 2). In addition and since 2010, the methodology enables users to assess continuous criticality, however, authors maintained a Boolean definition of criticality: a material is considered critical compared to thresholds on the two criteria. Figure 1 illustrates the classic representation in EC reports with the economic importance and the supply risk on a matrix (see figure 1 part a)). A critical raw material (CRM) is consequently identified when its economic importance and its supply risk values are higher than the defined thresholds (Cf. red zone). Otherwise, the raw material is deemed not critical (Cf. blue zones).

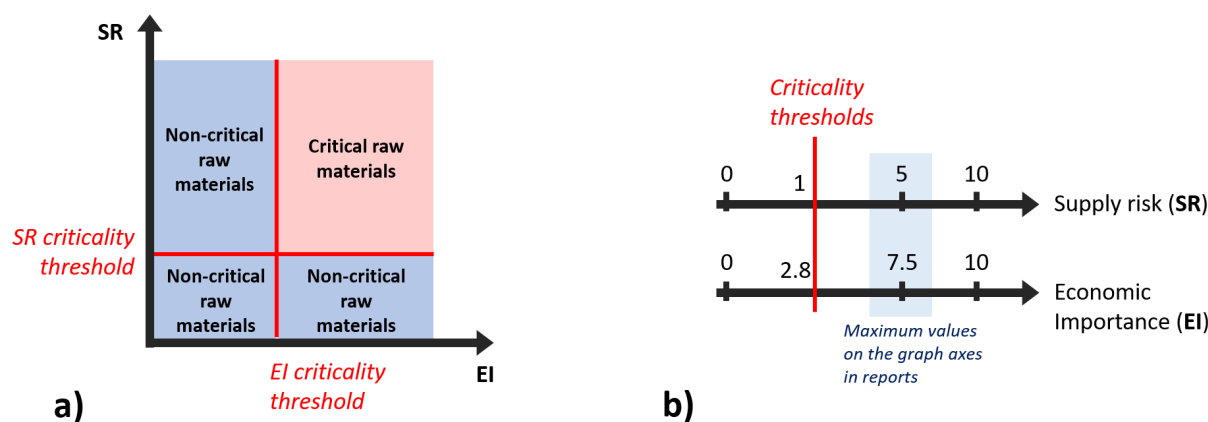


Figure 1: Usual representation associated with the updated EC RMC methodology (a) and synthesis of threshold values (b), published in 2017.

The SR and EI scale remained from 0 to 10 [29]. However, the criticality thresholds has been adjusted between 2014 and 2017 to maintain comparability with the previous assessments. The Supply Risk threshold remained at 1, while the Economic Importance threshold was lowered from 5.0 to 2.8 in 2017 [29]. Part b) of figure 1 synthesizes the range values and the current thresholds. As shown in this representation, if the economic importance and the supply risk are greater than their respective thresholds, the raw material is critical. The SR and EI scale remained from 0 to 10 [29].

The ongoing periodic assessment of critical materials, coupled with the evaluation of the criticality assessment methodology, has yielded valuable insights. Notably, certain materials have retained their critical status consistently in both 2010 and 2017 assessments (e.g. Tantalum in 2010 ( $EI = 7.4$ ,  $SR_{WGI} = 1.1$ ), in 2017 ( $EI = 3.9$ ,  $SR = 1$ )). Additionally, there are materials that were deemed critical in 2010 but no longer hold that status in the 2017 evaluation (e.g. Vanadium in 2010 ( $EI = 1.7$ ,  $SR = 0.7$ ), in 2017 ( $EI = 3.7$ ,  $SR = 1.6$ )). Conversely, some materials have gained criticality in the 2017 assessment despite not being identified as critical in 2010 (e.g. Baryte in 2010 ( $EI = 3.7$ ,  $SR = 1.7$ ), in 2017 ( $EI = 2.9$ ,  $SR = 1.6$ ))[30]. This nuanced analysis provides a comprehensive understanding of the dynamic nature of critical material assessments over time.

The 2020 publication of the EC RMC study introduces an alternative approach for examining the discrepancies between the 2017 and 2020 results. Rather than employing the traditional binary analysis of categorizing as critical or non-critical, a graphical representation has been incorporated to demonstrate the extent of increased or decreased criticality (or non-criticality) for each element.

While the EC methodology has been criticized for its static nature, providing only a snapshot of supply-demand equilibrium [31, 32], and for potentially overlooking key factors impacting criticality, such as raw material type and environmental risk [24], the aim of this study is not to evaluate the methodology's relevance but rather to explore its adoption and application in non-expert practices.

## 2 Materials and Methods

To assess the adoption of criticality methods by decision-makers, a literature review was conducted. The aim of this literature review was initially to collect the studies that refer to the EC RMC methodology, focusing on the ones that apply the EC RMC methodology and article reviews about critical raw materials or raw material criticality. In addition, case studies that cite the EC criticality topic and apply other methods were included in the review. The papers that do not address these topics have been excluded from the review. The literature review process is depicted in the figure 2. It presents the steps of filtering: first, keyword combinations have

been applied as requests on Web of Science, Google Scholar and Science Direct: ['Raw material criticality' OR 'critical raw materials' AND 'Metals' AND 'European commission' AND 'Criticality Assessment']. The extracted documents are filtered to be research articles and review articles. In parallel, publications that directly cite the EC RMC methodology reports have been selected in order to evaluate the significance and recognition of the methodology across different periods, providing insights into its enduring relevance and influence within the field of raw material criticality assessment.

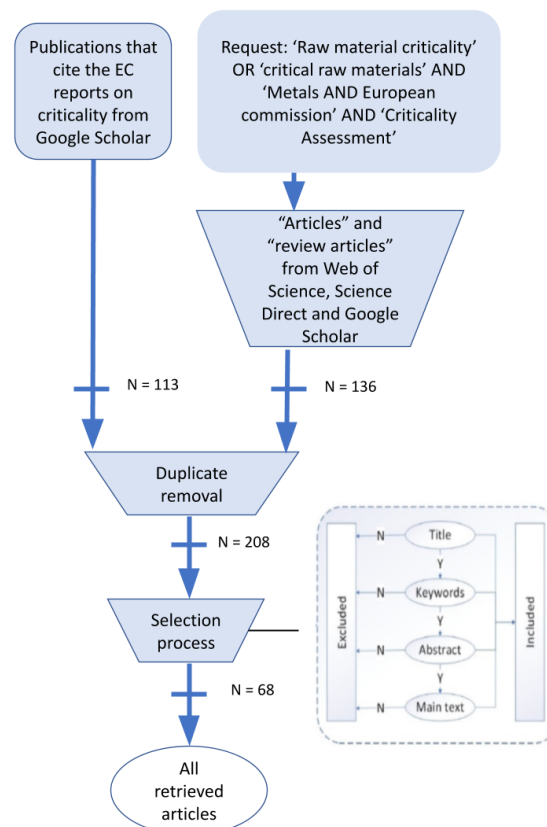


Figure 2: Literature review process. RMC stands for Raw Material Criticality.

This selection was carried out using the Google Scholar tool to identify citations to a particular reference. Additionally, it allows for an examination of trends in citation rates, revealing shifts in emphasis and interest over time. Two additional filtering steps are applied to this initial corpus of 249 articles: Removing duplicates reduced the number of items to 208. Then, the resulting corpus has been studied in detail based on the title relevance to the subject of raw material criticality, the keywords containing the keyword combination researched, the abstract including methods or assessments of critical raw materials, and then the text screening consisted of choosing papers that apply another raw material criticality method and the ones that apply the EC RMC method. The resulting 68 relevant papers include the studies that cover the RMC topic, either by citing the EC RMC reports, analyzing criticality methods, including the EC RMC method, or applying the EC RMC method on a case study.

Figure 3 details the analysis processes applied to the 68 retrieved articles and the associated results of the article. An Analysis of the distribution and citations over time is applied to the corpus "Articles applying an RMC method" to answer the research question (RQ1) *"How is the EC's raw material criticality methodology used in the literature?"*. This brings the result 1, presented as a quantification of the adoption of the EC RMC

method. To answer the second research question(RQ2) *“For what purposes is the EC’s raw material criticality methodology used in the literature?”*, a review of key criticality characteristics has been carried out. Then a methodological framework has been developed to characterize the purpose of users of a criticality assessment methodology (result 2a). Finally, this framework has been applied to 6 case studies applying the EC RMC methodology in its original form or a modified form. This results in the qualification of the EC RMC method application in the literature (result 2b).

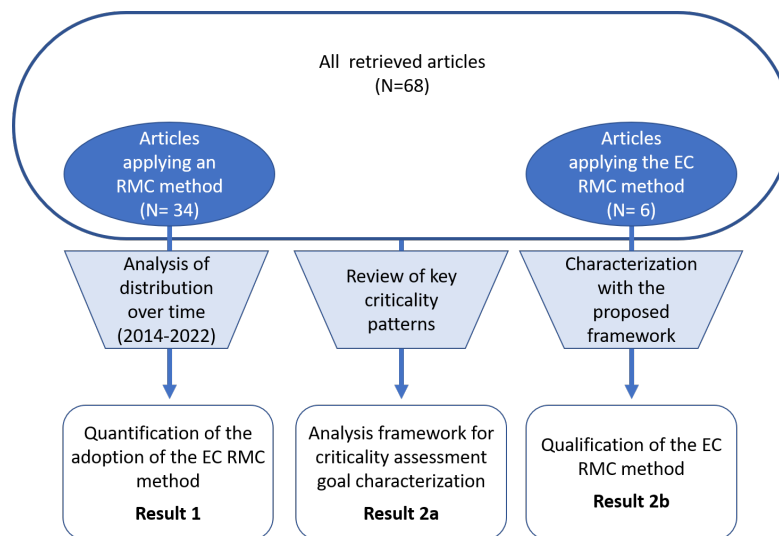


Figure 3: Analysis processes applied to the retrieved articles and corresponding results of the article.

Figure 3 outlines the sequential steps of our analysis. It starts with retrieving articles on raw material criticality (RMC), followed by reviewing key patterns and establishing an analysis framework. The figure then illustrates two primary results: Result 1 quantifies the adoption of RMC methods, focusing on the EC RMC method, while Result 2a examines the distribution of articles applying RMC methods over time. Result 2b further evaluates the EC RMC method using our proposed framework. Essentially, Figure 4 provides a clear roadmap of our research approach, guiding the exploration of RMC assessment methodologies and their evolution.

### 3 Results

Based on the clarification of the EC RMC methodology provided in section 1 and the fact that several versions coexist in the literature (mainly 2010 and 2017 [29] versions), this section presents an analysis of its use and adoption in the scientific literature. These results are intended for decision-makers, engineers and researchers wishing to use criticality indicators in their work, particularly in the design sciences.

#### 3.1 An examination of the citation patterns of the EC RMC methodology in literature

After the updated version of the EC RMC methodology was published [29], many articles on the assessment of CRMs were published. To address the first research question, the literature review directs our attention to the collection of articles that cited the EC RMC topic but may or may not have applied its methodology. This contributes to identifying orders of magnitude of the ratio of citation/application of a widely spread methodology.

### 3.1.1 Citations of the method

As a result of our literature review, the EC RMC topic is cited in all the papers that discuss raw material criticality or supply risk and critical raw materials. According to Google Scholar, the number of papers that cite the 2010 EC RMC methodological report [33] is 39, 21 cite the 2014 "Report on critical raw materials for the EU" [34], whilst 54 sources cite the 2017 EC RMC methodological report [29], and 19 cite the 2017 guidelines report [15].

The increasing citations from the 2010 report to the 2017 reports suggest a growing interest in and reliance on more recent EC methodologies and guidelines, reflecting an evolving landscape of research priorities and methodologies in raw material criticality and supply risk assessment. Particularly noteworthy is the high number of citations for the 2017 EC RMC methodological report.

From the selected articles in this study, 6 out of 68 (which can be found in supplementary data SD1) applied the methods to their studies, while the rest cited the EC RMC topic as a reference. Figure 4 presents the distribution of methodologies used in the corpus of research papers where RMC assessments are performed. The category "New" refers to articles developing new methodologies to assess raw material criticality and apply it to the case study, while the category "Indicators" assesses CRMs using RMC indicators instead of a particular established method. Among the diverse array of approaches, the "Indicators" method stands out as the most frequently utilized, suggesting its prevalence in scholarly discourse. Additionally, the chart highlights the noteworthy representation of the "EC RMC & EC RMC adapted" method, indicating its significant role in the landscape of criticality assessments.

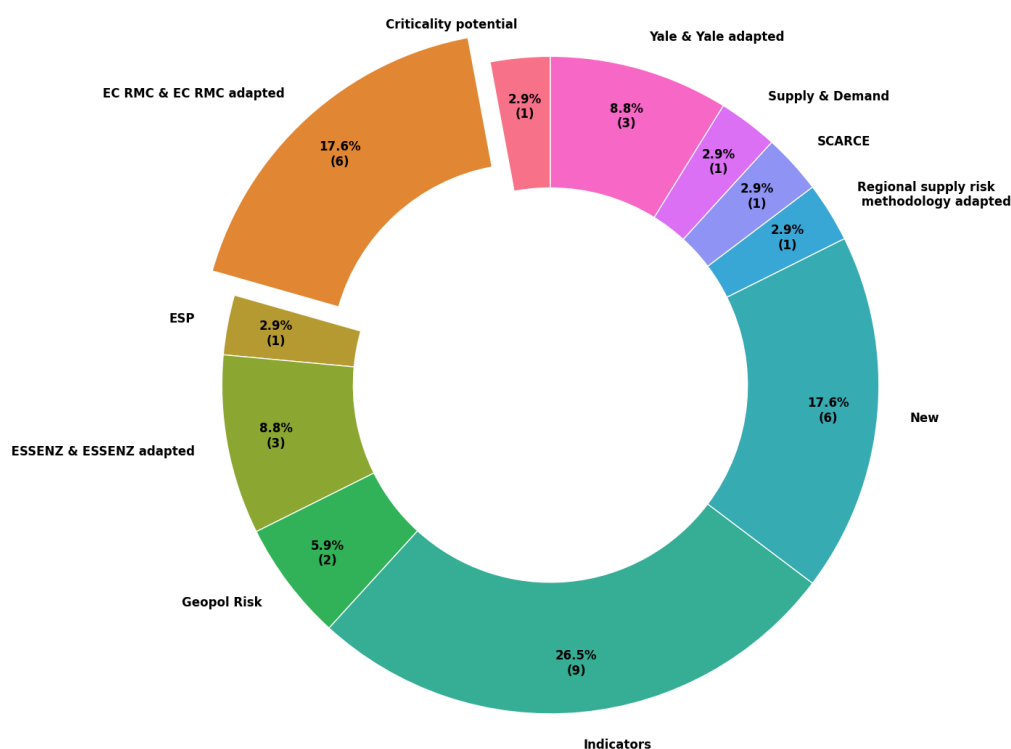


Figure 4: Distribution of the criticality assessment methodologies cited in conjunction with the EC-RMC methodology, in the selected case studies (34 papers analyzed, Supplementary data SD2).

According to figure 5, the EC RMC method has been used the most from 2019 until 2022, which means that it is still relevant in the literature. Furthermore, in figure 5, it is notable that new methods are still being

developed until 2022 despite the existence of criticality methods. This can reflect the need for methods or approaches that fit their study's characteristics and needs.

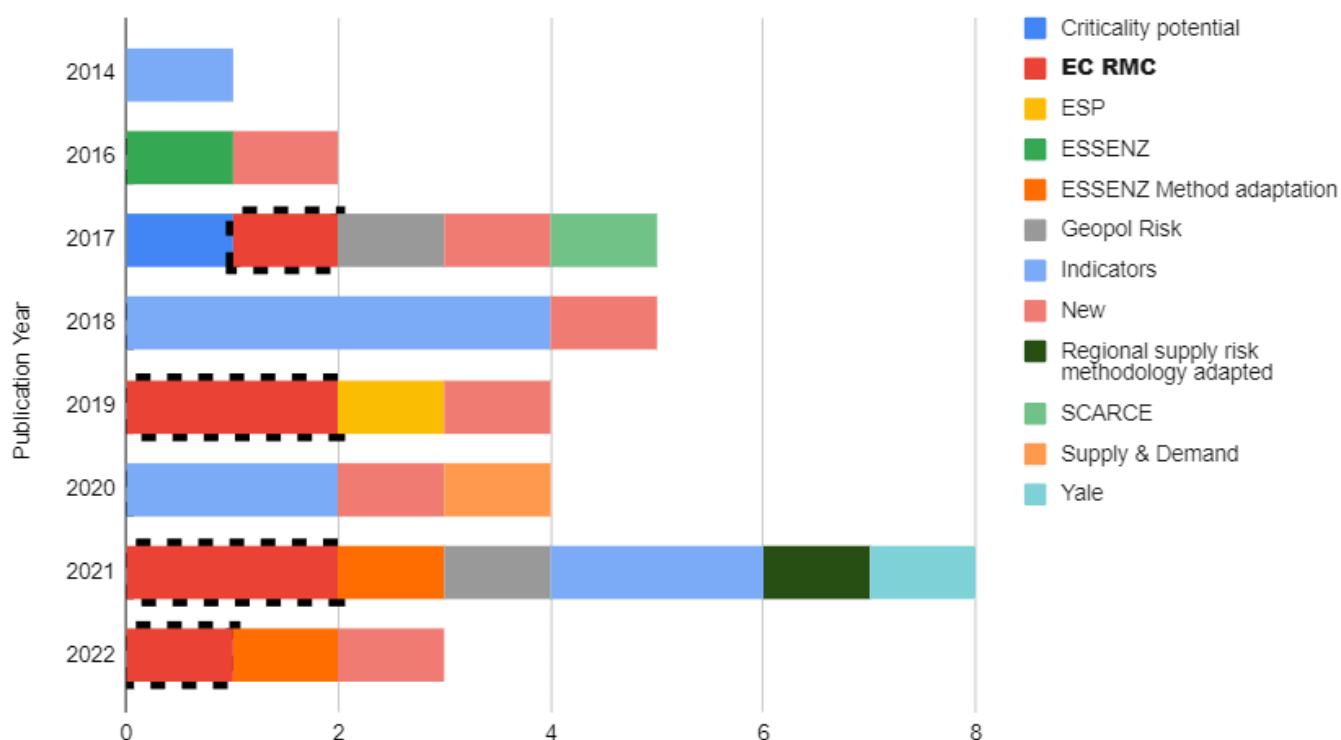


Figure 5: Number of retrieved articles applying a criticality method (i.e. case studies) over time between 2014 and 2022, (Supplementary data SD2)).

Finally, and as shown in figure 5, only 6 out of the 208 retrieved papers applied the EC RMC methodology between 2017 and 2022 (the dotted bars). This contributes to highlighting the difficulties of adopting the criticality assessment methodologies, even though they are widely spread and known, especially for the EC RMC method.

Table 1 compiles the 6 papers assessed in this review that mentioned the EC RMC methodology and applied it (colored in red in figure 5). For each case study, the version of the method (second column) and the year of publication (third column) are given. Column four presents the sources of these case studies. Remark that two papers apply the obsolete method (2014); one published in 2017 and the other in 2019. The reasons for the choice of the method instead of the updated version are unknown. For the first one, it may be because it was published in the same year as the report, which makes it probable that the author was not aware of or able to access the update.



Table 1: The selected case studies of criticality assessments applying the EC CRM method.

| Study                                                                                                                            | EC RMC version | Year | Source |
|----------------------------------------------------------------------------------------------------------------------------------|----------------|------|--------|
| Security of mineral resources: A new framework for quantitative assessment of criticality                                        | 2014           | 2017 | [35]   |
| Material flow analysis on critical raw materials of lithium-ion batteries in China                                               | 2017           | 2019 | [36]   |
| Materials selection in a critical raw materials perspective                                                                      | 2014           | 2019 | [18]   |
| Criticality assessment of metal resources in China                                                                               | 2017           | 2021 | [37]   |
| Evaluating critical metals contained in spintronic memory with a particular focus on Pt substitution for improved sustainability | 2017           | 2021 | [38]   |
| A comparative framework for criticality assessment of strategic raw materials in Turkey (Preprint)                               | 2017           | 2022 | [39]   |

Thus, to answer to the RQ1, the EC RMC methodology is one of the most cited and widely spread in the studied scientific literature concerning RMC assessment. Citations are mainly about the updated version (2017) but a large part of the sorted articles refers to older version which betrays a lack of awareness of the method. (see figure 3). Moreover, the adoption of the EC RMC methodology is only detected in a small percentage of the retrieved papers (3%), and an even smaller proportion apply the updated version of the methodology (2017).

Out of the six papers that apply the EC RMC method, some have different objectives than those of the EU. It may be unclear what the characteristics of the EC RMC methodology are, which makes it necessary to define them.

To complete the quantitative adoption assessment of the EC RMC methodology, the next subsection aims at presenting a qualitative evaluation based on a proposed analysis framework and a comparison of the guidelines of a RMC method (here, the EC RMC method) with the objectives of case studies applying it.

### 3.2 Analysis of the adoption of the EC RMC methodology by decision-makers.

The objective of this subsection is to assess the potential discrepancy between the objective and the validity domain of available criticality assessment methodologies, here the EC RMC method, and the objectives of case studies applying them in the literature. This leads to use of the framework proposed in the previous section and to the identification of deviations and potential incompatibilities between these objectives.

#### 3.2.1 Characterization framework for criticality assessment method selection

To analyse the adoption of a criticality assessment method, we propose a characterisation framework to clarify the application condition related to the objective of the methodology. Users, based on this framework, can therefore identify whether or not these conditions fit their own assessment. This characterisation framework was designed by collecting the main characteristics present in the literature and synthesizing them into categories.

Several studies offer an overview of indicator selection for vulnerability (to the economy) [40] and supply risk [41], [42], and also a review of methods and data to assess material criticality [4]. And, as the more specific the characterization of the method is, the better method choice would be made, a collection of key characteristics of the methods would aid decision makers to select the right method for their study and limit the readjustment

of the existing methods and thus, increasing transparency in assessments making comparability possible. The characteristics, gathered from various sources including those mentioned earlier, will be discussed in the next subsection, as depicted in table 2. The present characteristics are proposed for the EC RMC method as a framework for the analysis of the studies that applied this method and may have readjusted it or not to meet other requirements. Then, the identified version of the EC criticality assessment method is analyzed according to these characteristics. The presented characteristics serve as a suggested framework to elucidate the objective of a criticality study, enabling a comparison between the intended objective and the method employed in practice.

Some of these characteristics have been summarized from the literature. They are defined as follows :

#### Analysis context

- Material scope [42] : refers to the specific materials that are considered in the criticality assessment.
- Analysis type : refers to the specific discipline or field, such as engineering or economics.

#### Time dimension

- Time horizon [33] : It is the duration or period during which the analysis or decision is relevant.
- Time Frame [29] : It is a designated period that is used to measure the beginning and end of the criticality assessment.

#### Spatial dimension

- Entity at risk [4] : refers to the system that is exposed to the risks of raw material criticality.
- Geographical scope [40] : it is the extent or range of geographical locations or areas to which the criticality assessment applies.

#### Reproducibility

- Model availability : It represents the transparency of the model and its accessibility (e.g. dedicated website, publications etc.) [23],
- Data availability : It refers to the availability of the data sources.

Table 2: Proposed analysis framework to characterize a raw material criticality method.

| Category          | Characteristic          | Precision                                   |
|-------------------|-------------------------|---------------------------------------------|
| Analysis context  | Analysis type           | Attached to what expertise ?                |
|                   | Material scope [42]     | Individual elements, aggregated elements    |
| Spatial dimension | Entity at risk [4]      | Country, industry, corporate, product       |
|                   | Geographical scope [40] | Region, country, multi-countries, continent |
| Time dimension    | Time horizon [33]       | Retrospective or prospective                |
|                   | Time frame [29]         | Short, medium or long term                  |
| Reproducibility   | Model availability      | yes, no or use of proxy [23]                |
|                   | Data availability       |                                             |



These four categories could be completed by further work. However, this framework will enable us to criticize the use of EC CRM in literature and characterize any gap between the studied method's objective (i.e. the EC CRM objective) and the application's objective in case studies. (see section 3.4) in terms of context, spatial or time dimension, or reproducibility.

To illustrate the characterisation framework, some recommendations extracted from EC reports are provided. In the 2010 publication of the methodology, the specific time frame was not explicitly specified, but it was advised to conduct updates of the assessment every five years. It encompassed a time horizon spanning over 10 years [33]. For the version published in 2017, the data used in the method reflects the average for the past 5 years. It also proposes guidelines to follow in order to get more accurate results, by presenting a hierarchy of the data sources to be used ranging from high quality data (e.g. official statistical sources) to lower quality sources (e.g. data with very random updates) [29]. For example, it is recommended to use the supply risk method with actual supply to the European Union, only if the data is accessible and of high quality. And if not available, it is mentioned to utilize only global supply, as in the previous version of the method.

The analysis framework presented in this section is aimed at researchers who intend to align their need from a method with an existing method. This framework is applied to EC RMC method (2017) in the first row of table 4, and can be used more broadly to other methods as well to structure their purpose.

### 3.2.2 Analysis of case studies applying the EC RMC method with the proposed framework

The associated characterisation of the EC RMC method is presented in the first line of table 3. This serves as a reference against which the identified case studies will be compared.

Table 3, is used to define the characteristics of the six selected studies. In the first column, the study sources are listed, while the second column indicates the version of the EC RMC method employed in each study. If adaptations were made, the nature of these adaptations is described in column three, including modifications to the formula, incorporation of additional methods or indicators referred to as "completion," or no adaptations at all. the specific objectives of each study. If adaptations were made, the nature of these adaptations is described, including modifications to the formula, incorporation of additional methods or indicators referred to as "completion," or no adaptations at all. The fourth column states the specific objective of each study. The remaining columns of the table outline the specific characteristics associated with each study.

The analysis of the study's characteristics in relation to the EC RMC methodology is presented. The grey color is used to indicate misalignment with the method. No color signifies that the characteristics of the study align with the EC RMC's methodology, indicating no need for adaptations. This is the case for instance for the study of Yan *et al.*, [37].

On the other hand, a grey cell suggests a lack of alignment between the study's characteristics and the EC RMC's methodology. For instance, in the study by Song *et al.*, the entity at risk is limited to one industrial sector instead of encompassing all industrial sectors as required. To address this misalignment, certain studies adapt the method, as done in the article of Song *et al.*, while others do not explicitly specify any modifications.

In this illustration, it is notable that each study has a unique objective, but to answer whether it aligns with the EC RMC method, an analysis of the characteristics should be provided. Some papers, like [35], [39],[37] study the criticality of the raw materials to their respective countries, this aligns with the EC RMC's objective as it studies the criticality of raw materials to one geographical entity. Other papers like, [38], [36] study the criticality of raw materials used in a particular technology within a geographical entity, this does not align with the objective of the EC RMC method which is why we find the color grey, because its goal is to assess the raw materials to the EU market. This explains the readjustments made in the study of [36] as they modify the economic importance formula. Palomino *et al.*, did not state explicitly adjusting the method, even though they used it at a technological level [38]. As for Polat *et al.*, they incorporated other methods with the EC EMC method, which explains the use of predictive data in addition to historical data, the dynamic study, and the inclusion of other indicators [39].

For all the studies that assessed raw material criticality at the national level, they divided the economic importance by the GDP of their respective countries, except for Daw who use the same EI as the EU's for

geographical proximity, justifying it with the GDP values of France and the EU that are nearly equal. This study will not be examined further, as the suggestion it made for the adaptation of the supply risk were adopted in the new EC RMC method with the introduction of the import reliance [35]. Ferro and Bonollo opted for the 2010 version of the method rather than the newer 2017 version, but they didn't provide reasons for this choice. Furthermore, they adapted the method to suit their objective of evaluating the criticality of bike forks, aligning the material selection process with the method's intended purpose [18].

The requirement for readjustments in the methodology indicates two key aspects. Firstly, it signifies that the methodology may not align adequately with the scope and fundamental characteristics or criteria of the study. Secondly, it highlights the potential inflexibility of the EC RMC method, particularly in terms of sectorization for economic importance and at the entity level (such as technology or industry branch). Notably, the aspect that required the most adaptations was the entity level, indicating the need for modifications to ensure better alignment with the study's objectives. Furthermore, the economic importance considers all the applications of the raw material equally important, regarding the criticality of the material, for example, copper in this case will be of the same importance in the electronics industry as it is in bike manufacturing.

Some of these studies are transparent regarding the data they used and the changes they made, others not. None of these studies justified the use of this methodology.

The alignment between the analysis requirement and the application displayed by the color grey for some characteristics often led to the readjustment of the method in hand [36], or the use of other methods [39] to reach the study's objective.

Based on the comprehensive analysis of various elements, it is possible to derive and formalize specific rules. Firstly, the objective of the study involves evaluating the criticality of raw materials in the context of the EU economy, specifically pertaining to the entire economy of a single geographical entity. Secondly, the time horizon considered is prospective, indicating a future-oriented perspective. Thirdly, the geographical scope is limited to a single geographical entity. The time frame, however, is retrospective. Based on the findings of this analysis, adaptations to the method are recommended under the following circumstances: when the study's time frame is prospective, when the entity at risk is something other than the economy of a single geographical entity, when the material scope extends beyond chemical elements, when aspects other than economics, sustainability, and politics are involved, and when the study involves a dynamic analysis.

Grey cells represent nonalignment between EC RMC objective characteristics and case studies. It will be discussed if this nonalignment is an issue and if it presents interesting modification examples for appropriation of the method (in the light of the literature review).

Several observations can be made by analyzing the studies that are dissected by the four proposed categories in table 3 :

**Analysis content :** As the material scope of the criticality assessment is "products" (bicycle forks), adaptations are made to the methodology to select the chemical elements for which the criticality will be assessed, by completing it with a material selection method (Ashby's approach in this case) [18] to meet the study's needs. The analysis type, on the other hand, doesn't affect the methodology, as we can see it in the study of Palomino *et al.* [38].

**Time dimension :** the time horizon, if specified in the study, is generally prospective. The time frame encompasses the 4 to 6 years prior to the study, except for the study of Polat *et al.*, [39] which time frame extends to 23 years after the study was published, hence using predictive data. This is a step added to the methodology by the authors.

**Spatial dimension :** when the entity at risk is a material (bicycle forks) or an industry (The Lithium-ion Battery industry) adaptations are made either by completing the method or modifying it. Except for the study of Palomino *et al.*, which entity at risk is a technology (Spintronic memory) but no additions or adaptations were reported in the study.

**Reproducibility :** The model availability of the EC RMC method made it reproducible by the studies that employed it.

**Other dimensions :** when other dimensions than the ones that are comprised in the EC RMC method are

Table 3: Synthesis of objective and application analysis for the six case studies and the original EC RMC method.

| Study                            | Method             | Adaptations | Objective                                                   | Analysis context  |               | Time dimension  |             | Spatial dimension                |                    | Reproducibility | Other dimensions                                                                                                                                                                            |
|----------------------------------|--------------------|-------------|-------------------------------------------------------------|-------------------|---------------|-----------------|-------------|----------------------------------|--------------------|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                  |                    |             |                                                             | Material scope    | Analysis type | Time zone       | Time Frame  | Entity at risk                   | Geographical Scope |                 |                                                                                                                                                                                             |
| EC Report [27]                   | EC 2017            |             | Assess the CRM to the EU economy                            | Chemical elements | Economics     | Prospective [2] | 5 years     | EU                               | EU [3]             | Yes             | Economical, sustainability, political                                                                                                                                                       |
| (Daw, 2017a) [35]                | EC 2014 (Obsolete) | Formula     | Assess the Lithium criticality to the French economy        | Chemical elements | Economics     | NA              | 2009 - 2014 | France                           | France             | Yes             | Economical, political, sustainability, international transformation of materials (TIM)                                                                                                      |
| (P Ferro and Bonollo, 2019) [18] | EC 2014 (Obsolete) | Completion  | Assess CRM in bicycle forks                                 | Materials         | Engineering   | NA              | NA          | Bicycle Forks                    | EU                 | Yes             | Economical, sustainability, political                                                                                                                                                       |
| (Song et al., 2019) [36]         | EC 2017            | Formula     | Assess CRM in the lithium-ion batteries in China            | Chemical elements | Economics     | Prospective     | 2010 - 2016 | The Lithium-ion Battery industry | China              | Yes             | Economical, sustainability, political                                                                                                                                                       |
| (Yan et al., 2021) [37]          | EC 2017            | No          | Assess the CRM in China                                     | Chemical elements | Economics     | Prospective     | 2015 - 2019 | China                            | China              | Yes             | Economical, sustainability, political                                                                                                                                                       |
| (Polat et al., 2022) [39]        | EC 2017            | Completion  | Assess the criticality of strategic raw materials in Turkey | Chemical elements | Economics     | Prospective     | 2010 - 2025 | Turkey                           | Turkey             | Yes             | Economical, environmental, political, price, secondary production, environment, sociopolitical dimensions, and sub-dimensions in the criticality matrix and demand in the time series model |
| (Palomino et al., 2021)          | EC 2017            | No          | Assess critical metals contained in spintronic memory       | Chemical elements | Engineering   | NA              | 2010 - 2014 | Spintronic memory technology     | EU                 | Yes             | Economical, environmental, political                                                                                                                                                        |

needed, methodology adaptations are needed. Daw *et al.*, for instance proposed a new dimension (international transformation of materials (TIM)), and Polat *et al.*'s study required other aspects (political, price, secondary production, environment, sociopolitical dimensions, and sub-dimensions in the criticality matrix and demand in the time series model).

## 4 Discussion

### 4.1 Insights from EC RMC methodology study and recommendations

The results of this study demonstrate widespread recognition and citation of the EC RMC topic in all the articles included in the research sample. It however shows that European Commission documents dealing with criticality assessment are cited inconsistently. We therefore suggest that our readers refer to two sources when considering the EC RMC methodology (i.e. the 2017 version): methodology-related report and guidelines report. The guidelines report [15], functioning as a prescriptive document, delineates the 'ready-to-apply' methodology for the EU criticality assessment, while the background report [29] complements this with additional information, offering justifications and discussions pertaining to the methodology.

Moreover, the EC RMC method is actively employed in six of these articles to assess the criticality of raw materials, representing only 3% of the studied articles. It is also important to highlight that the utilization of the method without adaptations remains limited.

Thus, one significant observation is that none of the studies provides explicit justification for choosing the EC RMC method over alternatives that may align better with their specific research objectives. The absence of detailed explanations and variations in justifications hinder our ability to assess whether employing a different method or set of indicators would have been more suitable for certain studies. It is therefore encouraged to specify in the study the reasons for choosing the EC RMC method.

### 4.2 Limits and challenges for transmission of criticality expertise to society.

At present, the lack of consistency in EC RMC citations could be interpreted as superficial knowledge of this particular method. However, the results show that it is one of the most cited methods, which suggests that this can be extrapolated to other criticality assessment methods. These methods would thus be mastered only by experts and difficult to transfer, or only superficially, for example by using the results without discussing the modelling in detail. Criticality remains a large-scale planning concept (national or international): this implies work of transfer to smaller scales (region, industry, product) and this tends to be confirmed as more and more studies emerge on diversified application cases.

Three usage of criticality assessment can be seen in figure 5: 1) the updating of results from "classic or institutionalized" methods (e.g. EC RMC, Yale, ESSENZ) produced by the states/organizations themselves, 2) the adaptation of these methods for researchers/analysts' own purposes, 3) the selection of pre-established indicators and the composition of new methods. As methods such as the EC RMC method may not be universally applicable to all case studies, it prompts the question of whether indicator-based approaches tailored to the specific requirements of criticality assessments would be a more effective choice, rather than adjusting an existing method or creating a new one, depending on the actor who does the assessment, be it an engineer, a designer, or a political entity.

The inclination toward employing established methods, such as EC RMC method, as opposed to the indicators, suggests a possible predilection for readily available and reproducible approaches due to their user-friendly nature and perceived dependability. Yet, this inclination may inadvertently neglect the nuanced selection of indicators tailored to the unique objective of a given study.

This implies a need to better clarify the purpose and philosophy of existing methods to democratize criticality analysis for non-specialists, for instance for an engineering audience. It is worth noting that the lack of alignment between the EC RMC method and a particular study can be identified by utilizing the proposed analysis framework.

The eight proposed characteristics, divided into four categories in table 2 (analysis context, spatial dimension, time dimension and reproducibility), have been derived based on a review of "specialized" literature. A clear

limitation is therefore the possibility that additional characteristics could be suggested to further characterize criticality studies. Moreover, in wishing to transfer this framework to multiple audiences, other criteria could become prevalent. For example, the discipline or expertise of the study leaders (economics, engineering) brings different levers for reducing criticality. Obviously, the scope of the study can also be characterized differently according to the entity at risk (e.g. product and territory). Similarly, the time horizon needs to be specified, as "prospective" or "retrospective" does not yet provide sufficient information on the nature of the models and data collection required. The proposed analysis framework therefore needs to be refined to be even more operational.

Moreover, the opacity of models in some criticality methodologies hampers in-depth analysis and application, amplifying the appeal of the EC RMC method for its transparency, straightforwardness, and provision of available qualitative data sources.

We acknowledge the necessity of clarifying the objectives and constraints of available criticality analysis methods in the literature, particularly to facilitate their practical application in product or value chain design and territorial policy. Our framework aims to address this gap by guiding non-expert users, such as designers, towards the most suitable method for their specific analysis needs, thus enhancing the operational relevance of criticality assessments.

## Conclusion

In conclusion, our study underscores the significance of the EC RMC methodology, evident from its recurrent citation across a comprehensive literature review. We commend the methodology for its transparency, reproducibility, and the rigor inherent in its straightforward approach. Our analysis reveals a growing interest in and reliance on more recent versions of the EC RMC methodology, particularly the 2017 report. However, despite its widespread recognition, the current application of the EC RMC method remains relatively limited, with only a few instances where it is utilized without adaptations. This highlights the need for further exploration and examination of the method's adaptability to various research contexts.

Our research contributes to a better understanding of the EC RMC methodology by dissecting its characteristics and assessing its alignment with the objectives of selected articles. Through the proposed framework, we offer designers (or non-experts) a systematic approach to method selection and highlight potential points for adaptation, enhancing the decision-making process in criticality assessments. While our focus was primarily on the EC RMC method, we acknowledge the importance of considering other criticality methodologies to provide a comprehensive understanding of raw material criticality assessment.

Ultimately, this research emphasizes the importance of considering the appropriateness and compatibility of the EC RMC method, as well as other criticality methods, within the broader landscape of raw material criticality assessment. By employing a thoughtful and context-specific approach, researchers can enhance the effectiveness and relevance of their studies in addressing the complexities of raw material criticality.

Although, it is imperative to recognize the inherent limitations of this study. The focus primarily on the EC RMC method, though deliberate, introduces a potential bias in the literature review. The exclusion of certain criticality methodologies with non-transparent models may impact the comprehensiveness of the analysis. Additionally, the developed framework, while valuable, is not immune to evolution.

Looking ahead, there is ample room for further refinement of the framework. Future research endeavors may explore modifications or additions to its characteristics, thereby contributing to its continued utility in the evolving landscape of raw material criticality studies. Additionally, extending the framework's application to analyze and compare other criticality methodologies presents an avenue for comprehensive insights. Such comparative analyses would not only facilitate a broader understanding of existing methods, but also aid designers and non experts in navigating the nuanced differences between them. This research lays the groundwork for an ongoing dialogue on methodological advancements in raw material criticality assessments, fostering a more informed and discerning approach to research in this domain.

## Author contributions

Conceptualization, L. Labadi and L. Riondet; methodology, L. Labadi; validation, L. Riondet, H. Ben Rejeb and P. Zwolinski; formal analysis, L. Labadi; investigation, L. Labadi; data curation, L. Labadi; writing—original draft preparation, L. Labadi and L. Riondet; writing—review and editing, L. Labadi; L. Riondet, H. Ben Rejeb and P. Zwolinski; visualization, L. Labadi; supervision, P. Zwolinski.

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## Abbreviations

The following abbreviations are used in this manuscript:

|        |                                              |
|--------|----------------------------------------------|
| CRM    | Critical Raw Material                        |
| EC     | European Commission                          |
| EC-RMC | European Commission Raw Material Criticality |
| EI     | Economic Importance                          |
| EM     | Environmental Risk                           |
| EOL    | End-of-Life                                  |
| EPI    | Environmental Performance Index              |
| ET-TA  | Export Tax                                   |
| EU     | European Union                               |
| GS     | Global Supplier mix                          |
| HHI    | Herfindahl Hirschman Index                   |
| IR     | Import Reliance                              |
| OSR    | Old Scrap Ratio                              |
| RC     | Recycled content                             |
| RMC    | Raw Material Criticality                     |
| SCo    | Substitute Co-Production                     |
| SCr    | Substitute Criticality                       |
| SCP    | Substitute Cost Performance                  |
| SI     | Substitution Index                           |
| SP     | Substitute Production                        |
| SR     | Supply Risk                                  |
| WGI    | scaled World Governance Index                |



## Appendix

### Retrospective for EC-RMC assessment methodology

Tables 4, 5 and 6 compile the indicator definitions of each version of the EC RMC method and sorts them with “primary” category (i.e. *EI*, *SR* or *EM*), “secondary” category, i.e. parameters used in a primary category indicator or “tertiary” category, implying parameters used in a secondary category indicator.

Additionally, a presentation of the evolution of these criteria from 2010 to 2023 is available in the following sections.

#### Framework and model of criticality between 2010 and 2014

In 2010, the first EC RMC methodology was published [33], with the intent of the European Commission (EC) to assess and draw attention to the criticality of its raw materials. The Ad hoc working group is the defining group of critical raw materials for the European Commission. In addition to the three-yearly reports, it publishes supplementary details of the EC RMC methodology. The definition of this criticality indicator is then based on three criteria in 2010: Two risks, supply and environment-oriented and an “economic importance”.

- The *supply risk* criteria (*SR*), aims to evaluate the possibility of insufficient supply of a raw material to fulfil the industrial demand.
- The *environmental country risk* criteria (*EM*) refers to risks associated with policies adopted by producing countries to protect their environment, which may lead to a threat to the supply of raw materials to the European Union [33].
- The *economic importance* criteria (*EI*) intends to capture the importance of a specific raw material for the European Union economy [29].

#### Criticality indicators (2010-2014)

In 2010, the *EI* indicator and the two risk indicators (*SR* and *EM*) were implemented according to equations 1, 2, 3. The economic importance of a raw material *i*, named *EI<sub>i</sub>*, is subsequently determined by summing the individual megasectors identified as “*s*”, each weighted according to their gross value added  $\text{modif}(Q_s)$ , and then divided by the overall European gross domestic product (*GDP*) (see equation (1)). The economic importance also takes into account the end uses of the raw material (*A<sub>s</sub>*) and the value added of the sectors in which they are found.

$$EI_i = \frac{1}{GDP} \sum_s (A_s \cdot Q_s) \quad (1)$$

with:

- *i* : the raw material *i*
- *EI* : the economic importance of the raw material *i*,
- *s* : specific economic sector among the sectors defined by NACE Rev. 2 2-digit level sector standard (“NACE Rev. 2.1,” n.d.),
- *A<sub>s</sub>* : the share of end use of a raw material in the selected sector *s*,
- *Q<sub>s</sub>* : the Value Added of the selected sector *s*.
- *GDP* of the European gross domestic product

The  $SR$  indicator considers in equation (2) an estimate of the stability of the raw material producing countries using the level of concentration of those countries  $HHI_{WGI}$ , the substitution level of the raw material  $i$ , named  $SI_i$  and their level of recyclability  $EoL_{RIR_i}$ .

$$SR_i = HHI_{WGI} \cdot (1 - EoL_{RIR_i}) \cdot SI_i \quad (2)$$

with:

- $SR$ : the supply risk of the raw material  $i$
- $HHI$  : the Herfindahl Hirschman Index (used as a proxy for country concentration),
- $WGI$  : the scaled World Governance Index (used as a proxy for country governance),
- $EoL_{RIR_i}$  : the End-of-Life Recycling Input Rate of the raw material  $i$
- $SI_i$  : the Substitution Index of the raw material  $i$

The overall substitutability parameter  $SI_i$  identified in the equation (2) is computed with the following formula 2.1;

$$SI_i = \sum_s A_{is} \cdot Sub_{is} \quad (2.1)$$

with:

- $Sub_{is}$  is the estimated substitutability of the raw material  $i$  in the end use  $s$ .
- $A_{is}$  the share of end use of the raw material  $i$  in the selected sector  $s$

Moreover, the instability and level of concentration of producing countries used in  $SR_i$  calculation (i.e.  $HHI_{WGI}$  parameter in equation (2)) is estimated with the equation 2.2;

$$HHI_{WGI} = \sum_c (S_{ic}^2 \cdot WGI_c) \quad (2.2)$$

with:

- $HHI_{WGI}$  : the Herfindahl-Hirschmann-Index for country concentration
- $S_{ic}$  : the share of the country  $c$  in the world production data of the material  $i$
- $WGI_c$  : the Worldwide Governance Indicator of the country  $c$

Thus, equations (2) and (2.2) reflect the fact that the more unstable or monopolistic the producing country, the more critical the corresponding RM from the economic importance perspective. The  $WGI_c$  the Worldwide Governance Indicators encompass dimensions such as voice and accountability, political stability, government effectiveness, regulatory quality, rule of law, and control of corruption.

The *environmental country risk* parameter, noted  $EM$ , is implemented with equation 3 and 3.1:

$$EM_i = HHI_{EPI} \cdot (1 - EoL_{RIR}) \cdot SI_i \quad (3)$$

$$HHI_{EPI} = \sum_c (S_{ic}^2 \cdot EPI_c) \quad (3.1)$$

with:

- $HHI_{EPI}$  : the Herfindahl-Hirschmann-Index for the environmental performance



- $EPI$  : the environmental performance index of each country  $c$
- $S_{ic}$  is the share of the country  $c$  in the world production data of the raw material  $i$

It can be observed that the calculation of the indicator EM and SR are similar (see equation 2 and 3): both take into account a recycling rate ( $EOL_{RIR}$ ), a country specific dimension ( $HHI$ ) and a substitutability property relative to the studied material ( $SI$ ). The  $EI$  indicator or secondary indicators (e.g.  $HHI$  or  $SI$ ) are aggregated indicators relatively to industrial sectors and countries.

### Criticality criteria (2010-2014)

The equations 1, 2 and 3 make possible continuous criticality assessments, however authors decided to define criticality with Boolean criteria: a material is considered critical, in 2010, compared to thresholds on the three criteria; economic importance, supply risk and environmental country risk, as depicted in Figure 6 (part b). EC reports represent then the economic importance and the supply risk on a matrix and the environmental country risk on a vector (Figure 6, part a)).

The criticality of a raw material is determined as follows: if its economic importance is lower than the threshold, it is not considered critical (see blue zones on Figure 6 part a) [33]. Conversely, if the economic importance is high and at least one of the two risk indicators exceeds their corresponding threshold, then the raw material is critical. It leads to define a red zone (i.e. high economic importance and supply risk) as a criticality zone and a gray zone where criticality is defined with regard to the trespassing of environmental country risk threshold. This means that economic importance counts as a priority in the definition of criticality.

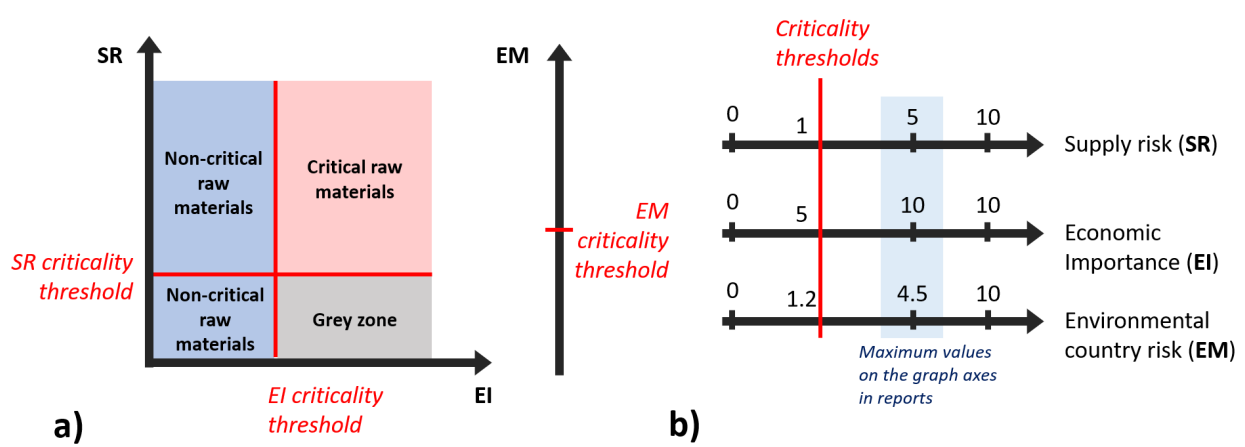


Figure 6: Usual representation associated with the EC RMC methodology (a) and synthesis of threshold values (b), published in 2010.

A normalization treatment is applied to display several raw materials on the same graph and affect the same criticality thresholds. Thus, they are stated at 1 for the supply risk with the scale from 0 to 10, 5 for the economic importance with a scale from 0 to 10, and 1.2 for the environmental country risk on a scale from 0.1 to 10 [33]. Figure 6 part b) synthesizes the range values observed on EC criticality graphs and the thresholds for 2010.

#### 1.1 Framework and model of criticality between 2014 and 2017

The Ad hoc Working Group published in 2014, that the environmental country risk was not taken into account, as it often fails to accurately “depict the reality” [34]. Therefore, since 2014, the criticality assessment only depends on supply risk and economic Importance, these two remained unchanged.

## .2 Framework and model of criticality since 2017

In 2017, the methodology was updated with the introduction of new parameters to the existing indicators. The aim of these updates was to refine specific aspects (e.g. economic allocation in industrial sector or EU raw material sourcing) according to “policy and or stakeholder needs or strong scientific reasons”, while ensuring high levels of comparability to the 2011 and 2014 assessment results [29].

### Criticality indicators (Since 2017)

This subsection details the updates of the EC RMC methodology provided in 2017, first for the economic importance, then for the supply risk. A distinction is proposed between *modification*, i.e. modification of existing parameters and *additions*, i.e. new parameters that were not in the previous version.

#### Economic importance (EI) updates

The EI updates concern mainly *additions*. The only *modification* to be noticed is the allocation of the raw material applications to their related economic sectors, so-called “NACE” sectors. It has moved from megasectors, combining several 3- and 4-digit NACE2 sectors in the previous assessments, to single NACE sectors, thus increasing the levels of sector-specific resolution.

At the same time, the *additions were more extensive*:

- A raw material's substitution index ( $SI_{EI}$ ) was introduced, recognizing its role in enhancing economic resilience, cost management, market competitiveness, and the diversification of supply chains, thereby contributing to the adaptability and sustainability of industries dependent on critical raw materials.
- A substitute cost parameter ( $SCP$ ) was added: the decision to the substitution of a material is made not only on the basis of the substitute's technical performance, but also its cost.
- The *GDP* “European gross domestic product” no longer appears directly in the general equation because the figures are already scaled within the range of 0 to 10, and the ranking is expressed in relative terms. Additionally, it is important to emphasize that the score is dimensionless.[43]

These additions lead to the update of equation 1 with the addition of a Substitution Index ( $SI$ ), depending on the economic importance of the studied material:

$$EI_i = \sum_s (A_s \cdot Q_s) \cdot SI_{EI} \quad (4)$$

where:

- $EI$  : economic importance of the raw material  $i$ ;
- $A_s$  : the share of a certain RM used in a NACE Rev. 2 2-digit level sector;
- $Q_s$  : the Value Added of the 2-digit-level NACE Rev. 2 sector;
- $SI_{EI}$  : the substitution index of an RM to be used in economic importance;
- $s$  : the corresponding NACE Rev. 2 sector.

The added parameter  $SI_{EI}$  is then computed as follows:

$$SI_{EI} = \sum_i \sum_a SCP_{i,a} \cdot Sub - share_{i,a} \cdot Share_a \quad (5)$$

with:

- $i$  : a substitute material
- $a$  : an application of the candidate material
- $SCP_i$  : Substitute Cost Performance parameter
- $Share_a$  : the share of the candidate material in an end-use application  $a$
- $Sub - share_{i,a}$  : the sub-share of each substitute  $i$  within a given application  $a$

This contribute to the taking into account of "sectorial" vision into criticality assessment. Thus, the criticality can vary according to the considered industrial sector and its use of the studied material. It can be understood as a way to reflect usage conflicts of resources between sectors, considering GDP participation and estimated substitutability of the RM in their identified contexts.

#### **Supply risk (SR) updates**

Several modifications have been made, *additions* of the methodology apply to:

- The trade component: global restrictions on exports of some raw materials may increase supply risk.
- The import dependency: in the previous RMC assessments, only the mix of global supplier countries was considered and did not reflect the import dependency of the EU.
- The Supply mix to the EU (domestic production and imports) : as the previous version of the methodology did not consider the domestic production and imports.
- Finally, a *Substitution Index* ( $SI_{SR}$ ) has been to reflect the possibility for industrial to substitute one material by another. It is modeled by including:
  - The *Substitute Production* ( $SP$ ) parameter: if substitutes are produced in insufficient quantities to replace the candidate material, they will increase supply risk.
  - The *Substitute Criticality* ( $SC_r$ ) parameter: if the substitute material is critical, then it may not be available readily as an alternative.
  - The *Substitute Co-Production* ( $SC_o$ ) parameter: the immediate supply of certain candidate materials, particularly minor metals like REE, In, Ga, Ge, could be significantly restricted due to limited availability.

The presented modifications have significantly increased the complexity of the supply risk model. The resulting equations for the general formula of  $SR$ , then to the parameter  $SI_{SR}$ , and finally to supplementary coefficients (e.g.  $HHI_{WGI-t}$ ,  $EU_{sourcing}$ ,  $IR$  and  $EOL_{RIR}$  for recycling modelling) are summarized in table 5 and 6 of appendix. Moreover, tables 4 and 7 do the same for the indicators  $EI$  and  $EM$ , respectively.

To conclude, the integration of substitution and recycling in the model logically reduce the supply risk and therefore the criticality compared to the previous version of the methodology.

Table 4: Modelling Equations of the *Economic Importance* (EI) of the EC RMC method in its two versions, 2010 and 2017. NA stands for "Not Applicable".

| Indicator      | 2010                                         | 2017                                                            | Details/Glossary                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|----------------|----------------------------------------------|-----------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $EI_i^*$       | $\sum_s \frac{1}{GDP} \cdot (A_s \cdot Q_s)$ | $\sum_s (A_s \cdot Q_s) \cdot SI_{EI}$                          | <ul style="list-style-type: none"> <li>• <math>i'</math> : the raw material <math>i'</math>,</li> <li>• <math>EI</math> : the economic importance of the raw material <math>i</math>,</li> <li>• <math>s</math> : specific economic sector among the sectors defined by NACE Rev. 2 2-digit level sector standard ("NACE Rev. 2.1," n.d.)</li> <li>• <math>A_s</math> : the share of end use of a raw material in the selected sector <math>s'</math>,</li> <li>• <math>Q_s</math> : the Value Added of the selected megasector (2010) or revised NACE sector (2017) <math>s</math>,</li> <li>• <math>GDP</math> of the European gross domestic product,</li> <li>• <math>SI_{EI}</math> : the substitution index of an RM to be used in economic importance.</li> </ul> |
| $SI_{EI}^{**}$ | NA                                           | $\sum_i \sum_a SCP_{i,a} \cdot Sub - share_{i,a} \cdot Share_a$ | <ul style="list-style-type: none"> <li>• <math>i'</math> : a substitute material,</li> <li>• <math>a'</math> : an application of the candidate material,</li> <li>• <math>SCP_i</math> : Substitute Cost Performance parameter,</li> <li>• <math>Share_a</math> : the share of the candidate material in an end-use application <math>a'</math>,</li> <li>• <math>Sub - share_{i,a}</math> : the sub-share of each substitute <math>i'</math> within a given application <math>a'</math>.</li> </ul>                                                                                                                                                                                                                                                                     |

(\*) for primary indicator, (\*\*) for secondary indicator.

Table 5: Modelling Equations of the *Supply Risk* (SR) criteria of the EC RMC method in its two versions, 2010 and 2017 (PART 1).NA stands for "Not Applicable".

| Indicator          | 2010                                                | 2017                                                                                                                                                                                        | Details/Glossary                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
|--------------------|-----------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $SR_i^{(*)}$       | $HHI_{WGI} \cdot (1 - EoL_{RIR_i}) \cdot SI_{SR_i}$ | $\left( (HHI_{WGI-t})_{GS} \cdot \frac{IR}{2} + \left( (HHI_{WGI-t})_{EU_{sourcing}} \cdot \left(1 - \frac{IR}{2}\right) \right) \cdot (1 - EoL_{RIR_i}) \cdot SI_{SR_i} \right) \quad (6)$ | <ul style="list-style-type: none"> <li><math>SR_i</math>: the supply risk of the raw material 'i',</li> <li><math>HHI</math>: the Herfindahl Hirschman Index (used as a proxy for country concentration),</li> <li><math>WGI</math>: the scaled World Governance Index (used as a proxy for country governance),</li> <li><math>EoL_{RIR_i}</math>: the End-of-Life Recycling Input Rate of the raw material 'i',</li> <li><math>SI_{SR_i}</math>: the Substitution Index of the raw material 'i' related to supply risk.</li> <li><math>t</math>: equals the trade adjustment (of WGI),</li> <li><math>IR</math>: Import Reliance,</li> <li><math>GS</math>: for global supplier mix,</li> <li><math>EU_{sourcing}</math>: the actual sourcing of the supply to the 28 EU Member States,</li> <li><math>EoL_{RIR}</math>: the End-of-Life Recycling Input Rate,</li> </ul>                                                                                                                                                                                                                                                                                                |
| $SI_{SR_i}^{(**)}$ | $\sum_s A_{i,s} \cdot Sub_{i,s}$                    | $\sum_i \left[ (SP_i * SCr_i * SCo_i)^{1/3} \cdot \sum_a (Sub - share_{i,a} \cdot Share_a) \right]$                                                                                         | <ul style="list-style-type: none"> <li><math>Sub_{i,s}</math>: the estimated substitutability of 'i' in the end use 's',</li> <li><math>A_{i,s}</math>: the share of end use of the raw material 'i' in the selected sector 's',</li> <li><math>a'</math>: an individual application of the material 'i',</li> <li><math>SP</math>: Substitute Production; reflects global production of the substitute and the material as an indicator of whether sufficient amounts of substitute material are available,</li> <li><math>SC_r</math>: Substitute Criticality; takes into account whether the substitute was critical in the previous EU list,</li> <li><math>SC_o</math>: Substitute Co-production; takes into account whether the substitute is a primary product or mined as a co-/by-product,</li> <li>"Share": the share of the candidate raw materials in the application <math>a</math>,</li> <li>"Sub-share": the sub-share of a substitute 'i' within each application 'a' of the raw material. The <math>SP</math>, <math>SC_r</math> and <math>SC_o</math> parameters are to be determined for each substitute of the relevant candidate material.</li> </ul> |

(\*) for primary indicator, (\*\*) for secondary indicator, (\*\*\*) for tertiary indicator.

Table 6: Modelling Equations of the *Supply Risk* (SR) criteria of the EC RMC method in its two versions, 2010 and 2017 (PART 2). NA stands for "Not Applicable".

| Indicator                               | 2010                       | 2017                                                                                                                  | Details/Glossary                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|-----------------------------------------|----------------------------|-----------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $(HHI_{WGI})_{or}(HHI_{WGI-t})$<br>(**) | $\sum_c S_c^2 \cdot WGI_c$ |                                                                                                                       | <ul style="list-style-type: none"> <li><math>S_c</math> : the share of country <math>c</math> in the global supply mix or in the EU sourcing mix of the raw material considered,</li> <li><math>WGI_c</math> : the scaled World Governance Indicators of country '<math>c</math>',</li> <li><math>t_c</math> : the trade-related variable of country '<math>c</math>' for a candidate raw material.</li> </ul>                                                                                                                                                                                                                                                                                                                                                 |
| $IR$ (**)                               | NA                         | $\frac{Import - Export}{Domestic\ production + Import - Export}$                                                      | <ul style="list-style-type: none"> <li>Import : the imported amount of the RM to the EU.</li> <li>Export : the exported amount of the RM from the EU.</li> <li>Domestic production : the local production amount of the RM in the EU.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| $EOL_{RIR}$ (**)                        | NA                         | $OSR \cdot RC = \frac{input\ of\ secondary\ material}{input\ of\ primary\ material + input\ of\ secondary\ material}$ | <ul style="list-style-type: none"> <li>OSR the "Old Scrap Ratio",</li> <li>RC the "recycled content".</li> </ul> <p>This parameter corresponds to the ratio between "old scrap" recycled quantities and the total scraps from primary production and recycling processes.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| $t_c$ (***)                             | NA                         | $(ET.TA_c\ or\ EQ_c\ or\ EP_c\ or\ EU_c)$<br>(7)                                                                      | <ul style="list-style-type: none"> <li><math>ET.TA_c</math> : parameter reflecting an export tax imposed (%) by country '<math>c</math>', possibly mitigated by trade agreement (<math>TA</math>) in force,</li> <li><math>EQ_c</math> : parameter reflecting an export physical quota imposed by country '<math>c</math>' (physical units, e.g. tonnes), - <math>EP_c</math> : parameter reflecting an export prohibition introduced by country <math>c</math> for a candidate RM, - <math>EU_c</math> : EU countries parameter <math>c</math> for a candidate RM equal to 0.8.</li> <li><math>t</math> is equal to the highest score of the restrictions parameters (<math>ET.TA</math> or <math>EQ</math> or <math>EP</math> or <math>EU</math>)</li> </ul> |

(\*) for primary indicator, (\*\*) for secondary indicator, (\*\*\*) for tertiary indicator.

Table 7: Modelling Equations of the *Environmental Risk* (EM) criteria of the EC RMC method in its two versions, 2010 and 2017.NA stands for “Not Applicable”.

| Indicator          | 2010                                         | 2017 | Details/Glossary                                                                                                                                                                                                                                                                         |
|--------------------|----------------------------------------------|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $EM_i^{(*)}$       | $HHI_{EPI} \cdot (1 - EO_{LRIR}) \cdot SI_i$ | NA   | <ul style="list-style-type: none"><li>• <math>HHI_{EPI}</math> : the Herfindahl-Hirschmann-Index (proxy for country concentration)</li><li>• <math>EO_{LRIR}</math>: End-of-life recycling input rate,</li><li>• <math>SI_i</math>: Substitution index related to supply risk.</li></ul> |
| $HHI_{EPI}^{(**)}$ | $\sum_c (S_{ic})^2 \cdot EPI_c$              | NA   | <ul style="list-style-type: none"><li>• <math>EPI_c</math>: the environmental performance index of each country 'c',</li><li>• <math>S_{ic}</math>: the share of the country 'c' in the world production data of the raw material 'i'.</li></ul>                                         |

(\*) for primary indicator, (\*\*) for secondary indicator.

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## 8.4 Article B - Apport 8 - Recommandations pour les non-experts pour le choix de principe de partage dans l'AESA (approfondissement de l'archétype 5)

### Stratégie de publication pour l'Article B

L'**Article B** est à soumettre au Journal *Design Science* pour le 30 Mai 2024. Ce journal présente, au 13 Mai 2024, un h-index de 25, un impact factor de 2.4, et est catégorisé Q1 pour le domaine de l'ingénierie généraliste (Miscellaneous Engineering) selon la banque [Scimago](#). Il a été choisi pour sa ligne éditoriale diversifiée à l'attention des concepteurs et pour sa dimension didactique.

L'**Article B** s'intitule « *Sharing principles in AESA : help designers get a foot on the ladder* » et constitue les **pages 223 à 247** de la thèse.

### Abstract

*The Absolute Environmental Sustainability Assessment (AESA) is a new approach, based in part on the framework of planetary boundaries and Life Cycle Assessment (LCA), aimed at assessing the sustainability of human activities. It emerges in the 2010s and obviously concerns industrial/product production. Integrating AESA into the design process is therefore a major challenge for ecological transitions. One major element is the use of "sharing principles", assigning an environmental limit to an object of study that must not be exceeded to be considered sustainable. This paper investigates the potential adoption of this concept by the designer intending to apply AESA in the design context. To address this question, a literature review has been carried out to 1) present a state of the art on AESA for designers, and 2) identify the key steps for conducting an AESA. A harmonized vocabulary is proposed, along with resources to explore each concept in greater depth, according to the authors who contributed to its development. Moreover, a step-by-step method for the designer is presented and applied to a power electronics case study. This work demonstrates the applicability of AESA to a technical object. From an eco-design perspective, this means adding normalization of environmental impacts in relation to the environment's ability to withstand them (i.e. carrying capacity). Additionally, recommendations are given to help users choose and/or develop sharing principles in keeping with the spirit of AESA. This involves adopting a socio-technical approach to sustainability in design.*

## ARTICLE B - Sharing principles in AESA: help designers get a foot on the ladder

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### Abstract

The Absolute Environmental Sustainability Assessment (AESA) is a new approach, based in part on the framework of planetary boundaries and Life Cycle Assessment (LCA), aimed at assessing the sustainability of human activities. It emerges in the 2010s and obviously concerns industrial/product production. Integrating AESA into the design process is therefore a major challenge for ecological transitions. One major element is the use of “sharing principles”, assigning an environmental limit to an object of study that must not be exceeded to be considered sustainable. This paper investigates the potential adoption of this concept by the designer intending to apply AESA in the design context. To address this question, a literature review has been carried out to 1) present a state of the art on AESA for designers, and 2) identify the key steps for conducting an AESA. A harmonized vocabulary is proposed, along with resources to explore each concept in greater depth, according to the authors who contributed to its development. Moreover, a step-by-step method for the designer is presented and applied to a power electronics case study. This work demonstrates the applicability of AESA to a technical object. From an eco-design perspective, this means adding normalization of environmental impacts in relation to the environment's ability to withstand them (*i.e.* carrying capacity). Additionally, recommendations are given to help users choose and develop sharing principles in keeping with the spirit of AESA. This involves adopting a socio-technical approach to sustainability in design.

Keywords: Absolute Environmental Sustainability Assessment, Sharing principles, Integrated design, Case study, Buck converter

### Glossary

**AESA** : Absolute Environmental Sustainability Assessment

**AF** : Allocation Factor

**AP** : Allocation Principle

**ASR** : Absolute Sustainability Ratio

**CC** : Carrying Capacity

**DJT** : Distributive Justice Theory

**IPCC** : International Panel on Climate Change

**IPBES** : Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

**LCA** : Life Cycle Assessment

**LCE** : Life Cycle Engineering

**LCI** : Life Cycle Inventory

**MO** : Mitigation Options

**PB** : Planetary Boundaries

**PE** : Power Electronics

**SoS** : Safe Operating Space

**SoSOS** : Share of Safe Operating Space

## 1 Introduction

### 1.1 The socio-ecological Earth System Sciences models based Planetary Boundary framework

The past decades Earth sciences publications and the latest understanding of the complex and dynamic interactions in the Earth system and the human activity have been drawing up an alarming statement of the consequences of human activities on the environment [Mahecha *et al.* (2020)]. The biosphere degradation, the soil erosion and the climate change are three crucial phenomena that underscore the critical nature of these consequences. The *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES) and the *International Panel on Climate Change* (IPCC) regularly publish reports, for citizens and decision-makers, summarizing the latest scientific findings respectively on the biodiversity erosion and climate change. The 2019's IPBES report informed that nearly 85 % of the surface area of wetlands disappeared in 2019 since the preindustrial era, 75% of the Earth's surface has seen major alteration, and 66% of the seas are seeing increasingly serious cumulative effects [IPBES (2019)]. Furthermore, IPCC established in 2023 that the observed global warming from 1850 to 2019 is plus 1.06 °C (with a range of uncertainty between 0.8 and 1.3 °C), causing worldwide changes to the weather and climate extremes in widespread regions, affecting and finally harmful impacts on nature and human populations [IPCC (2022)]. In 2009, Rockström *et al.* proposed a comprehensive theoretical framework based on environmental and systemic sciences to model the environment. The so-called *planetary boundaries* (PB) depict environmental limits that mankind should not cross to guarantee habitability on Earth [Rockström *et al.* (2009)]. Authors called for reconsidering all human activities through an environmental perspective in order to mitigate ongoing destabilization of the Earth system. This new paradigm has been updated in 2015 ([Steffen *et al.* (2015)]), 2020 ([Lade *et al.* (2020)]), 2022 ([Persson *et al.* (2022)] and 2023 ([Richardson *et al.* (2023)]) but still hinges on the idea that human activities are included in a planetary system and must not exceed limits for nine biophysical processes that regulate the stability and resilience of the Earth system [Lade *et al.* (2020), Persson *et al.* (2022)]. The goal of this framework is therefore to document a *Safe Operating Space* (SOS) to be safeguarded on a global scale. In other terms, PB quantifies the unsustainability of human societies. Steffen *et al.* (2015), Persson *et al.* (2022) and Richardson *et al.* (2023) successively showed that six of these boundaries have already been crossed on a global scale in 2023, including climate change [Persson *et al.* (2022), Richardson *et al.* (2023)]. Table 1 summarizes the nine dimensions of the planetary boundaries (also mentioned as "control variables") with their associated units (see column 1 and 2).

Column 3 precises the preindustrial values of the control variables, i.e. sets 1850 as a reference. Column 4 details the planetary boundaries, meaning the thresholds defining the sustainability of Earth system state (i.e. Holocene). Column 5 details the value of the control variables in 2023 extracted from [Richardson *et al.* (2023)].

Column 6 details the difference, in absolute value, of the planetary boundary and the preindustrial values for the control variables. This column therefore contains only positive values. Column 7 clarifies the situation regarding the planetary boundaries (exceeded or not) and quantifies it in value and in percentage. For example, the limit of climate change is quantified by two control variables: the CO<sub>2</sub> concentration and the radiative forcing (or energy imbalance) in the atmosphere. Their values are respectively 417 parts per million (ppm), counting what has been emitted since the pre-industrial era to 2023, and 2.91 Watt per meter square (W/m<sup>2</sup>). This planetary boundary is therefore exceeded for the two control variables respectively by 19% and 191%. Note that the planetary boundaries are aggregated at global level, but some have also been detailed regionally (e.g. by continent) to reflect the dynamics of the phenomena studied. This is mainly detailed for the *freshwater change*, the *land-system change* and the *biogeochemical flows*, but concerns also the *change in biosphere integrity* with endemic situations.

### 1.2 Quantify to support decision-making

Pigosso *et al.* (2015) review three decades of scientific literature dealing with ecodesign research and implementation [Pigosso *et al.* (2015)]. The paper compiles academics and practitioners publications of the integration of environmental concerns into the design process (i.e. ecodesigning). Among nine promising research topics, the "incorporation of planetary boundaries in evaluation of environmental [...] performance of product and technology". The planetary boundaries in this context can be seen by designers as a monitoring tool to transform scientific facts into decision-making. To do so, Ryberg *et al.* (2018) develop the *Absolute Environmental Sustainability Assessment* (AESAs) [Ryberg *et al.* (2018a)]. This methodology, coupled with Life Cycle Engineering (LCE), intends to assess the environmental sustainability of a product or a service. The differences between a planetary boundary-based approach and a classic LCE approach is

| Control variable<br>(1)                                                                                                  | Unit<br>(2)                                                          | Preindustrial<br>Holocene<br>base value<br>(3) | Planetary<br>Boundary<br>(4) | Current<br>value<br>(2023)<br>(5) | $\Delta$ (4) - (3)  <br>(6) | $\Delta$ (4) - (5)<br>(7)  |
|--------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------|------------------------------------------------|------------------------------|-----------------------------------|-----------------------------|----------------------------|
| <b>Climate change</b><br>CO <sub>2</sub> concentration                                                                   | ppm                                                                  | 280                                            | < 350                        | 417                               | 70                          | exceeded<br>(- 67; 19%)    |
| <b>Climate change</b><br>Energy imbalance                                                                                | Wm <sup>-2</sup>                                                     | 0                                              | < 1                          | 2.91                              | 1                           | exceeded<br>(- 1.91; 191%) |
| <b>Biogeochemical flows</b><br>Phosphate, global                                                                         | Tg P yr <sup>-1</sup>                                                | 0                                              | < 11                         | 17.5                              | 11                          | exceeded<br>(- 6.5; 59%)   |
| <b>Biogeochemical flows</b><br>Phosphate, regional <small>(mined and applied to erodible agricultural soils)</small>     | Tg P yr <sup>-1</sup>                                                | 0                                              | < 6.2                        | 22.6                              | 6.2                         | exceeded<br>(- 16.4; 265%) |
| <b>Biogeochemical flows</b><br>Nitrogen, global                                                                          | Tg N yr <sup>-1</sup>                                                | 0                                              | < 62                         | 190                               | 62                          | exceeded<br>(- 128; 206%)  |
| <b>Freshwater change</b><br>Blue water - global                                                                          | % of land area with deviations from                                  | 9.4                                            | < 10.2                       | 18.2                              | 0.8                         | exceeded<br>(- 6; 78%)     |
| <b>Freshwater change</b><br>Green water - global                                                                         | preindustrial variability                                            | -                                              | < 11.1                       | 15.8                              | 11.1                        | exceeded<br>(- 4.7; 42%)   |
| <b>Change in biosphere integrity</b><br>Genetic diversity                                                                | E/MSY                                                                | 1                                              | < 10                         | > 100                             | 9                           | exceeded                   |
| <b>Change in biosphere integrity</b><br>Functional integrity                                                             | % of HANPP <small>(in 10<sup>9</sup> t of C yr<sup>-1</sup>)</small> | 1.9                                            | > 90                         | 30                                | 88.1                        | exceeded<br>(- 60; 66%)    |
| <b>Land-system change</b><br>global                                                                                      | %                                                                    | 100                                            | > 75                         | 60                                | 25                          | exceeded<br>(- 15; 20%)    |
| <b>Novel entities</b><br><small>(Synthetic chemicals released to the environment without adequate safetytesting)</small> | %                                                                    | 0                                              | 0                            | -                                 | 0                           | exceeded                   |
| <b>Ocean acidification</b><br>Carbonate ion concentration                                                                | $\Omega_{arag}$                                                      | 3.44                                           | > 2.75                       | 2.8                               | 0.69                        | + 0.05; 1.8%               |
| <b>Stratospheric ozone depletion</b>                                                                                     | DU                                                                   | 290                                            | > 276                        | 284.6                             | 14                          | + 8.6; 3.1%                |
| <b>Atmospheric aerosol loading</b>                                                                                       | Interhemispheric difference in AOD                                   | 0.03                                           | > 0.1                        | 0.076                             | 0.07                        | + 0.024; 24%               |

Table 1: Planetary boundaries, associated control variables, and values in 2023, extracted from [Ryberg *et al.* (2018b)] and [Richardson *et al.* (2023)].

addressed with the aphorism “better – but is it good enough?” in [Hauschild (2015)]. Bjorn *et al.* (2020) separates these two approaches by specifying an “absolute” approach referring to the AESA versus a “relative” environmental performance approach, essentially comparing versions of products or systems in a relative manner ([Bjørn *et al.* (2020)]). In practice, the absolute approach is based on a Life Cycle Assessment (LCA) comparing results with a designed share of Safe Operating Space (SoSOS) ([Ryberg *et al.* (2020)]). Thus, beside AESA is a recent research topic and still discussed in the LCA community (*e.g.* time consideration) ([Guinée *et al.* (2022), Ryberg *et al.* (2018c)]), its operationalization is the motivation underpinning the most recent advancements ([Kara *et al.* (2023)]).



## 2 Background and theory

The AESA is a recent research topic supported with significant methodologies. Ryberg insisted on the need to pose absolute sustainability not as a classical engineering problem, but as an ethical matter. In [Ryberg *et al.* (2018a)] several justice theories are investigated to address the possible sharing principle of the SOS from the PB framework. [Hjalsted *et al.* (2021)] complemented this theoretical work by identifying the different downscaling PB strategies at individual and industry sector levels. These strategies will be discussed later in this article.

Concomitantly, Bjorn and Ryberg were the first contributors to investigate the interface between the planetary boundary framework and Life Cycle Assessment (LCA). Concretely, as the PB control variables are not LCA environmental indicators, two approaches were possible: directly develop new indicators, taking inspiration from the PB ([Ryberg *et al.* (2018b), Ryberg *et al.* (2016)]), or propose a translation of the limits into "classic" LCA indicators ([Björn *et al.* (2015)]). These two approaches are illustrated in Figure 1. Their common objective is to compute the *Absolute Sustainability Ratio* (ASR): It consists in the ratio of the Life Cycle Impact Assessment (LCIA) of the product to a dedicated environmental space, i.e. the left part on right part of figure 1. If the ASR is upper than 1, it means that the product is environmentally sustainable, i.e. reaches eco-effectiveness [Hauschild *et al.* (2020)]. This article is focused on sharing principle (highlighted in red), to help designers managing the definition of the environmental space associated with their product.

There is still room to improve and consolidate both approaches: data updates (e.g. population growth data) are required in [Björn *et al.* (2015)], and the method proposed by [Ryberg *et al.* (2018b)] directly affects the Life Cycle Inventory (LCI) by imposing a vision by flow, matching a pressure on the environment depending on time. The inventory data is therefore measured in mass per time spent ("kg/year") instead of only mass ("kg") as in classic LCA practice. Both approaches, furthermore, require precautions on the definition of system boundaries and the corresponding temporal considerations. For further details, please consult [Guinée *et al.* (2022)].

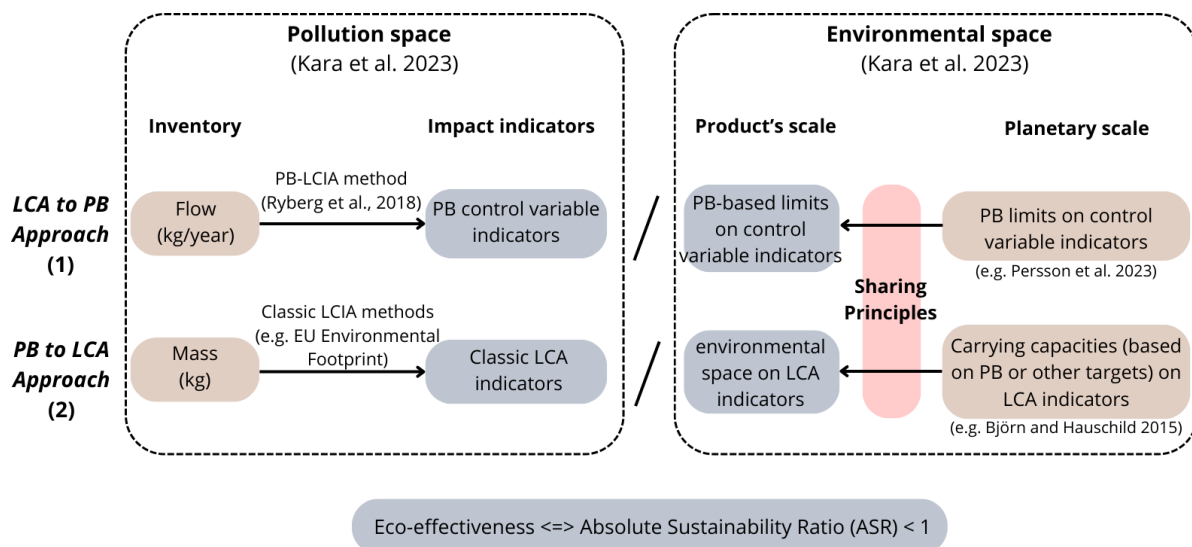


Figure 1: Illustration of the two interfacing approaches between planetary boundaries and LCA and the associated inventory and impact indicator properties. Sharing principles are needed in both approaches (red zone).

Although both approaches requires regular updates and methodological improvements, they contributes to the first step towards adopting AESA by LCA practitioners and design teams accustomed to the practice of LCA.

In line with these methodological works, [Kara *et al.* (2023)] proposed an iterative method to operationalize the life cycle engineering within the absolute sustainability paradigm. The method follows six steps: 1) definition of the environmental space for company or product, 2) application of Life Cycle Assessment to identify hotspots (*i.e.* the most contributing processes to environmental impacts), 3) review of existing engineering solutions to reach objectives defined in step 1, 4) prioritization of the most effective solutions concerning environmental aspects, 5) feasibility assessment and

selection of mitigation options (MO) based on techno-economic analysis, 6) redesign of the product and/or implementing of the selected MO. The novelty of this method is to integrate the absolute sustainable framework in classic life cycle engineering, making LCA practice central in the product design process. Kara *et al.* focus on the MO available in the LCE literature and seem to devolve the “environmental space” definition to external actors of the design team such as the specialized company [Smith (2024)]. The first two steps of the method are therefore less explicit/integrated than the following ones, despite their crucial importance for understanding absolute sustainability. Kara *et al.* are aware of this and promote more research “to elucidate consequences of different allocation principles and create the basis for commonly agreed choices”. Thus, this paper aims to clarify for beginners the main vocabulary and principles within the AESA literature, and to wrap up some basic practices with applying the theory on a practical case study. It can be seen as an extension of Kara *et al.*, (2023) giving a specific focus on the challenge of choosing the sharing principles addressed to designers in the absolute sustainability paradigm with a LCA-based approach.

### 3 Aim and significance

#### 3.1 Aim

This paper aims to support designers in conducting an AESA. This approach involves comparing the results of LCA and confronting these results with PBs to determine the object of study is sustainable within these limits. However, numerous studies focusing on AESA are rather addressed to researchers, *i.e.*, are confined to the academic sphere. In addition, the abundance of proposals does not provide designers with a clear vision and a straightforward approach to conducting AESA for the product they are developing.

The hypothesis driving this research is that a comprehensive step-by-step method, supported by practical recommendations for designers, will invite them to conduct an AESA and formulate some critical analysis of the method shortcomings. This dual practice with designers practical applications from one side, and the current AESA researchers developments on the other side will bridge the academic development with grounded issues related to absolute thinking integration by the designer's activities.

Motivated by easing this practice for the designer, the aims of this paper are:

- Providing the popularisation of the AESA concepts and related vocabulary to demystify this method for designers, and to enable designers to appropriate AESA at their level (skill, IT support, collaborators) in their own design context (project, design process step, product/service type, design goal and scope).
- Describing a step-by-step method for AESA, adaptable according to the practitioner's level of knowledge and resources.
- Guiding the calculation method and the supporting tool to choose.
- Suggesting new calculation support or tools for AESA, allowing political issues raised in this approach to be addressed to product designers through the socio-environmental complexity the designer has to deal with.

To support these results and practices, the paper apply the method to a case study as an example of the proposed step-by-step method. The critical analysis of AESA at the end of the paper aims to shed light on some current shortcomings, and motivate further research developments in the field of absolute sustainability thinking and life cycle environmental assessment.

#### 3.2 Significance

The paper's significance is threefold: first, to show the need for easing the work of designers to integrate absolute sustainability thinking in their practice. Second, to show specific recommendations for practitioners on AESA methods, to help designers consider the steps to follow, associated with relevant international methods to rely on. Third, to show designers and researchers in design the challenging opportunity brought by the democratisation of AESA methods in their practices, in addressing design questions that are specific to the absolute and strong sustainability thinking.



## 4 Method

The method used to conduct this study is the Design Research Methodology (DRM) [Blessing (2009)]. This method was delineated into four phases:

1. Research Clarification: The review of the literature is carried out based on AESA experts' research papers, formalising the core concepts of AESA from different sources and applications.
2. Descriptive Study I: An advanced literature review highlights the research gap of this paper. The AESA methodological steps found in the literature have been approached through the lens of applying a case study in power electronics, thereby elucidating the challenges for a designer in industry to apply the AESA method(s) in his or her activities. In particular, this descriptive study revealed the lack of support for product designers in defining and questioning the sharing principles during the first steps of AESA method process. The refined research question of this article is therefore: *"how to challenge Product Designers with the sharing principle?"*.
3. Prescriptive Study I: The proposition of the step-by-step method for AESA for designers has been formulated based on a compilation of (1) the AESA literature methods, (2) insights gathered from discussions with expert academics in AESA and with designers in industry interested with the topic, and (3) learnings outcome obtained from the practical experience gained during the case study conducted with a product designer and a researcher both experts in Power Electronics, but new to AESA. A specific focus is made on recommendations to best support the product designers in charge of the AESA to define the sharing principles and to challenge their design choices accordingly.
4. Descriptive Study II: outcomes from the proposition and critical analysis of the method addressed to Product designers for AESA steps and sharing principles.

### 4.1 Literature study methodology

The literature review was structured following the scheme outlined in Figure 2. Starting from a literature review conducted with skilled researchers in the field of AESA, the main relevant corpus of papers has been classified into three main categories of research results: conceptual, methodological, and operational (cases studies).

The articles best covering one or more of these categories were selected to constitute the research foundation of this article. Iterations of this process have been conducted over time and research networks (so-called the "ricochet" process) to end up with twenty articles.

At the end of the first iteration, six articles were identified as central in the field of AESA: [Hauschild *et al.* (2020)] ; [Bjørn *et al.* (2020)] ; [Ryberg *et al.* (2020)] ; [Hjalsted *et al.* (2021)] ; [Ryberg *et al.* (2018b)] ; [Riondet *et al.* (2022)]. From this corpus, additional articles were examined through a "ricochet" process, extracting articles cited and considered relevant to this research, and selected in regard of section 3 research question. The process ended when no new information on AESA and sharing principles issues for designers appeared in a new corpus of articles. A total of 20 articles were carefully studied during the period 2023-2024. This ground foundation of research output sat up the AESA (including sharing principles) concepts, the AESA methodological steps, as well as, provided some illustration base on operational case studies. A case study has been set up to test and validate the proposed methodology. The methodology associated with this case study is described in the next section.

### 4.2 Case study description: participant, timeline, etc.

The case study focuses on a DC-DC converter ecodesign project conducted at the G2ELab electrical engineering laboratory in France from Feb. 2023 to Sept. 2023. The product, also referred to as a "buck converter", is a converter prototype designed and manufactured by a Power Electronics (PE) engineer in the laboratory. The buck converter serves educational purposes in an electrical engineering school. It functions as a demonstrator to illustrate the operations of a buck converter and the design of control laws. In this case study, the PE designer and two lifecycle engineers collaborated together in the ecodesign project. The objective of this ecodesign project is to assist the PE designer in optimizing the functional structure and component selection of the product to minimize environmental impacts for ensuring its compliance with planetary boundaries.

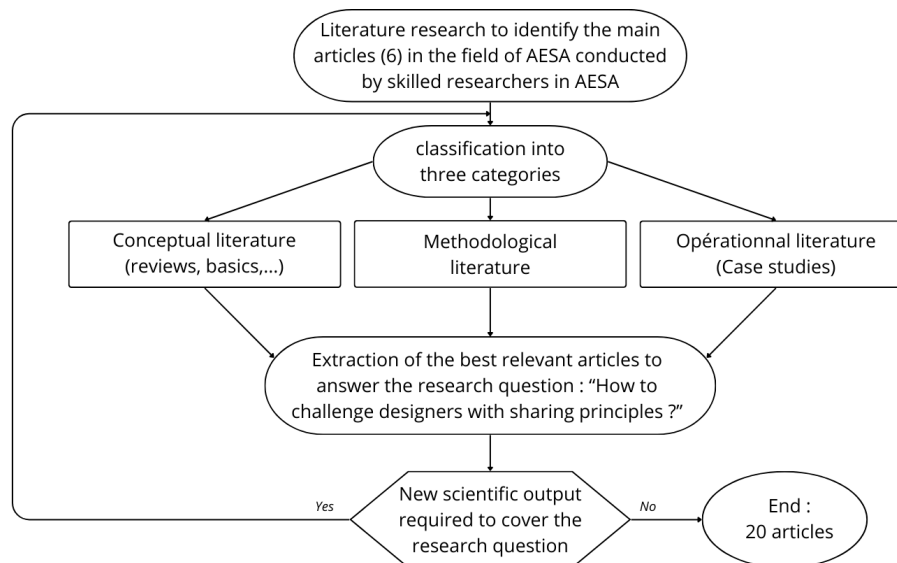


Figure 2: Literature review process conducted in this research focusing on supporting product designers in conducting an AESA, and be challenged by the sharing principles

An AESA is therefore employed to evaluate the converter's environmental impacts relative to the planetary boundaries ([Bjørn *et al.* (2020)]). This absolute comparison to planetary boundaries helped to identify key steps and practical difficulties to be clarified for designers. A specific focus on the step addressing the sharing principle choices to the PE designer in this case study was conducted.

### 4.3 Data collection and step-by-step analysis

The data involved in this case study are twofold: the Life Cycle Inventory data related to the case study product for environmental impact evaluation and the data used to calculate the SoSOS of the studied product.

Firstly, to construct the Life Cycle Inventory (LCI) of the case study product, detailed technical specifications and Bills of materials (BoM) were provided by the PE designer. Based on these documents, a cradle-to-gate analysis was conducted, and a list of the material and energy flows involved across the lifecycle of the reference DC-DC Buck converter was collected. The foreground system for LCA comprises all processes involved in each lifecycle stage, including manufacturing, distribution, usage, maintenance, and end of life. The background system provides support to the foreground system and manages the exchange of material and energy flows between the ecosphere and technosphere. As for secondary data, CODDE® 2023-02 database was used.

Both approaches of AESA (presented in Figure 1) were applied to the case study. The Environmental Footprint (EF3.0) method was used to evaluate six environmental impact categories as recommended by the European Commission ([European Commission (2021)]).

The SoSOS of the buck converter, as we will see, has been computed following:

- Carrying Capacities (i.e. normalized references) provided by Bjørn *et al.* (2015) ([Bjørn *et al.* (2015)]),
- Global population, retrieved from the statistics of the United Nations,
- Population of France, the data was retrieved from the website of the National Institute of Statistics and Economic Studies,
- French budget for higher education, the data was retrieved from the French Ministry of Higher Education and Research,

- Number of students in France and number of students in the electrical engineering school (Grenoble INP - ENSE3), the data were retrieved from the French Ministry of Higher Education and Research, and administration of the Grenoble INP - ENSE3,
- Annual budget for the teaching equipment and for the buck converter, the data were retrieved from administration of the Grenoble INP - ENSE3,

Following the AESA methodology, the environmental space (or SoSOS) associated with the buck converter was calculated for each environmental indicators. Then, the absolute sustainability ratios were then calculated to evaluate the environmental performances of the Buck converter relative to the designed absolute environmental limits.

## 5 AESA clarification for designers

### 5.1 Overview of the core vocabulary used in AESA

AESA is applied by LCA practitioners from various domain. The vocabulary they use varies and may create confusion. This section aims to clarify the keywords and concepts encountered in the literature in absolute sustainability to support designer conducting an AESA. Core AESA concepts that need to be understood by designers are: *Safe Operating Space*, *Share of Safe Operating Space*, *Carrying Capacity*, *Allocation Principle*, *Distributive Justice Principle*, *Environmental space*, *Upscaling method*, *Sharing Principle*, *Science-Based Target*, *Absolute Sustainability Ratio*, *Downscaling*, *Down-limiting*, as well as *Eco-effectiveness*.

These core concepts can be split into four categories relating to: 1) Earth system and environmental sciences, 2) expressions of sustainability; 3) sharing principles; and 4) environmental impact assessment.

Tables 5 and 6 in Appendices clarify the meaning associated to this core concepts by synthesizing the available definitions given by the literature. The concepts are ranked into the four proposed categories. Some terms are used as synonyms in the literature. For instance, the Share of Safe Operating Space and the environmental space are used respectively by [Ryberg *et al.* (2020)] and [Kara *et al.* (2023)] with similar meaning.

### 5.2 Overview of the core concepts used in AESA

Figure 3 presents the core concepts used in this paper to understand the method associated to AESA required for a designer.

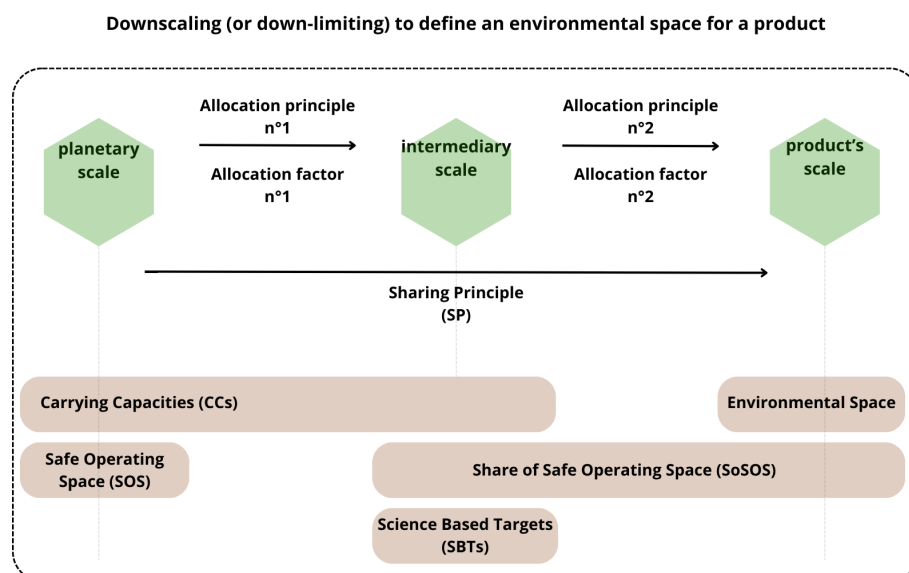


Figure 3: Clarification of the methodological core concepts used in AESA for designers, associated with the definition of an environmental space for a product in AESA (*i.e.* down-limiting).

The core methodological concepts are organized with regard to three scales: the environmental phenomena scale (*e.g.* planetary or regional), an intermediary scale (*e.g.* country, company or individual) and the target scale (*e.g.* the product designed). This scales clarify the articulations, detailed in the next paragraph, between the *sharing principle*, the *Allocation Principles* (APs) and the *Allocation Factors* (AFs).

In simple words, the process of downscaling the planetary boundaries (quantified in the related control variables units) is equivalent to applying a cascade of multiplication factors to the SOS, so as to obtain a SoSOS at a lower scale. In this article, the lower scale considered is the studied product one. The terms *Carrying Capacities* (CC) refers to the planetary or intermediary scales (*e.g.* region) and *Science Based Targets* (SBTs) to intermediary scales (*e.g.* country, industrial sector, company).

The concept of *environmental space* is assimilated, in this paper, to a SoSOS defined specifically for a product. Downscaling (or down-limiting) is not a simple process as it requires consideration of the allocation of CCs (based on PB or not). These systemic and global reflections must therefore take into account the object of the study as well as the dynamics related to the human factors influencing this allocation. [Häyhä *et al.* (2016)] reminds us that any downscaling should be viewed through three dimensions: biophysical (understanding the complex framework of PBs), economic (as human activities significantly impact the Earth system), and ethical (for climate justice purposes). In practice, allocation will be carried out based on Distributive Justice Theories (DJT) [Ryberg *et al.* (2020)]. For instance, questions might arise regarding whether to distribute the rights of impact equally among individuals, to prioritize those with fewer means to reduce their impact, or to favor those who have historically had a significant impact through acquired rights. Consequently, the *environmental space* could also be referred to as a socio-environmental space. These DJTs will be concretely translated into calculation rules called Allocation Principles (APs). An AP is characterized by its designation and the calculation formula to which it refers. This calculation formula is often a division that allows to share a right of impact based on a chosen DJT. For example, if an equal distribution among individuals is chosen as the DJT, the AP named "equal per capita" can be applied, which is calculated as the ratio between the *number of people in the destination space* and the *number of people in the starting space*. The result of this calculation is referred to as the "Allocation Factor (AF)." It is the number by which an right of impact must be multiplied to effect a downscaling. Often, when conducting downscaling, several steps are required to reach the targeted scale. For example, downscaling from a planetary scale to a national scale, then to a regional one, a household scale, etc. This sequence of downscalings corresponds to a chain of Allocation Principles (APs). This chain of APs is called the "Sharing Principle" (SP). Figure 3 schematically represents the entire vocabulary that has just been introduced. It is noteworthy that in the literature, the terms Allocation Principle, Allocation Factors, and Sharing Principle are used interchangeably. The distinction has been made in this article to facilitate the understanding and implementation of an AESA for designers.

### 5.3 Allocation principles for designers

To facilitate the choice of APs for designers, a classification for different APs found in the literature is proposed. Table 2 presents this classification of APs, describing each principle.

In addition, Table 3 details the calculation formula (*i.e.* AFs) associated with each AP, as well as a comment related to their implementation.

| Category of AP                      | Preferred target                | AP                               | Description                                                                                    | Source    |
|-------------------------------------|---------------------------------|----------------------------------|------------------------------------------------------------------------------------------------|-----------|
| Anthropocentric                     | Individuals, people, nation,... | Equal per capital                | Equal for all individuals concerned                                                            | 1,2,3,5   |
|                                     |                                 | Land surface                     | Proportional to the owned surface                                                              | 2         |
| Environmental impact as a benchmark | Nation, industry                | Acquired rights / Grandfathering | Proportional to the environmental impact in a reference year                                   | 1,2,3,4,5 |
|                                     |                                 | Historical debt                  | Inversely proportional to a cumulative environmental impact                                    | 2         |
| Utilitarian for impact reduction    | Nation, industry                | Capacity to reduce               | Inversely proportional to GDP per capital                                                      | 1,2       |
|                                     |                                 | Green incentive                  | Correlated proportionally to value produced and inversely proportional to environmental impact | 1         |
|                                     | Industry                        | Cost-effectiveness ratio         | Inversely proportional to the cost of reducing the environmental impact of production          | 2         |
| Economic                            | Industry, goods, and services   | Value added / Price              | Proportional to the value added / price                                                        | 2,3,4,5   |
|                                     |                                 | Final consumption expenditure    | Proportional to the final consumption expenditure                                              | 1,2,3     |
| Specific                            | Agriculture                     | Caloric content                  | Proportional to the caloric content of a product                                               | 2,4       |
|                                     | Building                        | Agricultural area                | Proportional to the owned agricultural area                                                    | 4         |
|                                     |                                 | Building area                    | Proportional to the building area                                                              | 6         |
|                                     | Education                       | ECTS credits                     | Proportional to the ECTS credits delivered by education                                        | 7         |

1=[Hjalsted *et al.* (2021)] 2=[Bjørn *et al.* (2020)] 3=[Ryberg *et al.* (2018b)] 4=[Chandrakumar *et al.* (2019)] 5=[Brejnrod *et al.* (2017)] 6=[Bendahmane (2023)] 7=Proposal

Table 2: Characterization of selected APs suitable for applying AESA during a design process, adapted from Hjalsted *et al.* (2021) and Ryberg *et al.* (2018).

| Category of AP                      | AP                            | Associated AF                                                                    | Analysis of the formula                                                                                                   |
|-------------------------------------|-------------------------------|----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| Anthropo-centric                    | Equal per capita              | $\frac{Pop_A}{Pop_D}$                                                            | Highly used and relevant (egalitarian principle)                                                                          |
|                                     | Land surface                  | $\frac{Owned\ area_A}{Owned\ area_D}$                                            | Rarely used, inequitable for global impacts                                                                               |
| Environmental impact as a benchmark | Acquired rights               | $\frac{Ref\ impact_A}{Ref\ impact_D}$                                            | Highly used, easy to implement, highly inequitable                                                                        |
|                                     | Historical debt               | $\frac{\sum Impact_D}{\sum Impact_A} \times \alpha$                              | Rarely used, useful in combating climate injustice                                                                        |
| Utilitarian for impact reduction    | Capacity to reduce            | $\frac{Pop_A}{Pop_D} \times \frac{GDP/cap_D}{GDP/cap_A} \times \alpha'$          | Rarely used but relevant for combating climate injustice. The choice of this criterion is especially politically engaging |
|                                     | Green incentive               | $\frac{Turnover_A}{Turnover_D} \times \frac{Impact_D}{Impact_A} \times \alpha''$ |                                                                                                                           |
|                                     | Cost-effectiveness ratio      | No data                                                                          |                                                                                                                           |
| Economic                            | Value added / price           | $\frac{Price_A}{Price_D}$ or $\frac{VA_A}{VA_D}$                                 | Easy to apply but significant economic bias                                                                               |
|                                     | Final consumption expenditure | % of FCE                                                                         |                                                                                                                           |
| Specific                            | Caloric content               | $\frac{Caloric\ content_A}{Caloric\ content_D}$                                  | Utilitarian but simplifies feeding principles                                                                             |
|                                     | Agricultural land             | $\frac{Agricultural\ land_A}{Agricultural\ land_D}$                              | Non-utilitarian (does not consider land yield)                                                                            |
|                                     | Real estate surface           | $\frac{Real\ estate\ surface_A}{Real\ estate\ surface_D}$                        | Relevant indicator for buildings with the same function                                                                   |
|                                     | ECTS credits                  | $\frac{Nb\ ECTS\ credits_A}{Nb\ ECTS\ credits_D}$                                | Representative of educational value                                                                                       |

Table 3: Complement to the characterization of the selected APs

## 6 A method for practicing AESA by key steps

To help designers appropriate sharing principles from AESA, the present section details a step-by-step methodology. Figure 4 represents the proposed methodology in the classic formalism of LCA, following the steps Goal and Scope, LCI, LCIA and Interpretations.

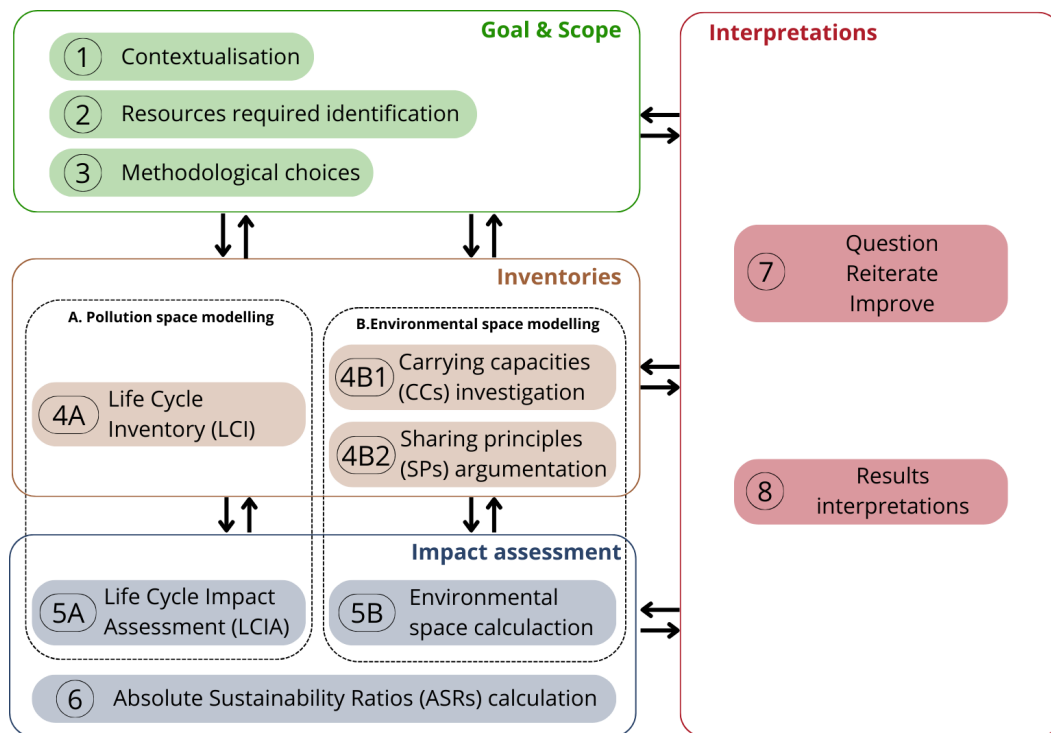


Figure 4: Overview of the proposed key steps to conduct an AESA

Each subsection is divided in two parts: a description of the corresponding step including theoretical aspects (general description and the associated references) and practical aspects to facilitate the implementation of the given step (recommendations, existing tools, experts to consult, etc.) ; an illustration based on the case study conducted during this research on a buck converter used for power electronic educational purpose in a french engineering school.

### 6.1 Contextualisation (step 1)

#### 6.1.1 Description

Formalize the context of the case study, including the object of study, study objectives, geographic scope, actors, decision-makers, time frame, budget, and the knowledge and skills of the practitioners.

#### 6.1.2 Illustrative case study

**Context and Objective** The question raised by this case study is "Can an educational mock-up for student practice be sustainable from the point of view of planetary boundaries?" It constitutes an illustrative case study to explore a new AP based on ECTS credits and test usual APs.

**Object of Study** The case study focuses on a Buck-type DC/DC power electronics converter used in an educational context. This buck converter is a prototype and transforms a continuous electrical flow oscillating between 25V and 30V with a maximum power of 100W into a stabilized 12V output voltage. The buck converter is divided into nine modules



detailed in Figure 5. It is used 8 hours per year for practical work by students in the Electrical Energy Engineering program at the ENSE3 School (Grenoble, France).

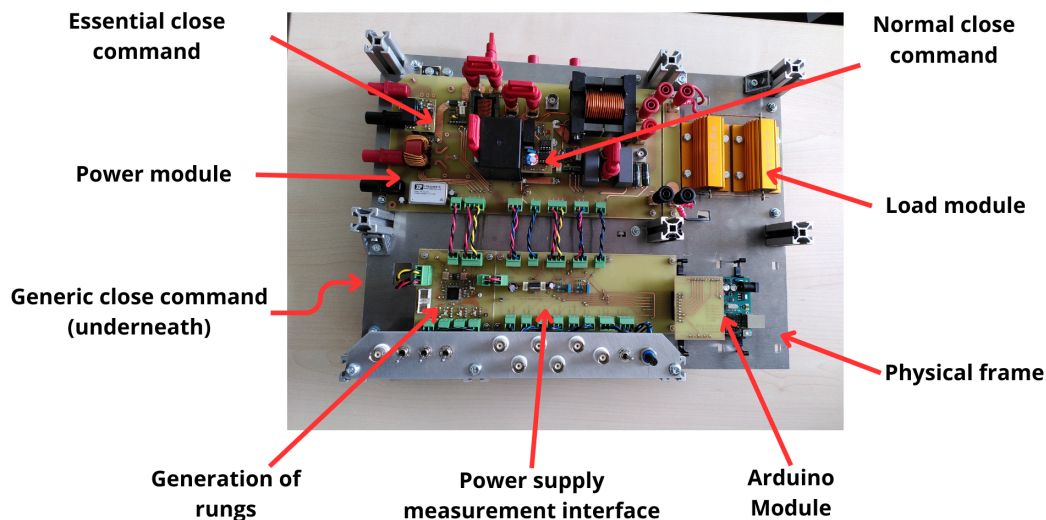


Figure 5: Photograph of the buck converter, the prototype intended for educational purpose and studied object of the AESA.

**Study Implementation Conditions** The study will be carried out in a pedagogical context. The analyst has a good understanding of LCA and AESA methodologies. He has a 6-month period to conduct this study in parallel with his research work. The necessary software for conducting the LCA are provided by the laboratory G-SCOP. He will be assisted by his research team, as well as the designer of the converter. There is no specific budget available for the realization of this study.

## 6.2 Resources required identification (step 2)

### 6.2.1 Description

Conduct a review of the development of AESA methods, the robustness of their models, their specificities, etc. Obtain information on the availability of local biophysical data with respect to the key indicators of different types of LCA. Various AESA methods have been developed, notably since 2015. Unlike standardized LCA approaches, these approaches are recent proposals by researchers.

Therefore, the person who wants to carry out an AESA must choose the method to be applied, the indicators, and the degree of study finesse (especially regarding spatial and temporal differentiation). These choices should therefore be based on an important contextualization phase and state of the art at the start of the study. The various constraints, preferences, frameworks, etc. must be formalized at the start of the study to facilitate the next methodological choice phase. The criteria to be taken into account are the following:

- **Context and objectives of the study:** It is necessary to prioritize the maximum coverage of the set of indicators studied, to avoid any burden shifting process<sup>1</sup>. If the context of the study does not allow for the quantification of the impact on all indicators (due to lack of time, resources, knowledge, data, etc.), it will be necessary to prioritize the presumed most impactful indicators ([Bjørn *et al.* (2020)]). For example, if the study focuses on a case study in

<sup>1</sup>A design strategy that results in transferring the majority of the environmental impacts from one indicator to another, sometimes making this impact invisible if it is not taken into account. A classic example is that of solar panels, which reduce greenhouse gas emissions but increase chemical pollution in water and soils

the field of agriculture, it will be essential to take into account indicators such as disturbance of phosphorus and nitrogen cycles, land use change, biodiversity and freshwater use while other indicators such as stratospheric ozone depletion will be less important. The analyst's skills are also a criterion to be taken into account (knowledge of the method, use of appropriate software, etc.).

- **Data and methods available, models robustness :** These criteria must necessarily be taken into account to choose the AESA approach. For example, it will not be possible to carry out a highly regionalized study if there is no bio-geophysical data available on the region under study. In addition, since the methods evolve very quickly, it is important to find out about the latest practices, and to favor those with strong robustness.

### 6.3 Methodological choices (step 3)

#### 6.3.1 Description

Choose the modalities for analyzing the case study, including the functional unit, the Type of AESA, the indicator set, and the boundary system in accordance with the target scale for defining the environmental space. These choices should result from the contextual analysis and the state of the art previously conducted.

As the AESA is a recent topic, the state of the art is currently an essential step to ensure the quality of AESA given the current state of academic knowledge on the subject.

#### 6.3.2 Illustrative case study

**Functional Unit** "Demonstrate the function of the DC/DC converter during an academic year for five student pairs in practical work + one lecture (a total of 16 hours and 12 minutes of usage)."

It is assumed that the use of the converter is consistent with that described in the functional unit over the entire lifespan: 3 groups of ASI students with 8 hours of practical work per group, in addition to 2 groups of IEE students with 8 hours of practical work per group, plus 4 hours of lectures using one of the ten prototypes available in the school (by assumption), and it is considered that during all these uses, the prototype is powered on at maximum power (100W) for half of the time. Thus, there are 16 hours and 12 minutes of usage and 1.620 kWh of energy consumed. All inventories and results will be constructed based on this functional unit.

**Selected Scenario and System Boundary** This LCA was conducted based on a single life cycle scenario. This scenario includes resource extraction, component manufacturing, transport, final assembly, use, maintenance, disassembly, and end-of-life. The end-of-life scenario chosen is as follows: the converter has a 25-year lifespan. The passive components of the close commands have a lifespan twice that of the converter. They will be desoldered at the end of life and reused if still functional, and may come from reuse. The active components will be replaced twice during their lifespan. All non-functional components will be considered sent to a WEEE treatment center near Angers from Grenoble, except for the metal which will undergo an additional treatment.

**Complementary modelling assumptions** Additional assumptions were made for the realization of this LCA based on discussions with the designer and the user of the converter :

- The transportation data, including type and distance, were considered as provided by the PEP Ecopassport program (<http://www.pep-ecopassport.org/fr/>), except for boat journeys, for which the country of origin was known, and the shipping to the treatment center in Angers.
- The electricity mix used is the average mix in France.
- The flows related to the desoldering process are neglected.
- It is assumed that the PWB printing flows in the laboratory are the same as those in factories.
- Each year of usage is allocated 1/25th (25-year lifespan) of the impacts related to extraction, manufacturing, transport, assembly, disassembly, and end-of-life processes.



**Chosen approach of AESA** For this study, the two approaches of the AESA (see Figure 1) have been applied on the same studied object. The results of the study will consequently be based on the characterization factors developed in [Ryberg *et al.* (2018a)] for AESA approach (1) and on the EF characterization factors for AESA approach (2).

**Selected Sets of Indicators** Table 4 synthesizes the selected set of indicators used in the case study for both AESA approaches: six for approach (1) and seven for approach (2).

| AESA approach (1)<br>(PB control variables) | AESA approach (2)<br>(EF categories)             |
|---------------------------------------------|--------------------------------------------------|
| Energy imbalance (W/m <sup>2</sup> )        | Climate change (kgCO <sub>2</sub> eq/year) (CC)  |
| Ocean acidification ( $\Omega$ aragon)      | Ozone depletion (kgCFC <sup>-11</sup> ) - (OD)   |
| Stratospheric ozone depletion (DU)          | Photochemical ozone formation (kgNMVOCeq)        |
| Atmospheric aerosol loading (AOD)           | Terrestrial eutrophication (molNeq) (TE)         |
| Biogeochemical flows - Regional P (Tg P)    | Freshwater eutrophication (molPeq) (FE)          |
| Biogeochemical flows - N (Tg N)             | Marine eutrophication (molN <sub>eq</sub> ) (ME) |
|                                             | Freshwater consumption (m <sup>3</sup> ) (FC)    |

Table 4: Set of selected indicators for each AESA approach to be applied in the case study.

## 6.4 Life Cycle Inventory (step 4.A)

### 6.4.1 Description

The methodological choices will have allowed us to determine the LCA method used for the study. According to this method, it will be necessary to construct the LCI of the study object.

## 6.5 Carrying Capacities investigation (step 4B1)

### 6.5.1 Description

Now that the Goal & Scope phase is completed, we will proceed with the inventory analysis. In an AESA, it is necessary, on one hand, to consider the flows associated with the studied functional unit (column B, on the right) to conduct a LCA using a bottom-up approach. But it is also essential to quantify an impact allocation to this functional unit: this represents the top-down approach (column A, on the right). We are focusing on this aspect now.

In this top down approach, we aim to consider a Safe Operating Space (SOS) at a large scale, and allocate it to the scale of our case study. This space is defined by a set of indicators related to the biophysical dynamics of the Earth. Each of these indicators is associated with a carrying capacity (CC): "the maximum sustained environmental intervention a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert" ([Bjørn *et al.* (2015)]). In this section, we explain how to establish our starting SOS, composed of its various CCs. This defined SOS can then be downscaled in order to obtain a SoSOS.

To sum up, for each selected indicator, it is necessary to define:

1. Its geographic and temporal extent of impact. Depending on the type of indicator, it may be more or less local. The level of detail will depend on the study context. For example, if the practitioner has limited data, global averages can be used to define the thresholds. If inventory data allow the differentiation of several local impact locations, multiple geographic extents will need to be defined.
2. Its CC. It may already be defined globally or calculated based on an intensive boundary and data from the geographic and temporal context.

It should however be noted that the definition of a CC depends on the type of AESA chosen.

**For AESA approach (1) (LCA to PB)** In the case of planetary boundaries, the method to define the CC depends on the nature of the studied phenomenon. If the phenomenon has a global-scale impact (such as climate change, stratospheric ozone depletion, biogeochemical flows, ocean acidification, and introduction of novel entities), the boundary is often known, and the SOS is calculated by subtracting the boundary value from the pre-industrial value of the studied phenomenon [Ryberg *et al.* (2018a)]. However, certain phenomena only manifest at a local scale (change in biosphere integrity, land system change, P-biogeochemical flow, freshwater use, and atmospheric aerosol loading). For these limits, the geographical scope of the study must be clearly defined for each limit (e.g., a watershed, a region, a continent, etc.). It will also be possible to differentiate temporally, and thus redefine this SOS for different periods of time (e.g., a season or month of the year). The definition of this global SOS will require additional expertise in the relevant limit field and cannot be based on average values larger than that of the geographical context of the case study.

**For AESA approach (2) (PB to LCA)** While the PB framework has numerous advantages, it can sometimes be challenging to conduct an AESA based on these indicators, mainly due to the lack of maturity of methods relying on this framework. In such cases, it may be possible to define CCs directly on the indicators related to the classical LCA indicator set (also known as Area of Protection). Two approaches are proposed here:

- The first method involves using normalization factors. These factors are based on the PB framework but have been translated to the classical LCA indicators. In a study by [Bjørn *et al.* (2015)], the authors compiled normalization factors for 11 indicators based on existing literature. The main drawback of this method is that it relies on a multitude of studies (making it tedious to list all the normalization factors proposed), and these factors can sometimes become obsolete due to the dynamics of the Earth system.
- Another method may involve moving away from the PB framework and its intrinsic CCs, instead defining thresholds based on one or several formulated assumptions or predictive scenarios of consumption/emissions. For instance, [Bendahmane (2023)] conducted an AESA on the use of materials in the French building sector. She defined CCs by assuming the construction of new buildings solely from the recycling output of dismantled buildings. It is not uncommon to see AESAs basing their impact on the "Climate Change" category on the CO<sub>2</sub>eq emission indicator and their CCs on scenarios or objectives proposed by governments. An example is the study by [Chandrakumar *et al.* (2019)], which performed an AESA based on a carbon emissions scenario aiming to stay below a 2°C global warming threshold.

### 6.5.2 Illustrative case study

For AESA approach (1), the CCs are provided by the general framework of PBs.

For AESA approach (2), the normalization factors are given in "Impact per person per year". It was sufficient to multiply these factors by the estimated world population of approximately 8,045,310,000 (on the date of the survey).

## 6.6 Sharing Principles argumentation (step 4B2)

### 6.6.1 Description

Selecting APs is currently not a designers or LCA experts practice. This operation, involving Distributive Justice Theories (DJTs), is purely political in nature. Indeed, determining who has the right to impact and to what extent is a collective consideration rather than an individual-scale decision.

The selection of APs must therefore be conducted through dialogue among various stakeholders such as citizens, political representatives, corporate executives, etc. The objective of the LCA practitioner here is to propose and facilitate this dialogue, aiming to enhance understanding of the stakes and to enable a collective and informed decision regarding the Allocation Principles. [Hjalsted *et al.* (2021)] advises always going through an individual scale before increasing the scale if necessary. This approach ensures that humans remain at the center of decisions and prevents the allocation of impact rights to corporate entities. However, this path down to the individual level is not mandatory and not systematic in the literature. [Ryberg *et al.* (2018b)] has shown the strong variability of the results of AESA depending on the chosen SP. This variability is even more pronounced for certain impact categories such as water resource use.

Ryberg *et al.* propose the following criterion for absolute sustainability: "Here, a criterion for stating that an activity is absolutely sustainable could be that at least four sharing principles are applied and that 95% of the iterations [...] should not exceed the assigned SoSOS."

### 6.6.2 Illustrative case study

For our case study, a specific AP have been proposed for the education sector: ECTS Credits. For this principle, the share assigned to an educational activity is proportional to the number of ECTS credits it delivers. Only one SP has been tested. We selected first the APs with strong recommendations, and selected the ones compatible with our case and with which we had data we can collect regarding our resources. Only the first step (global to national) were tested with a strong recommended AP (equal per capita). Then we reiterated the process with medium recommended APs (none were compatible with our time and data resources). Eventually, we completed the last downscalings with weak recommended APs. The method for sectioning APs leads us to a dominance of weak recommended APs, which is not an ideal situation, but illustrates the difficulty to conduct a robust AESA with little time and data. The SP and its corresponding AFs are schematically represented in Figure 6.

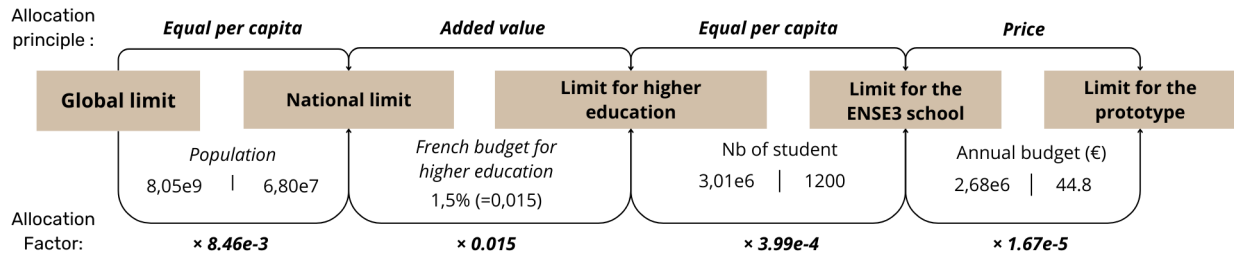


Figure 6: Schematic representation of the Sharing Principle in the case study

## 6.7 Life Cycle Impact Assessment (step 5A)

### 6.7.1 Description

The inventory and the chosen LCA methodology will ultimately allow us to calculate the environmental impacts of our study object.

## 6.8 Environmental space calculation (step 5B)

### 6.8.1 5B. Description

Once CCs and SPs have been determined, the environmental space (i.e. the SoSOS) can be calculated for each indicator using the formula:

$$\text{SoSOS} = \text{CC} \cdot \prod_i AF_i$$

with "i" the number of the intermediary scale between CC and the targeted scale.

### 6.8.2 5A. Illustrative case study

In the DC-DC buck converter case study, the SoSOS was calculated based on LCA and PB indicators (which means the right of impact of the DC-DC converter prototype throughout its life cycle). Taking the example of climate change. Referring to the PB based calculation, the SoSOS will be expressed in W/m<sup>2</sup>, and referring to the LCA based impact calculation, the SoSOS will be expressed in kgCO<sub>2</sub>eq/year. The following illustration is given for the DC-DC Buck converter for this (similar) indicator:

1. For LCA based indicator: the planetary carrying capacity to be  $7.93 \times 10^{12}$  kgCO<sub>2</sub>eq/year established by Bjørn (2015) [Bjørn *et al.* (2015)], the calculation of the SoSOS for CO<sub>2</sub> emissions is as follows :

$$\begin{aligned}\text{SoSOS} &= \text{CC} \times \prod \text{AFs} \\ &= 7.93 \times 10^{12} \times 8.46 \times 10^{-3} \times 0.015 \times 3.99 \times 10^{-4} \times 1.67 \times 10^{-5} \\ &= 6.7 \text{ kgCO}_2\text{eq / year}\end{aligned}$$

2. For PB based indicator: the planetary carrying capacity to be  $1 \text{ W/m}^2$ , the calculation of the SoSOS for energy imbalance is as follows :

$$\begin{aligned}\text{SoSOS} &= \text{CC} \times \prod \text{AFs} \\ &= 1 \times 8.46 \times 10^{-3} \times 0.015 \times 3.99 \times 10^{-4} \times 1.67 \times 10^{-5} \\ &= 3.44 \times 10^{-13} \text{ W/m}^2\end{aligned}$$

Certainly, for our case study, the entire set of SoSOS – encompassing those for all indicators, both for the method based on LCA and PB indicators – has been calculated. Only two examples of SoSOS calculations are presented above, but in practice, it is necessary to calculate these SoSOS for all the indicators under study.

## 6.9 Absolute Sustainability Ratios (ASRs) calculation (step 6)

### 6.9.1 Description

The general goal of our AESA is to compare the SoSOS calculated with A-steps (which corresponds to a right of impact) with the actual impact of our object of study calculated with B-steps. The results called ASR is the ratio between these two values ([Hjalsted *et al.* (2021)]). It is calculated as follows:

$$\text{ASR} = \frac{\text{Environmental impact of the product (= Pollution space)}}{\text{SoSOS allocated to the product (= Environmental space)}}$$

For each indicator, the object of study is considered 'absolutely sustainable' if its ASR is less than 1, meaning that its actual impact is below its impact right.

### 6.9.2 Illustrative case study

After conducting the B-steps with the software EIME for AESA approach (2), results of this paper case study have been exported and converted in PB indicators thanks to the method of [Ryberg *et al.* (2018a)]. The calculations of the different SoSOS enabled to calculate the ASRs presented in figure 7. ASRs values are expressed in each indicator unit below the graph, a) on the top, for LCA based indicators and b) above for PB based indicators. For instance, the ratio obtained for climate change is equal to 1.4, which appears slightly up to the red line drawn for a ratio equal to 1. This red line corresponds to the "impact right" in an absolute sustainability meaning. In the case of the energy imbalance calculated for PB based indicators for this same study, the ratio obtained is equal to 2.3, which also appears slightly up to the absolute sustainability ratio red line.

## 6.10 Question, Reiterate, Improve (step 7)

Once the ASRs are calculated, results need to be carefully analyzed to draw relevant conclusions regarding the remaining work to be done for designers. Indeed, both AESA and LCA are iterative processes. Depending on the available time and resources and the relevance of results that are targeted, it is required to conduct: a sensitivity analysis, an uncertainty analysis on the LCI and on the method, refine the inventory focusing on hotspots, test alternative scenarios for the object of study, question the methodology used, the choice of indicators, refine the quantification of CCs (*e.g.*, spatial and temporal refinement), try new SPs and analyze the influence of each allocation on the result, among other considerations.

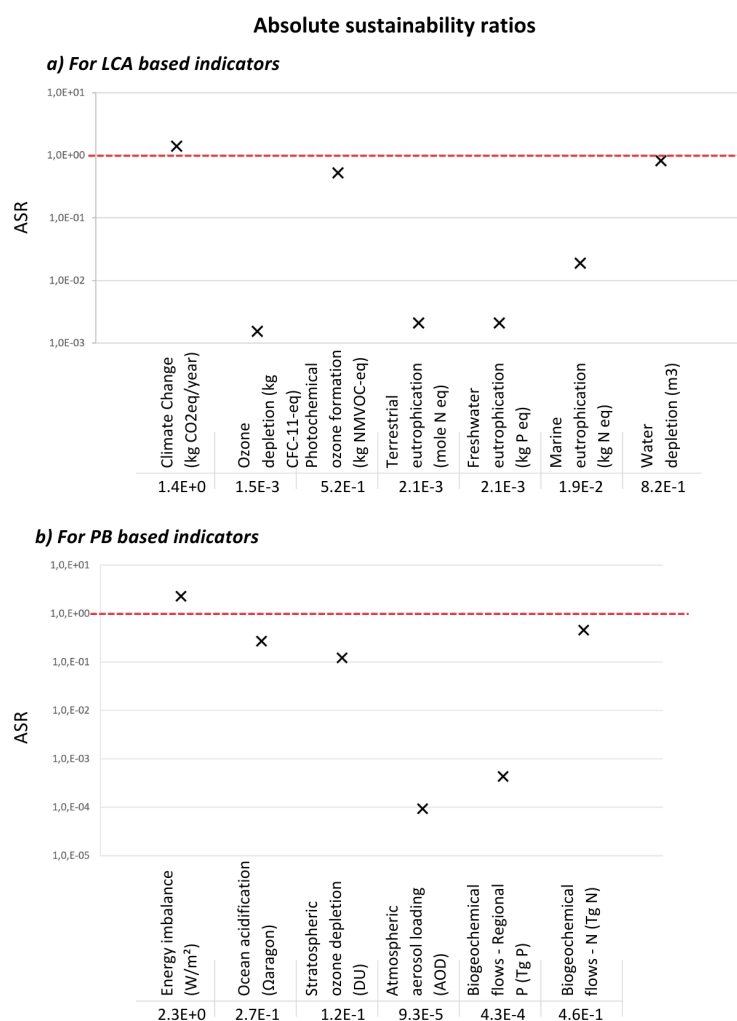


Figure 7: AESA results of the illustrative case study, a) for LCA based indicators; b) for PB based indicators

## 6.11 Result interpretation (step 8)

### 6.11.1 Description

This phase is crucial for designers capacity to get familiar to the AESA method, capturing principles that are distinct to the LCA method, and to the results graphical representation that differs from LCA ones. **The interpretation phase should highlight design and deployment queries in the context of current global and sub-global environmental crises.** Therefore, the quantitative nature of the absolute sustainability result should not necessarily take precedence; instead, it should allow for a critical analysis of the relationship between an artifact, its societal deployment, and the planetary framework within which it operates.

The added value of conducting an AESA for a designer rather lies in the approach to questioning the impacts of an object of study regarding PBs, rather than in obtaining a sustainability ratio from the calculation followed in the method. The ratio limit equal to "one" (cf. figure 7 displayed in red interrupted line) can be drawn on the results graph to catch the indicators associated with unsustainable estimated impact values. However, the consensual/current method bases the quantification of a given CC by the difference between the CC related boundary value and its pre-industrial value, without considering the

current bio-geo-physical situation [Ryberg *et al.* (2018b)]. It is therefore crucial to highlight to designers that presently, 6 out of the 9 planetary boundaries have been quantified as exceeding their boundaries [Wang-Erlandsson *et al.* (2022)]. The concept of absolute sustainability for an object of study is therefore somewhat abstract, and any seemingly 'positive' result needs to be put into perspective. Presenting a result indicating the sustainability of an artifact as an unused impact budget should not be the case; rather, the approach should involve questioning the Allocation Principles (APs) to contextualize the development of this artifact in society regarding planetary boundaries. The red line exceeded or not, for each ASR, should therefore be reinterpreted accordingly, in addition to the value added provided to the local society, by the product under study.

### 6.11.2 Illustrative case study

We initially observe that the **product is sustainable in absolute terms** for both SPs, for all represented indicators, except for the climate change indicator.

This result should be analyzed with a perspective on several points :

- No sensitivity or uncertainty analysis was performed.
- The choice of indicators is very limited due to data availability constraints. Nevertheless, we observe that the prototype is particularly impactful in terms of climate change, photochemical ozone formation, water depletion, ocean acidification, and disruption of the nitrogen cycle.
- Defining a SoSOS at the scale of a single product is heavily criticized by [Ryberg *et al.* (2016)]. The interpretation of absolute sustainability can sometimes lose its meaning due to the result's dependence on the choice of APs. Additionally, this approach does not promote questioning the product's function in a more comprehensive context (company scale, sector scale, etc.). Therefore, the study of absolute sustainability was not conducted at the scale of each module and sub-function.

While the absolute sustainability of a prototype created in a non-optimized manner with highly impactful materials might seem surprising, it should be noted that it is part of an academic context, particularly within higher education. The significant budgetary importance associated with this sector may explain the considerable size of the allocated SoSOS to the prototype, thus making its absolute sustainability more comprehensible.

## 7 Discussion, reflexions and subjects of thinking

### 7.1 Integrating AESA into ecodesign practices

**Design scale and absolute sustainability** Downscaling to a small scale (*e.g.* a single consumer product) is widely criticized, notably by [Ryberg *et al.* (2016)]. Indeed, beyond a certain scale, uncertainties have such an influence that the absolute sustainability ratio becomes solely related to the type of APs chosen and no longer linked to the actual impact of the product. Furthermore, the principle of AESA aims to promote discussions for changes in corporate strategies, or even beyond that, for sectoral or societal structural changes. Thus, conducting an AESA at too small a scale does not facilitate radical questioning of the productive functioning mode or consumption patterns, for instance. In response to this, [Riondet *et al.* (2024a)] favour the scale of a technology deployment, making the link between the scale of the product and the needs to which its integration into society responds. Considering fleets of products and the associated cumulated service is a way to question the massification of a product by requiring an explicit deployment strategy from the company.

**Time dependency of the sharing principle** Sharing principles evolving over time can also be applied. Some authors propose them in prospective assessments for specific case studies from different industries (*e.g.* concrete ([Kara *et al.* (2023)]), photovoltaic ([Riondet *et al.* (2023), Riondet *et al.* (2024a)]), battery ([Lavissee *et al.* (2024)])). These case studies are mainly related to industrial sector net-zero emissions strategies. [Ryberg *et al.* (2018b)] and [Wenzel *et al.* (1997)] pointed out the associated issue is regularly updating the sharing principles. Another option is to build evolution scenarios coupled with sensitivity analysis on time-depend parameters (*e.g.* population, economic data, technology mix). In this type of long-term exercise, it is preferable to adopt a forward-looking approach, aimed at representing the field of future possibilities rather than focusing on a specific “predictive” scenario. Indeed, the lack of data, the large number of parameters, and their socio-technical nature render the idea of prediction obsolete. Therefore, the notion of sensitivity of results to key parameters and modelling assumptions is to be preferred. This aspect ties in with the recommendation to propose several sharing principles for a given study.

**Results interpretations in absolute sustainability paradigm** AESA, as presented in this paper, can be understood as a new way to normalize LCA results in a design context. As any normalization computation, it enables to contextualize the impacts, but does not stand alone. It must be combined with other types of analysis (sensitivity analysis, other normalisation process, impact per value added, etc.). AESA enables users to identify hotspots with regard to environmental carrying capacities. However, note that every PB-indicators are hotspots. It means that prioritization must not be applied in AESA as in a traditional LCA because all the PB indicators are hotspots.

**A consensual recommendations for the APs choice: an illusion** Concerning recommendations for the APs choice, there is currently no consensus. [Ryberg *et al.* (2020)] and [Hjalsted *et al.* (2021)] advice to stick to the equal per capita principle whenever possible.

This principle is often used for downscaling in the initial stages of allocation, enabling the distribution of right of among individuals or territories. Unfortunately, in some situations, it is impossible to use this principle. This is particularly the case for upscaling to smaller scales, especially for applications centered on industrial and technical spheres rather than on humans. In such situations, it is advisable to avoid using factors based on economic criteria, which are commonly used due to their ease of application, and to prioritize factors that are more specific to the context of the change of scale (*e.g.* for the agricultural, building, or educational sectors).

However, the application of the calculation must reflect a broader, questioning approach to “rights to pollute, to meet what need”. the ultimate aim of this process is to transform the design process and the entities/institutions behind it. Focusing on which AF to choose, without asking why and what the implications of this decision are, is the opposite of a transformative approach, and puts the practitioner back in the position of a technician.

### 7.2 Integrating AESA into decision-making

**Who is in charge of the APs associated to a product?** As seen in the general methodology, a crucial aspect of AESA is the selection of APs from a global scale for impact rights to a smaller scale. This step is complex as it involves political



considerations and goes beyond the designer's scope in AESA. Usually it is the technical designer and the company leaders who associate a 'right to pollute' with the product (explicitly or otherwise). An (eco-)designer alone cannot justify and question the company's sustainability strategy. He is one of its contributors. The role of the designer, supported by a lifecycle engineer, in the AESA may be to argue about the implementation and eco-effectiveness of the company's strategy. Through their ability to characterise the value produced, this minimal ecodesign team is able to identify relevant metrics and APs to compare the social value generated and the associated environmental impacts.

In the absence of a standard or legislation, the choice of APs must be elaborated by deliberation, as transparent as possible, and justified by arguments. This deliberation can enable the involvement of the stakeholders associated with the product's life cycle and its appropriation by society.

Citizens' convention, elected representatives, opinion poll or referendum can be seen as decision making support to justify a sharing principle. This is possible provided that the final design decision is part of a broader democratic process (*e.g.* questioning needs for a given population).

**The challenge of interdisciplinary sciences and cross-sectorial industries** Multiple expertise are therefore required to support the designer questioning the Sharing Principles and allocations. The allocation per industrial sectors are not adapted to cross-sectorial industrial infrastructures, such as energy production and use, or agriculture. In addition, industrial sectors are subject to specific treatments (*e.g.* military sectors), that slip away from sharing principles associated to individual needs, but are rather related to citizen needs.

In companies, the Absolute Sustainability thinking can have a chance to address the environmental impact roadmap at the strategic level of the organisation.

## 8 Conclusion and perspectives in integrated design

Two main features emerge from the application of Absolute Environmental Sustainability Assessment (AESA) in a design context:

1. AESA requires users to be educated and introduced to justice theory. It implies for instance to be aware of the political aspects of the design choices made.
2. AESA must find a trade-off between systemic vision and operational levers for actions. The product's scale (and its life cycle) is historically associated with the designer's levers, but is potentially not suitable to implement sustainability into the industrial system. That is why Kara *et al.* (2023) work at the scale of the deployment of a product (or industrial sector). However, at this scale, socio-technical phenomena appear. For instance rebound effect. Designers cannot ignore the systemic effects involved with the adoption of products by societies.

Paradoxically, a growing number of engineers and designers ask for adaptation methodologies to ease AESA during their design process. The present article is a response to that call. However, using a SWOT approach could help designers explicit the possible evolution of their design process due to the practice of AESA. After reading this article or similar works, Designers should then, ask themselves the following questions: "*Am I ready to address AESA-associated questions, including ethical questions?*", "*what are the risks and the weaknesses of this approach on my engineering activities?*", "*What could an environmentally constrained design process bring to designers, design teams and companies, or to society as a whole ?*" (*i.e.* the "Strength" and the "opportunities" of AESA practice in product design. To conclude, this work paves the way to further research in integrated design dealing with the research question "*How AESA methods support designers capacity to address socio-technical and political responsibilities of the design choices he is in charge of?*"

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## A Vocabulary clarification

| Keyword                                    | Definition                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | References                                                                                     |
|--------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| <b>Allocation Principle (AP)</b>           | <p>"allocation principle is used to mean a principle by which decisions about how to allocate a given resource between individuals can be made." Hjalsted <i>et al.</i> (2021).</p> <p>"In the literature allocation principle is used interchangeably with the terms sharing principle (Ryberg <i>et al.</i> (2018a)), equity principle (Häyhä <i>et al.</i> (2016)), and distributive principle in the field of political philosophy (Lippert-Rasmussen &amp; Holtug (2007))."</p>                               | [Hjalsted <i>et al.</i> (2021)]                                                                |
| <b>Distributive Justice Theory (DJT)</b>   | "Essentially distributive justice concerns ideal just distribution of benefits and burdens. However, exactly how such ideal just distribution would look is not given. Thus, different distributive theories have been put forward and are being discussed in political philosophy and theory. Indeed, when resources are scarce, distributive justice is prevalent. In much political philosophy and theory studying distributive justice, sustainability itself is considered a matter of distributive justice." | [Ryberg <i>et al.</i> (2020)]                                                                  |
| <b>Upscaling method</b>                    | "It is deemed natural that the first step in allocating shares of the available SOS must always be to downscale it [SOS] to the level of the individual. The main choices to be made are in the first three vertical boxes of Figure 1, namely choices of environmental boundaries to address, allocation principles, and upscaling methods to apply." Hjalsted <i>et al.</i> (2021)                                                                                                                               | [Hjalsted <i>et al.</i> (2021)]                                                                |
| <b>Sharing Principle (SP)</b>              | "An allocation principle together with an upscaling method constitutes a sharing principle" Hjalsted <i>et al.</i> (2021)                                                                                                                                                                                                                                                                                                                                                                                          | [Ryberg <i>et al.</i> (2020),<br>Hjalsted <i>et al.</i> (2021)]                                |
| <b>Science Based Target (SBT)</b>          | "the Science Based Targets (SBTs) has been initiated to organize corporate climate change mitigation measures and help organizations determine the relevant sector reduction pathway towards sectoral decarbonization achieve the 1.5 °C reduction goal." Kara <i>et al.</i> (2023). Can also refers to Science Based Target for Nature.                                                                                                                                                                           | [Kara <i>et al.</i> (2023)]                                                                    |
| <b>Absolute Sustainability Ratio (ASR)</b> | "The third stage is upscaling from the individual to a higher level such as a company, organization, product, service, sector, household or nation. The assessment results in the absolute sustainability ratio (ASR), which is the ratio between the actual impact of the stakeholder in question and the assigned SoSOS. If the ASR $\geq 1$ , the stakeholder can be deemed not absolute sustainable" Hjalsted <i>et al.</i> (2020)                                                                             | [Hjalsted <i>et al.</i> (2021)]                                                                |
| <b>Eco-effectiveness</b>                   | "An eco-effective product can be defined as "a product or a generation of products developed to fulfill a need in the society whose total environmental impact will stay within the allocated environmental space when taking into account the development in volume and technology through its lifetime"                                                                                                                                                                                                          | [Hauschild <i>et al.</i> (2020),<br>Hauschild (2015)]                                          |
| <b>Downscaling</b>                         | "assigning a share of the safe operating space or otherwise downscaling PBs to the scale of the studied activity. Ryberg <i>et al.</i> (2020)"                                                                                                                                                                                                                                                                                                                                                                     | [Ryberg <i>et al.</i> (2020),<br>Hachaichi and Baouni (2020),<br>Riondet <i>et al.</i> (2022)] |
| <b>Down-limiting</b>                       | Used as a synonym of "allocating a SoSOS" and "downscaling" to the product scale.                                                                                                                                                                                                                                                                                                                                                                                                                                  | [Riondet <i>et al.</i> (2022)]                                                                 |

Table 5: Glossary associated with absolute sustainability targets and the definition of an environmental space

| Keyword                               | Definition                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | References                                                                                                                                                     |
|---------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Safe Operating Space (SOS)</b>     | <p>"planetary boundaries [as a concept,] for estimating a safe operating space for humanity with respect to the functioning of the Earth System. We make a first preliminary effort at identifying key Earth System processes and attempt to quantify for each process the boundary level that should not be transgressed if we are to avoid unacceptable global environmental change. Unacceptable change is here defined in relation to the risks humanity faces in the transition of the planet from the Holocene to the Anthropocene" Rockstrom <i>et al.</i> (2009).</p> <p>"The PB framework aims to help guide human societies away from such a trajectory by defining a "safe operating space" in which we can continue to develop and thrive. It does this by proposing boundaries for anthropogenic perturbation of critical Earth-system processes. Respecting these boundaries would greatly reduce the risk that anthropogenic activities could inadvertently drive the Earth system to a much less hospitable state." Steffen <i>et al.</i> (2015).</p> <p>"For each Earth-system process, a "safe operating space" (SOS) can be defined as the distance between a boundary (regional or global) and a reference value, usually representing pre-industrial conditions." Bjorn <i>et al.</i> (2020).</p>                       | <p>[Rockström <i>et al.</i> (2009), Steffen <i>et al.</i> (2015), Ryberg <i>et al.</i> (2018a), Bjørn <i>et al.</i> (2020), Hjalsted <i>et al.</i> (2021)]</p> |
| <b>Remaining Safe Operating Space</b> | <p>"For instance, the PB for Climate change as atmospheric CO<sub>2</sub> concentration is defined as 350 ppm CO<sub>2</sub>, the natural background level is defined as 278 ppm CO<sub>2</sub>. Thus, the remaining "safe operating space available for humanity" is 72 ppm CO<sub>2</sub> (see Table 1). Table S2-2 in Supporting Information S2 provides additional information on the Planetary Boundary level, the natural background level, and the safe operating space available for human activities. In this study, we have used the "safe operating space available for humanity" as boundary rather than the "remaining safe operating space" (i.e., the PB minus the current control variable value). This means that all activities (existing or future) can be evaluated in terms of their occupation of an SoSOS for humanity." Ryberg <i>et al.</i> (2021).</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                             | <p>[Ryberg <i>et al.</i> (2021)]</p>                                                                                                                           |
| <b>Share of SOS (SoSOS)</b>           | <p>"Relating the impact scores to the SOS is similar to normalization in traditional LCAs, where impact scores of the studied system are related to the impact of a common reference to indicate the magnitude of each impact category relative to the reference (ISO, 2006a; Ryberg <i>et al.</i>, 2014). However, such normalization will not show whether the studied system actually can be considered environmentally sustainable because the impact scores will, for all products in practice be below the PBs. To facilitate assessment of the studied system's environmental sustainability, the SOSs have to be allocated into smaller portions which represent the share of the SOS that the studied anthropogenic system can be considered entitled to occupy. It is important to note that such a PB-LCIA methodology can only be used for determining whether or not the studied system exceeds its allocated SOSs and, thus, whether or not it can be considered sustainable." Ryberg <i>et al.</i> (2018).</p> <p>"a company, or in fact any agent, can only be absolute sustainable if they do not exceed their share of the safe operating space (SOS) which is defined by a quantitative set of environmental load limits, such as the PBs (Fang, Heijungs, Duan, &amp; de Snoo, 2015)" Hjalsted <i>et al.</i> (2021).</p> | <p>[Ryberg <i>et al.</i> (2018a), Ryberg <i>et al.</i> (2021), Hjalsted <i>et al.</i> (2021)]</p>                                                              |
| <b>Carrying Capacity (CC)</b>         | <p>"The maximum persistent impact that the environment can sustain without suffering perceived unacceptable impairment of the functional integrity of its natural systems or, in the case of non-renewable resource use, that corresponds to the rate at which renewable substitutes can be developed." Bjorn <i>et al.</i> (2020) (review)</p> <p>defined as "the maximum sustained environmental intervention a natural system can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert" Bjorn_2015</p> <p>"The environment is here considered as a constraint like a planetary boundary or an environmental carrying capacity that the society needs to respect, and the environmental impact of the society's current and future economic and industrial activities must respect this constraint and their environmental impacts must stay within the associated safe operating space." Kara <i>et al.</i> (2023).</p>                                                                                                                                                                                                                                                                                                                                                 | <p>[Bjørn <i>et al.</i> (2020), Kara <i>et al.</i> (2023)]</p>                                                                                                 |
| <b>Environmental space</b>            | Used as a synonym of "Carrying capacity" and "SOS" or "SoSOS" according to the context.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | <p>[Kara <i>et al.</i> (2023)]</p>                                                                                                                             |

Table 6: Glossary of vocabulary associated with carrying capacity

# 9

## Vers l'éco-conception de technologies par prise en compte du changement d'échelle ?

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Ce chapitre a pour objectif de discuter les travaux réalisés dans un contexte plus large que celui des discussions des articles. Il nous apparaît important en effet d'interroger les résultats de la thèse à la lumière de deux sujets : 1) les archétypes et leurs usages et 2) l'ACV pour la soutenabilité. Chacun de ces deux sujets se confronte plus ou moins directement aux hypothèses de travail postulées pendant les travaux de recherche (Cf **chapitre 2**). Ce chapitre est donc subdivisé en deux sections et comporte, pour chacune, une discussion en deux temps : d'abord une clarification du domaine de validité des résultats de la thèse, c.-à-d. ce qui peut ou ne peut pas en être déduit ou ce qui nous semble manquer. Puis, des pistes de réflexion, dans la continuité des travaux réalisés, ou avec une perspective différente vers de nouveaux champs de recherche.

## 9.1 Les archétypes du changement d'échelle et leurs usages

Cette thèse est un travail exploratoire pour expliciter la relation entre changement d'échelle de technologie et soutenabilité en conception. Nous l'avons vu, la typologie des archétypes a impliqué un travail conséquent de veille et de formalisation portée par une vision de l'ingénierie interdisciplinaire. Nous proposons dans ce contexte de discuter des usages présentés dans cette thèse et potentiellement futurs des archétypes de changement d'échelle en conception.

### 9.1.1 Clarifications et limites des archétypes proposés

Nos communications scientifiques ont eu pour but de donner une vue d'ensemble du champ de recherche étudié.

Cette section vise à éclaircir les propos relatifs à la complétude et à la construction des archétypes abordés en premier niveau d'analyse dans les publications présentées dans le manuscrit.

#### La complétude des archétypes vis à vis du changement d'échelle

Par construction, les archétypes expriment des composantes hétérogènes et de natures différentes du changement d'échelle : les archétypes 1 (*scaling-up*) et 2 (*mass-producing*) regroupent des pratiques déjà intégrées en conception ou présentant une vision produit. Ils sont associés aux expertises mobilisées en recherche et développement en laboratoire et en entreprise. Pour certains secteurs d'activité, la nuance entre

ces deux archétypes s'estompe : dans l'ingénierie produit par exemple, un prototype a pour vocation d'être dupliqué en masse. A l'inverse, les systèmes de production en continu (e.g. procédé de chimie, centrale énergétique, chaîne de production de puce électronique) sont parfois conçus en tant que seule unité à produire. Les contraintes d'industrialisation ne s'appliquent alors pas et le système développé reste un prototype, mais avec des caractéristiques de production (rendement, productivité) considérées comme industrielles. D'autres secteurs, non traités dans nos travaux, comme l'armée, l'industrie du luxe ou plus directement l'aérospatial peuvent s'inscrire dans cette nuance car peu orientés vers la massification. Les archétypes 1 et 2 pour la plupart des produits sont ainsi perçus comme un continuum décrit par l'échelle de maturité *Technology Readiness Level* (TRL). Ils représentent les pratiques de conception de technologie déjà structurées et formalisées (e.g. Design for X).

De même, l'archétype 3 (*reaching a level*) et l'archétype 4 (*integrating a complex system*) partagent le fait de se concentrer à des échelles dépassant le périmètre d'étude habituel d'un produit et de son cycle de vie. Ils se focalisent davantage sur des échelles nationales, régionales et sectorielles et sont donc, par contraste avec les premiers archétypes, des facettes du changement d'échelle moins intégrées en conception. Par exemple, la prise en compte de l'archétype 3 dans nos travaux a été traitée à partir des scénarios prospectifs de RTE [47]. Ces scénarios ont été mis en œuvre pour représenter les évolutions possibles du système énergétique français en accord avec l'objectif de neutralité carbone en 2050. Il existe cependant une grande variété de pratiques prospectives que nous n'avons pas abordées par manque de temps ou d'expertise. Certains travaux, par exemple les quatre scénarios de l'ADEME [46], intègrent une vision trans-sectorielle dans laquelle le développement de nouvelles technologies est remis en cause en tant que seule voie vers la soutenabilité. Le scénario *technologies vertes* est ainsi accompagné de trois autres scénarios mettant en avant d'autres leviers d'actions correspondant à « des choix de société différents » (*génération frugale, coopérations territoriales, pari réparateur*). Les activités de conception et d'ingénierie sont évidemment présentes dans chacun de ces scénarios, mais dirigées vers des idéaux différents. Les caractéristiques de ces travaux font ainsi écho à la vision sectorielle et prospective de l'archétype 3, mais également à la vision systémique et socio-technique de l'archétype 4.

Dans la même idée, l'archétype 4 dans nos travaux fait coexister deux formes inégalement représentées : les approches multi-physiques ou multi-techniques (e.g. appliquées à l'étude de réseau hybride électricité-chaleur, mobilité électrique et stockage d'énergie) sont mise en avant en tant qu'approches systémiques ou holistiques en ingénierie



[110]-[113]. A contrario, les approches socio-techniques faisant appel aux Sciences Humaines et Sociales (SHS) sont moins présentes dans la littérature en conception liée au changement d'échelle [71].

Ces quelques illustrations de la porosité entre les archétypes montrent qu'ils forment une typologie dont les frontières sont susceptibles d'évoluer. C'est d'autant plus appuyé pour l'archétype 5 (*down-limiting*) que la soutenabilité environnementale absolue est une thématique de recherche en cours de formalisation. Bien que progressivement décliné sur plusieurs secteurs d'ingénierie (bâtiment, mobilité, énergie) et à plusieurs échelles d'application (e.g. produit, service, système socio-technique), l'archétype 5 est pour l'instant identifié comme complémentaire et d'une nature différente des autres archétypes. Cela peut s'expliquer par le fait qu'en plus de s'appuyer sur les sciences environnementales, il fait intervenir des raisonnements éthiques, tous deux peu enseignés en ingénierie aujourd'hui.

Pour résumer, les archétypes ne s'appuient pas exclusivement sur des pratiques de conception et sont élaborés par un effort d'interface des sciences de la conception avec d'autres champs et disciplines de recherche (e.g. prospective, réseau, régionalisation). D'autres archétypes pourraient ainsi émerger en considérant d'autres interfaces (e.g. histoire des techniques, marketing, sociologie, anthropologie). Autrement dit, il n'est pas possible d'affirmer que les archétypes proposés couvrent de façon complète le phénomène de changement d'échelle de technologie. En revanche, cette typologie n'est pas figée et la méthode de recherche employée (caractérisation par invariants) peut l'être à nouveau en proposant par exemples d'autres invariants pour fusionner plusieurs archétypes ou en faire émerger d'autres.

### **Connotation et positionnement des archétypes par rapport à « la technologie »**

Au regard des critiques présentées dans la **section 1.1.4 « Critiques de la transition énergétique et du technosolutionnisme »** et dans leur forme actuelle, les cinq archétypes proposés sont imprégnés de technosolutionnisme. On peut en effet y voir une superposition de contraintes à respecter (techno-économiques, sociales et environnementales) pour garantir l'industrialisation de masse d'une technologie, « écologique et responsable », pour le mieux et la société. Dans cette optique, la question de la relation entre technologies et société (aussi « populations ») est par exemple traitée sous l'angle de l'*acceptabilité*, c.-à-d. imposant à l'utilisateur des choix de conception. Une partie des sciences de la conception en interface avec les sciences sociales (e.g. la conception collaborative), invitent à poser la question différemment en intégrant l'utilisateur dans la



conception. On parle alors d'*appropriation* ou d'*adoption* d'une technologie.

Plus généralement, « la technologie » fait le lien entre les différents archétypes. Nous n'avons pas eu besoin de la définir en tant que concept pour constituer nos propositions puis lors des communications scientifiques, de contextualiser le terme de *technologie* pour nos interlocuteurs. Selon l'archétype, la technologie se réfère à un *composant*, un *système ou sous-système technique*, ou encore à une classe permettant le regroupement de produits sur une caractéristique commune (e.g. la technologie photovoltaïque). Ce qu'est une technologie a été explicité par la pratique, notamment dans les exemples d'application et les cas d'étude.

Autrement dit, la cohérence des archétypes résiste à l'application de plusieurs définitions du terme *technologie émergente*, mais aussi à la définition de *technologie* tout court. C'est une propriété intéressante car elle permet de construire du vocabulaire commun sans pour autant lisser les spécificités propres aux utilisateurs. Elle permet également, comme nous le verrons dans la section suivante, d'investir d'autres visions de la technologie que celles de la littérature consultée, c.-à-d. en ingénierie et en conception sans impératifs de soutenabilité.

### 9.1.2 Perspectives de recherche

Nous proposons trois perspectives à la thèse pour viser l'opérationnalisation des archétypes de changement d'échelle en conception : 1) la poursuite de la caractérisation et de l'illustration par les cas d'étude, 2) la confrontation à la vision low-techs, et 3) la mise au service des archétypes pour le développement de nouvelles compétences en ingénierie pour le renoncement de pratiques technologiques non-soutenables.

#### Poursuivre l'opérationnalisation par les cas d'étude

Approfondir la documentation des archétypes par de nouveaux cas d'étude s'inscrit naturellement dans la continuation des travaux de thèse.

L'archétype 4 (*integrating a complex system*) étant le moins traité dans la thèse, il serait intéressant de développer un cas d'étude sur le photovoltaïque en étudiant ses interactions avec le réseau de distribution électrique et/ou les systèmes de stockage. L'entreprise ENEDIS et le chercheur Arthur Clerjon (CEA) pourraient être approchés pour préparer un cas d'étude industriel sur l'analyse du changement d'échelle du photovoltaïque en tant que source d'énergie intermittente sur un système énergétique territorial ou national [114]. Ce cas d'étude, conforterait de façon complémentaire les

travaux de modélisation du changement d'échelle entrepris durant la thèse.

Ensuite ou en parallèle, il serait souhaitable d'étendre la méthode d'analyse à d'autres systèmes techniques, dans d'autres secteurs industriels. On peut également interroger les pratiques de scénarisation prospectives identifiées dans la thèse à partir d'analyses rétrospectives de changement d'échelle de technologie. Les modèles phénoménologiques (e.g. courbe en S) régulièrement utilisés en prospective pourrait être rediscuter en cherchant des produits technologiques et éléments d'infrastructure ayant déjà subi des développements rapides et/ou massifs observés (e.g. téléphone portable, trottinette électrique, pompe à chaleur, châteaux d'eau, système d'éclairage public). Puis, en identifiant les facteurs (e.g. économiques et industriels, sociaux, politiques) ayant permis leur essor, leur maintien, et potentiellement leur déclin dans le temps. Cette démarche pourrait affiner l'hypothèse de représentativité des archétypes par rapport au changement d'échelle et potentiellement donner des clefs d'anticipation du phénomène.

Enfin, cette multiplication des cas d'étude pourrait être rendue disponible par une version actualisable de la matrice UA-EF (e.g. sur GIT ou EcoCloud [115]). Ce support rendrait ainsi possible la capitalisation de nos travaux par d'autres chercheurs de différentes communautés de conception. Une forme collaborative pourrait également être constituée afin d'ouvrir les contributions à tout chercheur se positionnant sur le changement d'échelle pour compléter la version actuelle (Cf **Figure 5.5**). Reste que la méthode de classement par invariant développée dans la thèse devrait alors être simplifiée pour permettre une catégorisation efficace des cas d'étude et faciliter le suivi de l'outil collaboratif. Cela ouvrirait la voie à des processus de co-construction de méthodes en complétant les analyses multi-disciplinaires déjà identifiées. Cela résulterait ultimement à la constitution d'un catalogue des méthodes adaptés à l'analyse d'un ou plusieurs archétypes de changement d'échelle.

## Les archétypes de changement d'échelle et les low-techs

Nous l'avons vu, les archétypes sont compatibles avec différentes visions de la technologie. Une perspective intéressante de recherche serait de croiser les archétypes de changement d'échelle avec un certains type de technologie : les « low-techs ».

Les low-techs désignent un courant de pensée pour l'instant minoritaire en science de la conception plaçant en son coeur la soutenabilité et les pratiques sociales qui la sous-tendent. En d'autres termes, elles se positionnent sur des principes de conception laissant plus de place à la valeur sociale des technologies et critiquent la place actuelle des technologies dans la société [116].

Plusieurs définitions et pratiques gravitent autour des low-techs : Philippe Bihoux développe le terme en opposition aux « high-techs », partageant des similitudes avec notre définition de « technologie émergente » (nano-bio-technologies, réseau intelligent) [117]. D'autres organismes [118] et chercheurs [119] proposent des invariants pour caractériser les low-techs, comme l'*utilité*, l'*accessibilité*, la *durabilité* de la technologie ou des pratiques sociales en lien avec la technique et son usage (*sobriété*, *frugalité*) [118].

Les leviers pour « changer l'échelle des low-techs » sont de plus en plus débattus [120], [121]. Via les archétypes de changement d'échelle, la massification (ou reproductibilité) des low-techs pose question : pour les high-techs, la reproductibilité passe par l'industrialisation et la standardisation. Pour les low-techs qui sont dépendantes d'une communauté souvent localisée, il est plus difficile de les transposer directement à d'autres régions ou d'autres formes d'organisation. Une adaptation est donc nécessaire relevant, à la fois des sciences de la conception (e.g. choix de matériaux locaux, choix d'une structure technique simplifiée, réparable), et de pratiques socio-économiques (e.g. construction d'un modèle économique, mise en place d'un collectif, formation et implication de communautés). Ces éléments investissent alors d'une autre lecture des archétype 2 (*mass-producing*) et 3 (*reaching a level*). En revanche, les low-techs s'appuyant sur une culture de l'essai-erreur et du prototypage, et répondant à un cahier des charges porté par une communauté, s'inscrivent plus facilement dans les archétypes 1 (*maturing*) et 4 (*integrating a complex system*). Un recensement des méthodes et pratiques pour le cas précis des low-techs permettrait ainsi d'affiner les archétypes de changement d'échelle. Ces éléments de réflexion sont abordés dans les travaux de Sacha Hodencq avec la proposition de pratiques de modélisation ouverte pour la reproductibilité [122]. De même, Alexandre Gaultier vise l'outillage « méthodologique pour une ingénierie Low-tech » [119]. Les démarches low-techs pourraient présenter une affinité avec l'archétype 5 (*down-limiting*) et l'AESA à travers la notion de *frugalité* (*sufficiency* en anglais), exprimant une forme de limitation volontaire appliquée aux caractéristiques (e.g. fonctionnalité, présence de composants numériques, interruption consentie du service) et aux potentiels développements d'une technologie. Cette limitation ne se résume cependant pas à des critères sociaux et/ou environnementaux mais peut s'appuyer sur des visions politiques et philosophiques de la place de la technologie dans la société. Pour finir, le changement d'échelle selon cet axe de réflexion, est toujours considéré comme un phénomène de développement de technologie. Il sous-entend une montée d'une échelle basse vers une échelle plus haute (e.g. de maturité, de productivité, de portée, d'accessibilité). La section suivante propose de prendre le contre-pied de cette connotation en rapprochant les archétypes avec le concept de *fermeture*.

## Les archétypes et le concept de fermeture

En effet, les archétypes de changement d'échelle peuvent également servir d'appui pour soutenir le concept de *fermeture* développé par Emmanuel Bonnet, Diego Landivar et Alexandre Monin [123]. Ce concept fait référence au fait de planifier le renoncement à des industries, technologies et organisations en désaccord avec les objectifs de soutenabilité et dont nous, en tant que citoyens et/ou concepteurs, héritons. Cela se traduit par une phase de mesure de la non-soutenabilité (environnementale et/ou sociale) d'une entité pour la mise en oeuvre, avec les parties prenantes, de son démantèlement de façon délibérée et maîtrisée. L'industrie pétrolière et une partie des industries adossées (énergie, mobilité, fret), le tourisme de masse ou historiquement l'industrie de l'amiante sont des exemples d'entité dont la non-soutenabilité est démontrée et la pérennité est, ou a été, remise en question.

Les archétypes, à la lumière de ce concept, permettent de formaliser de nouvelles expertises en science de la conception pour viser la mise en oeuvre de systèmes soutenables.

- Archétype 1 : identifier suffisamment tôt dans le processus de conception (bas TRL) la non-soutenabilité des technologies pour renoncer aux nouveaux projets. Cette expertise est à rapprocher de la proposition de *go/no-go* présentée à la conférence CIRP Design 2022 et réaffirmée à la conférence CIRP LCE 2023.) Les critères de renoncement peuvent s'appuyer sur des raisons environnementales (archétype 5) mais également sociales ou économiques à moyen et long termes. Dans le cas d'une technologie en fin de développement, cela reviendrait à implémenter des restrictions physiques pour circonscrire son utilisation à des cas minoritaires et ainsi limiter sa généralisation. On retrouve une idée similaire dans l'échelle de maturité *Manufacturing Readiness Level* (MRL) qui précise une fin de vie de la technologie et potentiellement leurs modalités (e.g. horizon temporel) [124].
- Archétype 2 : démanteler ou réorienter les chaînes de valeurs et de production, pour faire bénéficier la société de l'expertise technique des parties prenantes. Cela implique notamment d'adapter le tissu industriel aux besoins des populations et possiblement de repenser l'organisation et les finalités des moyens de production.
- Archétype 3 : identifier des métriques de coordination de la reconversion et de démantèlement à l'échelle des secteurs industriels avec une vision prospective à long terme. L'arrêt de la production de véhicules thermiques en Europe pour 2040 est un exemple de conséquence de ce processus [125]. On retrouve également cette idée dans le secteur du numérique avec le concept de « désescalade du

numérique » du chercheur Felix Tréguer [126]. Cette thématique est investie notamment par Valentin Girard au G-SCOP [127].

- Archétype 4 : identifier les interactions de la technologie à *fermer* avec le système socio-technique et pouvoir l'en retirer de façon maîtrisée et sûre. Cela implique une maîtrise du système complexe existant et une anticipation de ses évolutions possibles et souhaitables. L'intérêt scientifique pour la *résilience* dans l'industrie est peut être lié à ce besoin. Cela ne doit cependant pas empêcher de remettre en question le devenir de certaines infrastructures et réseaux (e.g. mobilité individuelle carbonée, réseaux de distribution de gaz, fret mondialisé). Pour ces systèmes là, devenir résilient serait une échappatoire à la fermeture, mais constituerait alors une forme de verrouillage pour l'ensemble du système socio-technique, privant les parties prenantes de voies contrôlées vers la soutenabilité.
- Archétype 5 : guider et organiser le cheminement des fermetures de systèmes industriels, des technologies et d'infrastructures que nous pourrions juger collectivement comme non-compatibles avec des objectifs de soutenabilité à plusieurs échelles (e.g. produit, site de production, ville, région, pays, continent). Les pré-supposés démocratiques et de justice sociale de l'AESA (i.e. principes de justice à choisir) peuvent faciliter la prises de responsabilité du processus en impliquant des parties prenantes.

## 9.2 L'ACV et la soutenabilité

Dans cette section nous souhaitons revenir sur l'hypothèse de travail consistant à investir la pratique de l'ACV afin de promouvoir une approche systémique, multicritères, multi-étapes et itérative de la soutenabilité environnementale en conception. Nous commencerons par préciser les limites de nos contributions (**section 9.2.1**) avant de proposer deux réflexions et perspectives de recherche sur la pratiques de l'ACV pour la soutenabilité environnementale (**section 9.2.2**).

### 9.2.1 Clarifications et limites des pratiques d'ACV proposées

Dans cette thèse, nous avons étudié ce qu'il était aujourd'hui possible de modéliser en ACV, puis développé des pratiques d'ACV spécifiques pour construire une vision environnementale du changement d'échelle en conception. La section suivante permet de remettre en perspective ces pratiques par rapport à nos hypothèses de travail.

#### La vision multicritères et l'interprétation des résultats

Lors de la thèse, compte tenu du temps et de nos ressources disponibles, nous avons focalisé les cas d'étude sur des preuves de concepts (Apport 6, voir **sections 8.1** et **8.2**). En l'occurrence, en reprenant les scénarios de RTE dans nos cas d'étude, nous avons construit une partie de nos cas d'étude autour de l'indicateur de changement climatique. Un des intérêts de ces travaux a été de montrer la possibilité d'effectuer des analyses prospectives sur plusieurs décennies dans un cadre de conception. Améliorer la robustesse de ces analyses requière cependant un travail de caractérisation des aspects dynamiques spécifiques à chaque indicateur environnemental. Ce travail a été en partie réalisé pour le  $\text{CO}_2$  *equivalent* [128] mais fait pour l'instant défaut pour les autres indicateurs en ACV classique ce qui limite l'intégration en conception d'une vision prospective et multicritères.

En parallèle, le travail d'approfondissement de l'AESA (Apport 8, voir **section 5.3.4**) développe une analyse statique avec sept indicateurs d'ACV classiques et six indicateurs associés aux limites planétaires. Nous invitons alors à adopter des stratégies de compromis, sans pour autant aboutir à une méthode d'interprétation générique. Et pour cause, la plupart des limites environnementales (e.g. limites planétaires) étant dépassées, prioriser les dépassements au niveau du produit n'a de sens qu'après la reconnaissance de son utilité sociale. Autrement dit, l'AESA dans nos travaux est utilisée comme vecteur de discussion collective des règles d'allocation appliquées aux systèmes à concevoir. Nous

revenons ainsi au cahier des charges initial du produit et appelons alors à questionner la nécessité de son développement (Cf stratégie de go/no-go) avec les parties prenantes concernées (e.g. concepteurs, citoyens, entreprises, collectivités, états).

En complément, les travaux sur la criticité des matières premières visaient à défendre une vision multicritères par une hybridation entre indicateurs d'ACV et indicateurs de criticité en conception. Nous n'avons pas atteint l'implémentation de cet objectif, cependant la grille d'analyse proposée en Apport 7 (Cf **section 8.3**) permet d'identifier le mésusage de la criticité Européenne en conception. Comme évoqué en discussion de l'**Article A**, l'application de cette grille d'analyse à d'autres indicateurs permettrait d'orienter les concepteurs vers les méthodes adaptées à leurs besoins. Nous avons par exemple pu voir lors de la rédaction du manuscrit de thèse que la méthode Geopolrisk émergeait comme un indicateur possiblement utilisable en parallèle d'indicateurs environnementaux [129]. Nous recommandons d'être vigilant sur l'hybridation ACV-criticité car la criticité n'est pas un indicateur environnemental et évolue au cours du temps et en fonction d'évènements socio-économiques (e.g. géopolitique, climatique). Un choix de conception basé sur une analyse de la criticité a donc une validité dans le temps qui peut s'approcher de durées de processus de conception ou d'industrialisation (e.g. trois à cinq ans). Cette validité dépend de la construction de l'indicateur (e.g. variables et paramètres, périmètre, horizon temporel, qualités des données) mais reste en général court-termiste par rapport aux échelles de temps des systèmes socio-techniques (e.g. décennies, voir siècles). Nous suggérons donc de ne pas utiliser la criticité de la même manière que des indicateurs environnementaux, à moins d'explicitier leur différence de nature et de séparer l'interprétation des résultats.

Pour finir, l'étape d'interprétation des résultats (prospectif ou non) pour la conception manque d'approfondissement : plusieurs leviers d'action pour le concepteur ont été identifiés grâce à l'analyse environnementale (e.g. amélioration technique minimale à respecter pour que la technologie en développement soit considérée comme soutenable à un horizon temporel donné, comparaison par rapport à une référence environnementale, analyse de criticité). Il reste à étudier est-ce que ces leviers d'action sont identifiés en tant que tels par les concepteurs et s'ils peuvent les intégrer dans une stratégie de conception vers la soutenabilité, par exemple aux côtés d'autres méthodes d'éco-conception ou de re-conception (e.g. liste des « R », REACH, indicateur de réparabilité). Il est également envisageable, pour certaines technologies, telles que les low-techs par exemple, que l'ACV ne soit pas une méthode d'analyse adaptée pour attester de leur soutenabilité environnementale.



## Le processus EAU et l'étape de méta-modèle

Le processus EAU sert de guide à un processus de conception, mais ne décrit pas explicitement ce processus dans son entièreté. Les quatre étapes de l'ACV sont revues pour préciser les points importants à prendre en compte pour le changement d'échelle. Nous ne voulons cependant pas laisser le sentiment que le processus EAU aboutit **forcément** à une approche prospective de l'AESA. Selon nous, c'est une des formes que peut prendre le processus d'analyse mais d'autres combinaisons de mode d'ACV sont à explorer. De même, n'étant pas impliqué dans une équipe de conception ou dans un consortium industriel, il n'a pas été possible d'appliquer l'entièreté du processus EAU à un cas d'étude pendant la thèse. Un des enjeux de la thèse était de proposer un cadre méthodologique pratique permettant de faire bénéficier les concepteurs d'une vue d'ensemble sur les avancées méthodologiques et opérationnelles développées par les experts en ACV. En retour, il devient crucial de maintenir un regard critique sur les nouvelles approches qui ne sont pas forcément stabilisées et qui peuvent s'avérer infructueuses dans un cadre de conception. En l'occurrence, un questionnement émerge de manière récurrente avec les concepteurs :

*« Quelles données, modèles et/ou règles d'extrapolation avons-nous à notre disposition pour le changement d'échelle d'une technologie ? »*

Pour être clair, il n'existe pas de modèle générique, environnemental ou technique, du changement d'échelle d'une technologie. Nous l'avons vu, chaque champ d'ingénierie peut avoir ses propres représentations et modèles du phénomène. Il faut donc procéder, la plupart du temps, au cas par cas. En parallèle, la collecte de données pour l'inventaire de cycle de vie, comme en ACV classique, reste une problématique de taille dans le processus EAU : la méthode s'appuie sur des données et modèles techniques pour pouvoir les traduire en effets sur l'environnement. Autrement dit, il n'y a pas d'analyse environnementale du changement d'échelle sans données d'inventaire fournies par l'expertise technique de l'équipe de conception. Cela implique une évaluation de la transférabilité des modèles techniques (ou socio-techniques) de prime abord par la partie de l'équipe de conception en charge de l'expertise technique. De même, le changement d'échelle est souvent pris en compte en conception sur la base d'hypothèses simplificatrices (linéarité des quantités d'inventaire, profils d'usages génériques, interactions faibles avec les autres systèmes techniques). Le cadre proposé en tant que « méta-modèle » servirait de catalyseur pour faire s'interroger les membres de l'équipe de conception sur les données et hypothèses socio-techniques nécessaires à l'analyse environnementale de leurs objectifs.



## **L'équipe de conception et l'organisme hébergeant le processus d'éco-conception**

Enfin, nous avons identifié certaines expertises techniques, industrielles, économiques et stratégiques des entreprises requises pour représenter le changement d'échelle. Certaines ont été illustrées dans nos cas d'étude mais nos travaux ne visent pas à être exhaustifs sur ce sujet. Les interactions avec les parties prenantes que les approches supposent sont évoquées à plusieurs reprises et sont, la plupart du temps, considérées acquises par l'équipe de conception. De même, l'utilisation de l'ACV comme outil d'aide à la décision dans un processus de conception est une hypothèse utilisée dans la littérature scientifique mais encore peu effective en entreprise [76]. Par ailleurs, nous n'avons pas exploré les besoins organisationnels qu'implique la prise en compte du changement d'échelle. Nos résultats de thèse sont dirigés vers des profils types d'ingénieurs experts d'une technologie et/ou d'ingénieurs ACVistes dans une organisation (e.g. entreprise, institut de recherche) qui supporte une équipe de conception en termes de moyens humains (e.g. recrutement si nécessaire, formation), organisationnels (e.g. partenariats inter-sectoriels, identification des parties prenantes) et matériels (e.g. logiciels, bases de données). Pour finir, nos travaux supposent que l'organisation permet également le déroulement d'un processus d'éco-conception comme celui décrit par le processus EAU ou l'AESA dont les conclusions peuvent aboutir à ne pas développer un produit. Les premiers utilisateurs de nos résultats de thèse concernant l'ACV sont donc potentiellement des organismes avec des moyens humains et matériels conséquents, et positionnés au moins en partie sur l'adoption de l'ACV comme outil d'aide à la décision (e.g. CEA, RTE, instituts de recherche technologique (IRT) ou instituts Carnot).

Pour résumer, il n'existe pas de recette « toute faite » pour intégrer le changement d'échelle en conception avec une vision soutenable. Cette intégration suppose des méthodes d'interprétation des résultats d'ACV (vision multicritères), et repose sur d'importants présupposés en termes d'expertises. Enfin, le processus EAU et l'AESA supposent peut être, pour l'organisme porteuse du processus d'éco-conception, une capacité de questionnement interne et un impératif de changement d'organisation que peu d'entreprises envisagent aujourd'hui.

### **9.2.2 Perspectives de recherche et réflexions d'ouverture**

Pour conclure le chapitre de discussion, nous proposons dans cette partie deux perspectives de travaux de recherche à l'attention 1) d'expert ACV, 2) d'expert en éco-conception et concepteurs.

## Caractériser la compatibilité entre modes d'ACV et l'évolutivité du processus EAU

Puisque le processus EAU s'appuie sur la combinaison entre modes d'ACV, il peut être pertinent de définir un cadre théorique et pratique des compatibilités et incompatibilités entre les modes identifiées dans l'Apport 3 (Cf **section 7.1**). La **Figure 9.1** présente un format qui pourrait être complété à partir d'entretiens avec des spécialistes en ACV et/ou le recensement de pratiques dans la littérature.

| "Classic"<br>LCA |                 |               |               |             |         |               |              |        |          |          |            |              |                 |             |         |
|------------------|-----------------|---------------|---------------|-------------|---------|---------------|--------------|--------|----------|----------|------------|--------------|-----------------|-------------|---------|
|                  |                 | Attributional | Consequential | Prospective | Ex-ante | Retrospective | Anticipatory | Hybrid | Absolute | Relative | Transition | Regionalized | Territorialized | Spatialized | Dynamic |
|                  | Attributional   |               | •             | •           | •       | •             |              | •      | •        | €        | •          | •            | •               | •           | •       |
|                  | Consequential   |               |               | •           | •       |               |              |        | •        | €        | x          | x            | x               | •           |         |
|                  | Prospective     |               |               |             | €       | x             | €            | •      | •        | •        | •          | •            |                 | •           |         |
|                  | Ex-ante         |               |               |             |         | x             | •            | •      | •        | x        | •          | •            |                 |             | •       |
|                  | Retrospective   |               |               |             |         |               | x            | •      | •        |          | •          | •            | •               | •           | •       |
|                  | Anticipatory    |               |               |             |         |               |              | •      | •        | •        | •          | •            |                 |             |         |
|                  | Hybrid          |               |               |             |         |               |              |        | •        | €        |            |              |                 |             |         |
|                  | Absolute        |               |               |             |         |               |              |        | x        |          | •          | •            |                 |             | •       |
|                  | Relative        |               |               |             |         |               |              |        |          | •        | •          | •            | •               | •           | •       |
|                  | Transition      |               |               |             |         |               |              |        |          |          | •          | €            |                 | •           |         |
|                  | Regionalized    |               |               |             |         |               |              |        |          |          |            |              | €               | •           | •       |
|                  | Territorialized |               |               |             |         |               |              |        |          |          |            |              |                 | •           | •       |
|                  | Spatialized     |               |               |             |         |               |              |        |          |          |            |              |                 |             | •       |
|                  | Dynamic         |               |               |             |         |               |              |        |          |          |            |              |                 |             | x       |
|                  | Static          |               |               |             |         |               |              |        |          |          |            |              |                 |             |         |

|                         |   |
|-------------------------|---|
| Compatible              | • |
| Opposed or incompatible | x |
| Inclusion relation      | € |
| Undetermined            |   |

**FIGURE 9.1** – Représentation possible des compatibilités entre modes d'ACV

Dans cette perspective, nous proposerions de caractériser les compatibilités entre modes d'ACV avec les catégories *compatibles*, *incompatibles* car structurellement opposés (e.g. prospectif et rétrospectif) ou pour des raisons opérationnelles (e.g. modèles incompatibles), *avec une relation d'inclusion* (e.g. prospectif et ex-ante) et, enfin, *indéterminé* car non-observé dans la littérature par exemple. Ce travail permettrait d'une part de cartographier les pratiques d'ACV, et d'autre part d'illustrer de nouvelles formes d'analyses résultants du processus EAU. Ces cas d'étude devraient idéalement être réalisés en conditions réelles, c.-à-d. pour aboutir à la conception ou re-conception d'un ou plusieurs prototypes de technologie émergente. Enfin, la caractérisation des compatibilités entre mode permet aussi de toucher du doigt l'évolution des pratiques liées à

l'ACV, et de les comparer à une approche jugée « classique » en conception, à un instant donné (Cf. colonne de gauche, ). Cette approche, pour l'heure, pourrait se résumer à un usage focalisé sur l'ACV *attributionnelle*, majoritairement *rétrospectif*, sans prise en compte de limites environnementales (i.e. *relatif*) ni de facteurs temporels (i.e. *statique*).

### **Approfondir le processus d'éco-conception par prise en compte du changement d'échelle**

Cette perspective fait directement écho au potentiel verrou organisationnel relevé dans la sous-section « *L'équipe de conception et l'organisme hébergeant le processus d'éco-conception* ». Une première approche pourrait être de préciser les conditions d'organisation et d'échanges nécessaires entre parties prenantes pour aboutir à un processus d'éco-conception d'une technologie émergente. A l'échelle de l'équipe de conception, on peut mentionner les travaux de Yassine Baouch et Lou Grimal en conception collaborative : La thèse de Yassine Baouch développe des méthodologies de suivi des besoins *de discussions et de partage de raisonnements* pour la modélisation entre concepteurs [130]. On peut alors envisager le même type d'approche pour des utilisateurs de l'ACV dans un contexte d'éco-conception pour le changement d'échelle de produits technologiques. Dans cette perspective, la thèse de Lou Grimal pointe les difficultés de collaboration dans un cadre de construction de connaissances en ACV par des non-experts. Cela contrevient ainsi à l'idée que l'ACV peut être un outil fédérateur, dans une équipe de conception élargie, pour l'analyse de la soutenabilité [131]. Lou Grimal soutient en revanche qu'il est crucial de développer une expertise *interactionnelle*, pour développer une ingénierie de la soutenabilité et pallier aux manquements de l'ACV comme medium de collaboration en conception. Cette expertise est définie par « la capacité de comprendre un domaine d'expertise classique sans être expert de celui-ci. » [131].

Pour conclure, ma thèse s'inscrit dans ce même constat car c'est en partie ce type de compétences qui m'a permis de développer une définition puis une analyse du changement d'échelle de technologie. Il me semble donc également nécessaire de chercher à faire acquérir aux membres de l'équipe de conception des compétences de différents champs de l'ingénierie pour guider leur propre processus d'éco-conception de technologie vers la soutenabilité. L'ACV, en tant que méthode d'analyse quantitative et normée, a été utilisée comme vecteur d'intégration de la soutenabilité environnementale pour des concepteurs avec une expertise principalement technique qui se reconnaît dans les archétypes de changement d'échelle. Il n'est cependant pas souhaitable que

la compréhension des enjeux de soutenabilité des concepteurs se réduise à cette méthode. On peut ainsi se demander ***quel potentiel de transformation une méthode d'analyse de la soutenabilité (ACV incluse) a sur les concepteurs, sur le processus de conception et sur les artefacts produits ?*** Si la méthode en question modifie significativement les pratiques de conception et a un effet sur les objets d'étude des équipes de conception, alors on peut attendre des concepteurs qu'ils se saisissent des enjeux de soutenabilité. Par conséquent, il apparaît nécessaire de positionner les futurs travaux de recherche par rapport à la question de recherche suivante :

***« Comment faire se saisir les concepteurs des enjeux de la soutenabilité avec comme repoussoir la technicisation des transitions écologiques ? »***

Ces questionnements peuvent également être étendus, non plus seulement pour les concepteurs mais à la société civile dans son ensemble dans un souci de didactique.

Pour résumer, ce chapitre a clarifié les apports de la thèse : une première discussion a porté sur l'utilisation des archétypes de changement d'échelle et une seconde sur les limites de l'ACV comme outil d'analyse de la soutenabilité environnementale en conception.

Il a été réaffirmé que les archétypes constituent une typologie susceptible d'être complétée et d'évoluer. En l'état, cette typologie est soutenue par une vision *techno-push*. De plus, à l'image d'une partie de la littérature en ingénierie sur le changement d'échelle, cette typologie est dissociée d'objectifs de soutenabilité à l'exception de l'archetype 5 (*down-limiting*). Trois perspectives de poursuite de la thèse ont été évoquées : 1) le développement de nouveaux cas d'étude, et l'investigation des liens possibles entre les archétypes et 2) les *low-techs* et 3) le concept de *fermeture*.

Une seconde discussion a été tenue sur les pratiques d'ACV développées durant la thèse et notamment sur les difficultés d'adopter une vision multicritères ou encore de modéliser le changement d'échelle via l'ACV. Enfin, une réflexion est menée sur les conditions opérationnelles et organisationnelles requises pour appliquer les méthodes d'ACV développées lors de la thèse. Cette réflexion aboutit à deux perspectives de recherche : 1) étudier les compatibilités entre modes et pratiques d'ACV, et 2) aborder l'éco-conception de technologie émergente avec l'ACV via le prisme de la conception collaborative. Ainsi, des profils transdisciplinaires de concepteurs semblent faire partie des modalités de conception collaborative nécessaires pour faciliter la prise en compte du changement d'échelle en conception.

# 10

## Conclusion

### Sommaire

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Ce chapitre rappelle le contexte, les hypothèses de travail et les questions de recherche de la thèse, ainsi que les apports associés. Il synthétise également les discussions et perspectives en concluant sur l'ensemble des travaux de la thèse.

## 10.1 Contexte et enjeux

La non-soutenabilité à l'échelle planétaire de nos sociétés industrialisées n'est plus à démontrer. La science du *système Terre* étudie les capacités des environnements et du Vivant à résister aux pressions qu'exercent sur eux les activités humaines. Elle articule l'étude de plusieurs phénomènes bio-physiques dont les changements climatiques et l'effondrement de la biodiversité. Cette science interdisciplinaire développe des modèles systémiques et multi-variables dont le cadre des *limites planétaires* fait partie. Pour ce cadre, des seuils de prévention de l'emballement des dynamiques du système bio-physique ont été établis pour caractériser la soutenabilité environnementale des activités humaines à l'échelle planétaire. Le dépassement prolongé d'une majorité de ces seuils témoignent de l'urgence à faire évoluer la plupart des systèmes socio-techniques sur lesquels s'appuient nos sociétés.

Le cadre des limites planétaires, dans ce contexte, peut prendre la forme d'une boussole vers la soutenabilité pour les acteurs de la construction et le maintien des systèmes socio-techniques, incluant les concepteurs de technologies.

En revanche, ce cadre étant formulé à l'échelle planétaire, des stratégies de planification (ou transition) aux échelles locales (e.g. nationale, régionale, sectorielle) sont à développer, adossées à des connaissances des systèmes socio-techniques. Pour reprendre la métaphore du voyage vers la soutenabilité, les stratégies de transitions écologiques se doivent d'être des itinéraires réalisables et balisés. Une partie de ces stratégies repose sur le développement (l'émergence) de technologies, matures ou en laboratoire, à des échelles de temps et de production inédites (e.g. énergies renouvelables, mobilité électrique, réseaux intelligents). Les concepteurs de technologies sont ainsi chargés d'un rôle de garant de la soutenabilité environnementale de leur objet d'étude. L'éco-conception de technologies émergentes dépend cependant d'analyses qui ne sont pas toutes intégrées en science de la conception (e.g scénarios prospectifs socio-techniques, soutenabilité absolue, criticité des matières premières). L'enjeu de la conception de technologies émergentes est donc d'intégrer des méthodes, expertises et indicateurs d'analyse pour libérer des leviers d'action vers la soutenabilité environnementale.

## 10.2 Questions de recherche, démarches et propositions

Cette thèse est ainsi un travail de recherche exploratoire en conception intégrée pour la soutenabilité environnementale. Elle pose la question de recherche « *Comment aider les concepteurs à prendre en compte le changement d'échelle de technologies émergentes dans une approche de soutenabilité environnementale ?* ». Pour répondre à cette question de recherche deux hypothèses de travail ont été formulées : 1) l'Analyse de Cycle de Vie (ACV) est considérée comme un vecteur d'intégration de la soutenabilité environnementale en conception, 2) le questionnement des concepts associés au « changement d'échelle de technologie émergente » peut permettre de formaliser les phénomènes à prendre en compte dans l'ACV.

Afin d'orienter les travaux de recherche, trois verrous ont été isolés :

1. la polysémie des termes « changement d'échelle » et « technologie émergente » et leurs liens avec la science de la conception,
2. les difficultés d'identification de méthodes et d'indicateurs adaptés,
3. la nécessité d'une expertise spécifique pour appliquer certaines des méthodologies identifiées comme adaptées pour traiter le changement d'échelle de technologie émergente en conception.

Ces verrous sont respectivement catégorisés en tant que verrous *conceptuel*, *méthodologique* et *opérationnel*. Ils interagissent cependant les uns avec les autres et imposent donc des contributions de recherche interdépendantes pour y remédier.

Une proposition pour chacun de ces verrous a été formulée :

1. Développer un cadre théorique en ingénierie et conception pour caractériser le changement d'échelle de technologies émergentes,
2. Orienter le choix de méthodes de conception soutenable par une méthode de prise en compte du changement d'échelle intégrée dans une approche ACV,
3. Guider les pratiques des concepteurs par des recommandations et supports dédiés.

Ces propositions s'appuient sur une méthodologie de recherche intégrant la mise en oeuvre de revues de littérature en science de la conception, en modélisation et en analyse environnementale, et ont mobilisé trois formations et de multiples échanges avec des experts de différents domaines. Ces travaux ont ainsi mené à la constitution de cas d'étude en collaboration avec d'autres chercheurs pour tester itérativement les premiers résultats, ou opérationnaliser les apports de thèse.

## 10.3 Contributions et perspectives de recherche

Trois contributions, conceptuelle, méthodologique et opérationnelle, ont été formalisées pour lever les verrous 1, 2 et 3 : La thèse étant une thèse par articles, les apports associés à ces trois axes de recherche sont répartis dans plusieurs publications scientifiques.

### Contributions conceptuelles

Les contributions conceptuelles sont les suivantes :

**Apport 1 : Un cadre théorique et la caractérisation de cinq archétypes de changement d'échelle.** Il a notamment été établi que le changement d'échelle est un concept d'ingénierie, et n'est pas directement alimenté par des pratiques de prise en compte de l'environnement et du vivant. Il découle donc en grande partie de pratiques de conception et de logiques industrielles qui ne visent pas la soutenabilité.

**Apport 2 : La caractérisation de l'articulation entre les concepts de « changements d'échelle » et de « technologie émergente ».** Cet apport montre que les archétypes couvrent les différentes définitions de « technologie émergente ».

Ces contributions sont présentées dans l' **Article de Conférence 1** et l'**Article 1**.

### Contributions méthodologiques

Les contributions méthodologiques sont les suivantes :

**Apport 3 : Un cadre méthodologique :** l'explicitation d'une démarche d'ACV par archétype permettant la mise en relation entre des besoins en modélisation et les différents modes d'ACV existants.

**Apport 4 : Un processus intégré :** la formalisation du processus *Environmental Assessment for Upscaling* (EAU) pour l'intégration d'archétypes dans un projet d'éco-conception.

Ces contributions sont présentées dans les **Articles 2** et **3**.

### Contributions opérationnelles

Les contributions opérationnelles sont les suivantes :



**Apport 5 : Des représentations graphiques** : l'illustration générique des archétypes et l'explicitation de bonnes pratiques via le recensement de cas d'application par secteur d'ingénierie et par archétype.

**Apport 6 : Une illustration de la mise en usage du processus EAU** sur le cas du déploiement du photovoltaïque en France.

**Apport 7 : Une grille d'analyse pour les non-experts pour le choix de méthode de criticité des matières premières**, illustrée sur le cas de la méthode Européenne. Cette grille permet de préciser les objectifs des indicateurs de criticité des matières premières existants afin de les utiliser à bon escient.

**Apport 8 : Un guide pour les non-experts pour appliquer l'AESA**, illustré sur un cas d'étude en électronique de puissance.

Ces contributions sont présentées dans les **Conférences 2 et 3** ainsi que les **Articles A et B**.

## Perspectives de recherche

Deux principaux axes de perspectives pour la thèse ont été explorés en discussion :

- **les usages, actuels et futurs de la typologie des archétypes de changement d'échelle en conception**. Cette discussion détaille quelques éléments de contexte peu présents dans les publications et met en lumière une lecture techno-solutioniste des archétypes dans nos travaux. Des pistes de réflexion sur un usage plus compatible avec des objectifs de soutenabilité sont abordés avec le changement d'échelle de *low-techs* et une confrontation au concept de *fermeture*.
- **le questionnement de l'ACV comme vecteur d'intégration de la soutenabilité environnementale**. Cette discussion présente les difficultés d'appliquer une approche multicritères, et de collecte de données associée au changement d'échelle. Ces difficultés interrogent sur l'utilisation de l'ACV dans un processus d'éco-conception et le type d'organisation que cela sous-tend. Deux perspectives ont été proposées : l'approfondissement des compatibilités entre modes d'ACV à l'attention des experts ACV, et l'identification des organisations et compétences nécessaires à la prise en compte environnementale du changement d'échelle à l'attention des chercheurs en conception collaborative et en éco-conception.

Pour finir, s'intéresser au changement d'échelle revient à questionner la place des technologies dans la société, et par extension celle des concepteurs. Une place dans

laquelle réside aujourd'hui un paradoxe : les concepteurs et ingénieurs sont à la fois la source de choix ayant une influence certaine sur la société dont ils peinent (conceptuellement et méthodologiquement) à en identifier la portée. En outre, ils sont dépendants d'un cahier des charges et sommés (par ricochet) de s'aligner sur des stratégies politiques et environnementales qui dépassent le cadre de la conception et pour lesquels, souvent, ils n'ont pas été consultés ou formés. Ces travaux, me semble-t-il, contribuent à montrer, parfois par l'absurde, qu'une vision technique et utilitariste de la soutenabilité est une impasse. La technologie, en tant qu'étude des techniques mobilisées dans nos sociétés, a une responsabilité forte qui ne peut être laissée à la discrétion des seuls ingénieurs et entreprises qui les emploient. Je me joins à d'autres dans le souhait d'avoir participé avec cette thèse à la recherche d'une juste place de la conception dans la société, à l'élaboration de meilleures formations pour les futurs concepteurs, et au partage des responsabilités pour la soutenabilité.



# Annexes

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## A.1 Acronymes

### Acronymes Français

**ACV** Analyse de Cycle de Vie

**ADEME** Agence de la transition écologique

**AIE** Agence internationale de l'énergie

**CEA** Commissariat à l'énergie atomique et aux énergies alternatives

**COSYS** Equipe Conception Systémique : humain, environnement, technologies

**EW-MFA** Economy Wide Material Flow Analysis

**GIEC** Groupe d'Experts Intergouvernemental sur l'Evolution du Climat

**G2Elab** Laboratoire Grenoble Génie Electrique

**Idex** Initiative d'excellence

**IPBES** Plateforme intergouvernementale scientifique et politique sur la biodiversité et les services écosystémiques

**IRT** Institut de Recherche Technologique

**ODD** Objectifs de Développement Durable

**OIE** Observation, Impacts, Energie

**QR** Question de Recherche

**RTE** Gestionnaire du réseau de transport d'électricité Français

**SHS** Sciences Humaines et Sociales

**SNBC** Stratégie Nationale Bas Carbone

**TW** Téra watt

### Acronymes Anglais

**AESA** Absolute Environmental Sustainability Assessment

**AF** Allocation Factor

**AC/DC** Alternating Current / Direct Current

**ASR** Absolute Sustainable Ratio

**BoM** Bill of Materials

**CC** Carrying Capacities

**CDP** Cross Disciplinary Programs

**CLD** Causal Loop Diagram

**CRM** Critical Raw Material

**DfST** Design for Sustainability Transitions

**DRM** Design Research Methodology

**EAU** Environmental Assessment for Upscaling  
**EC** European Commission  
**EC-RMC** European Commission Raw Material Criticality  
**ECTS** European Credit Transfer and Accumulation System  
**EF** Engineering Fields  
**ETH** Federal Institute of Technology Zurich  
**EV** Electric Vehicle  
**GWP** Global Warming Potential  
**IAM** Integrated Assessment Modelling  
**IEA** International Energy Agency  
**IPCC** Intergovernmental Panel on Climate Change  
**IRENA** International Renewable Energy Agency  
**IT** Information Technology  
**ITPV** International Technology Roadmap for Photovoltaic  
**LCA** Life Cycle Assessment  
**LCE** Life Cycle Engineering  
**LCI** Life Cycle Inventory  
**LCIA** Life Cycle Impact Assessment  
**LCM** Life Cycle Management  
**LCT** Life Cycle Thinking  
**MFA** Material Flow Analysis  
**MO** Mitigation Options  
**MPI** Mining, Production and Installation  
**MRL** Market Readiness Level  
**MSA** Material System Analysis  
**OECD** Organisation for Economic Co-operation and Development  
**PB** Planetary Boundaries  
**PB-LCIA** Planetary Boundary - Life Cycle Impact Assessment  
**PV** Photovoltaic  
**PWB** Printed Wiring Board  
**REACH** Registration, Evaluation, Authorization and Restriction of Chemicals  
**SDS** Sustainable Development Scenario  
**SBT** Science Based Target  
**SOS** Safe Operating Space  
**SoSOS** Share of Safe Operating Space  
**SSP** Shared Socio-economic Pathways

**SR** Sharing Principle

**TEA** Techno-Economic Analysis

**TRL** Technology Readiness Level

**UA** Upscaling Archetypes

**UA-EF** Upscaling Archetypes - Engineering Fields

**UEA** Upscaling Environmental Assessment

## A.2 Synthèse de la communication scientifique des travaux de thèse (10 Octobre 2024)

| Papier                                                        | Fonction dans la thèse                                                                                                                                                                             | Statut                                                                                                                                                                                                                              | Titre                                                                                                                                                                | Revue                                                                             | Lien                                                                                                                                                                                        |
|---------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Conférence 1</b>                                           | Cadre méthodologique d'analyse du changement d'échelle                                                                                                                                             | <b>Publié</b> (28/03/2022)                                                                                                                                                                                                          | <i>For an upscaling assessment integration in design</i>                                                                                                             | CIRP Design 2022                                                                  | <a href="https://doi.org/10.1016/j.procir.2022.05.219">https://doi.org/10.1016/j.procir.2022.05.219</a>                                                                                     |
| <b>Article 1</b>                                              | Revue de la littérature, définitions et proposition de guidelines pour prendre en compte le changement d'échelle selon une facette/définition donnée.                                              | <b>Soumis le 12/10/2023</b><br>En review : 22/10/23<br><b>Accepté (06/07/24)</b>                                                                                                                                                    | <i>Designing emerging technologies taking into account upscaling</i>                                                                                                 | Design science                                                                    | <a href="https://doi.org/10.1017/dsj.2024.33">https://doi.org/10.1017/dsj.2024.33</a>                                                                                                       |
| <b>Article 2</b>                                              | Revue de la littérature et mise en regard des « modes d'ACV » avec les archétypes pour une prise en compte environnementale du changement d'échelle.                                               | <b>Soumis le 06/06/2024</b><br>En review : 07/06/24<br>Revision: 21/06/24<br><b>Accepté (31/07/24)</b>                                                                                                                              | <i>Emerging technology upscaling: A Framework for matching LCA practices with upscaling archetypes</i>                                                               | Sustainable Production and Consumption                                            | <a href="https://doi.org/10.1016/j.spc.2024.07.032">https://doi.org/10.1016/j.spc.2024.07.032</a>                                                                                           |
| <b>Conférence 2</b>                                           | Application du cadre de soutenabilité absolue et démonstration du manque de méthode unifiée pour prendre en compte toutes les facettes du changement d'échelle                                     | <b>Publié</b> (02/2023)                                                                                                                                                                                                             | <i>Assessing energy technologies sustainability: upscaling photovoltaics using absolute LCA</i>                                                                      | CIRP LCE 2023                                                                     | <a href="https://doi.org/10.1016/j.procir.2023.02.120">https://doi.org/10.1016/j.procir.2023.02.120</a>                                                                                     |
| <b>Article 3</b>                                              | Proposition d'un processus « unifiée » pour préparer une ACV dans une démarche de changement d'échelle d'une technologie                                                                           | <b>A resoumettre</b><br><br><b>Soumis le 31/07/23</b><br>Major Revision : 11/23<br>Resoumission : 01/03<br><b>Rejeté par IJ-LCA (04/ 2024)</b>                                                                                      | <i>Environmental Assessment for Upscaling: a LCA-based eco-design process for design teams</i>                                                                       | International Journal of Sustainable Engineering ou Journal of Cleaner Production | <a href="https://www.sciencedirect.com/journal/search.php?q=19700181207&amp;tip=sid&amp;clean=0">https://www.sciencedirect.com/journal/search.php?q=19700181207&amp;tip=sid&amp;clean=0</a> |
| <b>Conférence 3</b>                                           | Validation/illustration de la méthode EAU par cas d'étude : ACV prospective sur photovoltaïque                                                                                                     | <b>Publié</b> (05/2024)                                                                                                                                                                                                             | <i>Towards ecodesign for upscaling: an illustrative case study on photovoltaic technology in France</i>                                                              | CIRP LCE 2024                                                                     | <a href="https://doi.org/10.1016/j.procir.2024.01.059">https://doi.org/10.1016/j.procir.2024.01.059</a>                                                                                     |
| <b>Article A</b><br>1 <sup>er</sup> auteur<br>Liticia Labadi  | Travail sur l'archétype 3 avec la criticité des matières premières (définitions, étude de l'utilisation et mise en évidence de problématique d'intégration en conception...) pour des non-experts. | <b>A resoumettre</b><br><b>En cours de finalisation de rédaction en fonction du journal ciblé</b><br><br><b>Soumis le 31/07/23</b><br>Re-soumission : 10/23<br>Re-soumission : 03/24<br><b>Rejeté par Resources MDPI (03/ 2024)</b> | <i>A review of the use of the European Commission Raw Material Criticality Assessment Methodology: Towards a comprehensive framework for criticality assessments</i> | Sustainable Materials and Technologies                                            | <a href="https://www.sciencedirect.com/journal/sustainable-materials-and-technologies">https://www.sciencedirect.com/journal/sustainable-materials-and-technologies</a>                     |
| <b>Article B</b><br>1 <sup>er</sup> auteur<br>Valentin Girard | Travail sur l'archétype 5 avec l'utilisation de principes de partage dans l'AESA pour des non-experts.                                                                                             | <b>En cours de finalisation de rédaction</b><br>A soumettre en Novembre 2024                                                                                                                                                        | <i>Sharing Principles in AESA: help designers get a foot on the ladder</i>                                                                                           | Design science                                                                    | <a href="https://www.cambridge.org/core/journals/design-science">https://www.cambridge.org/core/journals/design-science</a>                                                                 |

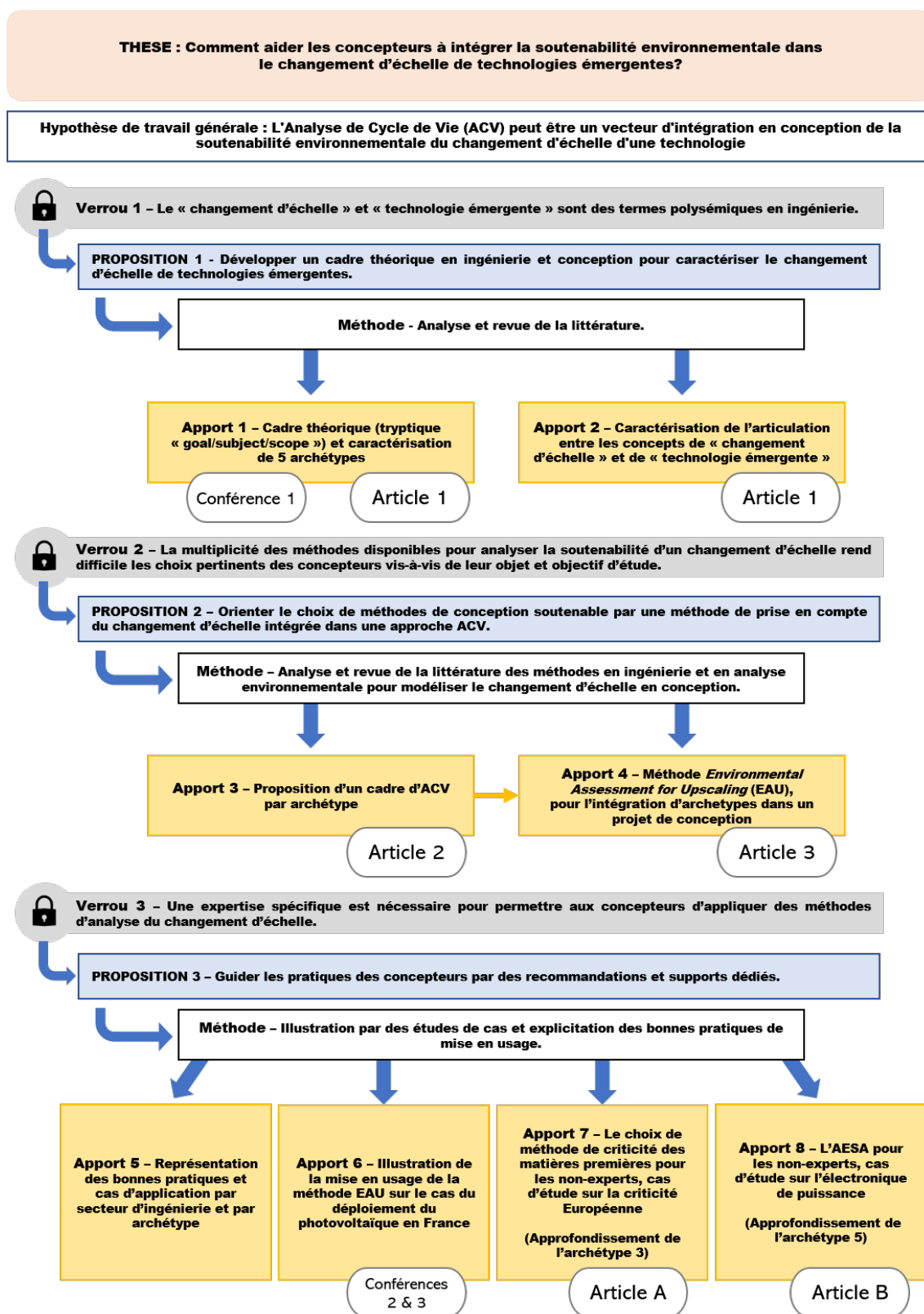
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Accepté

En révision

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## A.3 Figure de structure de la thèse





## A.4 Matrice UA-EF

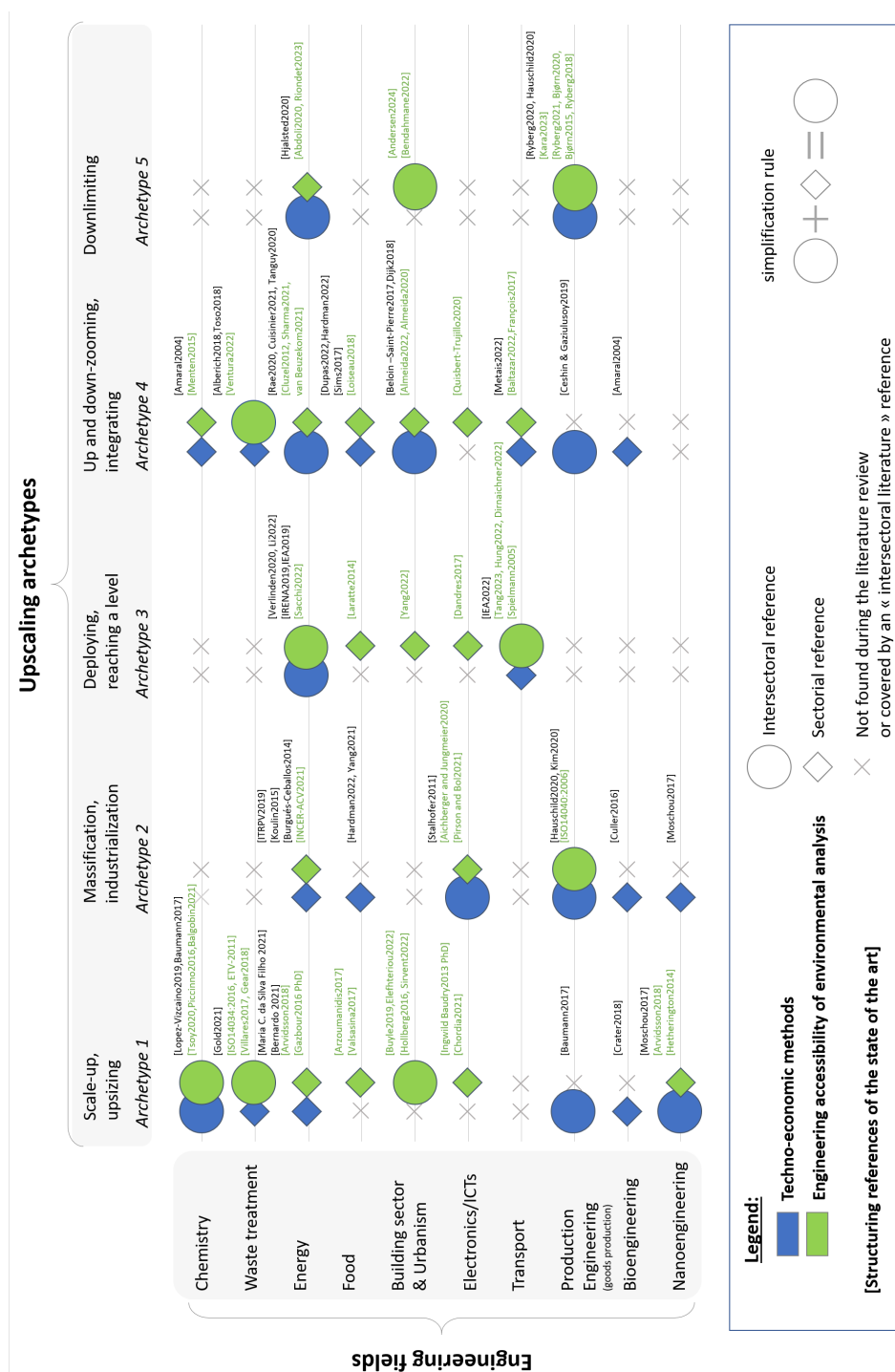


**FIGURE A.1** – Matrice *Upscaling Archetypes - Engineering Fields* (UA-EF) présentant les méthodes techno-économiques (bleu) et d'analyse environnementales (vert) identifiées dans la littérature en 2023.

## A.5 Agrandissement (Article 1, Table 1)

Table 1 - Synthesis of archetypes definitions with associated keywords and symbolic illustration (extracted from ARTICLE 1)

| Upscaling archetype                         | Definition                                                                                            | Usual Goal                                             | Usual subject                                                                                          | Focus                                                                           | Associated keywords                                                                                                                                                                                                                                                                                                                                                                                                 | Illustration adapted from (Riondet et al., 2022) nonreCature |
|---------------------------------------------|-------------------------------------------------------------------------------------------------------|--------------------------------------------------------|--------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------|
| Arch. 1<br>Upsizing                         | Phenomenon generating a "prototype" at industrial or commercial scale.                                | Maximize maturity (often associated with productivity) | Technology/service upscaled (e.g. emerging technology)                                                 | Technology upscaled                                                             | Technology, Readiness Level (TRL), Maturity, Industrial scale, Scale-up, Pilot Prototype, Size technology, Miniaturization, Early-stage technology, Scalability, Novel technology, Commercial scale, Scale up, Emerging technology, Upscaling                                                                                                                                                                       |                                                              |
| Arch. 2<br>Mass producing                   | Phenomenon adapting a technology to be mass-produced.                                                 | Maximize producibility                                 | Technology/service upscaled (e.g. novel technology)                                                    | Technology upscaled in manufacture                                              | Manufacturing, Readiness Level (TRL), Learning by doing, Mass-manufacturing, Commercialization, Design standardization, Commercialization, Industrialization process, Economy of scale, Scalability, Novel technology, Commercial scale, Scale up, Scaling, Emerging technology, Upscaling                                                                                                                          |                                                              |
| Arch. 3<br>Reaching a level                 | Phenomenon translating requirements into technology sector perspective.                               | Reaching a sufficient level of cumulated service       | Technology upscaled / boundary of analysis (e.g. early adoption-diffused technology, niche technology) | The cumulated service of the group of produced technology                       | Large-scale deployment, Market penetration, Technology diffusion, Market Readiness Level (MRL2), Planification, Teawatt level, Growth dynamic, Reaching 'materiality', Large-scale production, Raw material criticality, Transitioning, Low-carbon transition, Energy transition, Levels, Niche technologies, Deployment, Technology adoption, Infrastructure, Scale up, Emerging technology, Scaling up, Upscaling |                                                              |
| Arch. 4<br>Up and down-zooming /integrating | Integration phenomenon of a technology as a part of a larger and complex system.                      | Maximize the efficiency of a complex system            | Boundary of analysis                                                                                   | The technology interoperability to support its systemic integration             | Grid integration, Interoperability, Acceptability, Network, Smart technology, Complex system, Urban metabolism, Socio-technical systems, Societal transformation, Multi-level, Transition pathways, Territory scale, Transitions, Levels, Niche technologies, Deployment, Technology adoption, Infrastructure, Scaling, Upscaling                                                                                   |                                                              |
| Arch. 5<br>Down-limiting                    | Phenomenon tending to restrict technologies or activities according to sustainability considerations. | Assess the sustainability of a technology / service.   | Science-based limit of the domain (environmental limit)                                                | The sustainability of a service provided by one or several products, or systems | Planetary boundaries, Safe operating space (SOS) Downscaling, Carrying capacity, Share of S&S (SoS&S), Absolute Environmental Sustainability Assessment (AES), Justice principle, Science based target, Planetary scale, Regional scale, Production, Allocation, Characterization factor, Normalization factor, Scaling                                                                                             |                                                              |

### DIAGRAM LEGEND

- Upscaling is represented with an arrow from subject to its result

- Upscaling takes place in a chosen performance Domain D

Subject Result of the upscaling

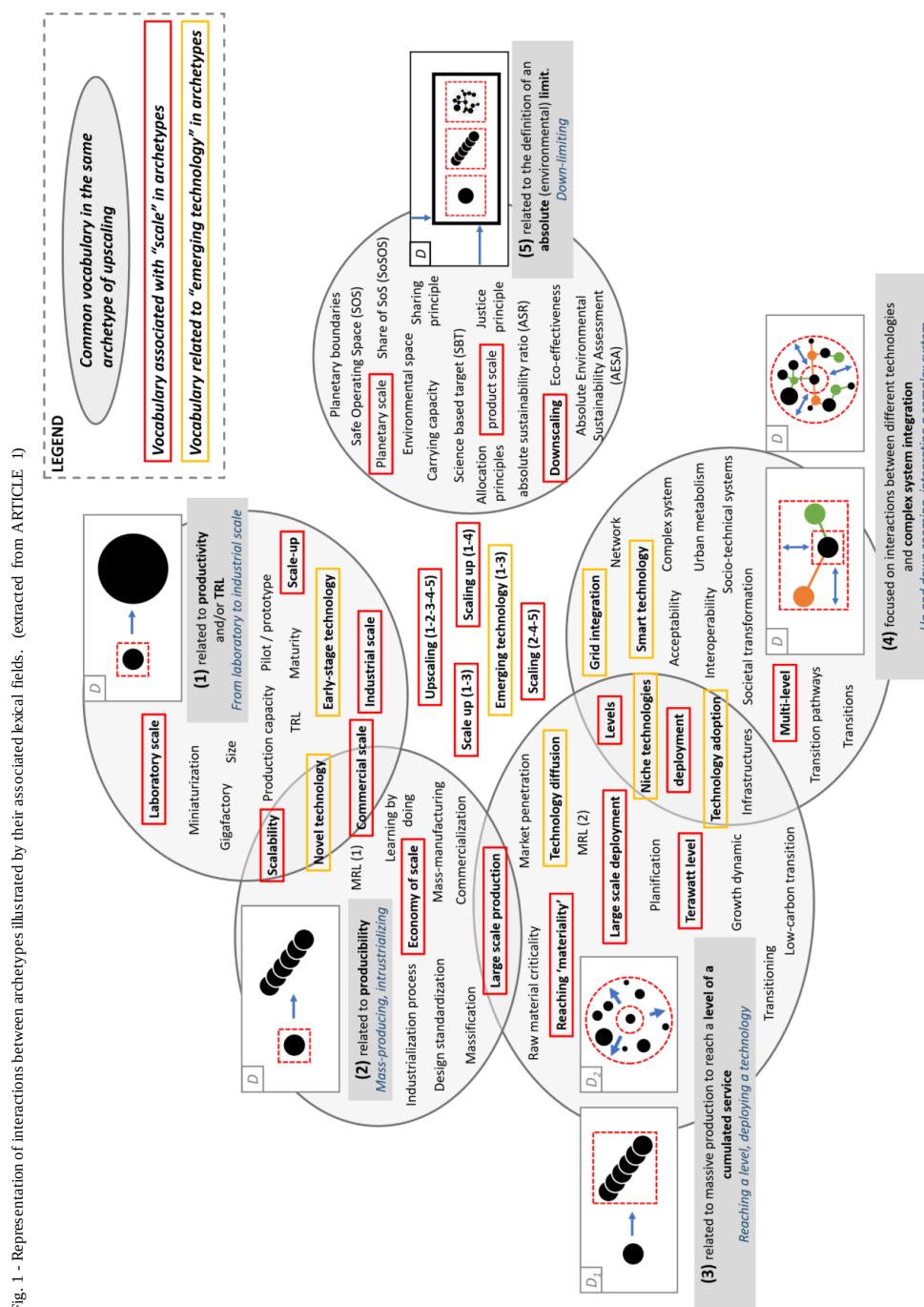
- Three types of subject

A technology or service performance in domain D  
The analysis boundary Of « focus »  
The limit of the Domain D

- Three types of entity on which focus is made

A technology or a group of the same technology  
A group of technologies with varying levels of performance  
A complex system: Large scale system with high number of interconnected subsystems/technologies

## A.6 Agrandissement (Article 1, Fig. 1)



## A.7 Agrandissement (Article 2, Table 2)

Table 2 - Synthesis of environmental methods and guidelines for LCA practitioners by upscaling archetype. (extracted from ARTICLE 2)

| Upscaling archetype                                            | Methodological requirements                                                                                                                                                                                                                                                                                                                                  | Main used environmental assessment modes                                                                                                                          | Additional LCA modes                                                                                                                          | Recommendations / clauses and constraints                                                                                                                                                                                                                                                             |                                                                                                                                                                                                                                                                                                                           | Additional resources                                                                                                                                                                                  |
|----------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                |                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                                   |                                                                                                                                               | Geographical/ Temporality                                                                                                                                                                                                                                                                             | LCA specificities                                                                                                                                                                                                                                                                                                         |                                                                                                                                                                                                       |
| <b>Archetype 1</b><br>Scaling, upscaling                       | <ul style="list-style-type: none"> <li>Define the specific technical expertise;</li> <li>ensure strong interactions between researchers and engineers;</li> <li>implement a future-oriented design.</li> </ul>                                                                                                                                               | <ul style="list-style-type: none"> <li>Ex-ante LCA</li> <li>Simplified (attributional) LCA</li> <li>EIV</li> </ul>                                                | <ul style="list-style-type: none"> <li>Regionalized</li> <li>Parametrized</li> </ul>                                                          | <ul style="list-style-type: none"> <li>Mainly use phase-focused, integrative life cycle. Studied: the product.</li> <li>Expertise's timescale is over months.</li> </ul>                                                                                                                              | <ul style="list-style-type: none"> <li>Foreground system caution and clear scenario of use phase in the comparative framework: "to which incumbent technology the prototype is compared?";</li> <li>data production/collecting challenges;</li> <li>parameterization of the LCI with design parameters useful.</li> </ul> | Available means in literature for data collection: (Zargar et al., 2022)                                                                                                                              |
| <b>Archetype 2</b><br>Mass producing, industrializing          | <ul style="list-style-type: none"> <li>Follow an integrative and normative approach;</li> <li>develop techno-economic expertise;</li> <li>Identify the stakeholders of the value chain.</li> </ul>                                                                                                                                                           | <ul style="list-style-type: none"> <li>ISO Standards-based LCA (attributional, consequential)</li> <li>Prospective dynamic LCA</li> </ul>                         | <ul style="list-style-type: none"> <li>Regionalized</li> <li>Dynamic</li> </ul>                                                               | <ul style="list-style-type: none"> <li>Life cycle-based, regionalized approach if possible over the value chain.</li> <li>Studied: The product system.</li> <li>Expertise's timescale is over years.</li> </ul>                                                                                       | <ul style="list-style-type: none"> <li>Industrial trend focus (e.g. favor dynamic LCI);</li> <li>End-of-life modelling challenges;</li> <li>data collection/extrapolation challenges.</li> </ul>                                                                                                                          | Design for X (Manufacturing) LCA standards and European commission ("European Platform on LCA   EPLCA," 2011)                                                                                         |
| <b>Archetype 3</b><br>Reaching a level, deploying a technology | <ul style="list-style-type: none"> <li>Develop a market maturity and sectoral long-term expertise;</li> <li>characterize a cumulative technology's performance;</li> <li>Set up scenario expertise and specific data uncertainty management.</li> </ul>                                                                                                      | <ul style="list-style-type: none"> <li>Prospective, attributional and dynamic LCA</li> <li>Integrated LCA - dynamic modelling</li> </ul>                          | <ul style="list-style-type: none"> <li>Attributional, consequential</li> <li>Regionalized</li> <li>Transition</li> </ul>                      | <ul style="list-style-type: none"> <li>Large spatial/social scale (regional, national - sectorial or group of technology).</li> <li>Studied: The industry sector associated with the product.</li> <li>Phenomenon's timescale is over decades. Expertise's timescale is over months/years.</li> </ul> | <ul style="list-style-type: none"> <li>Background system accuracy challenges: rigorous scenario hypothesis is required;</li> <li>avoidance of temporal mismatch (i.e. favor dynamic LCA);</li> <li>Natural resources focus, and more broadly cumulative properties of the environmental impacts.</li> </ul>               | Material indicator: mineral resource dissipation (Charpentier Poncelet et al., 2022)<br>Prospective scenario management: (Langkau et al., 2023)<br>Uncertainties and prospective (Maier et al., 2016) |
| <b>Archetype 4</b><br>Integrating a complex system             | <ul style="list-style-type: none"> <li>Mobilize system dynamic engineering with interoperability focus;</li> <li>adopt a culture of trade-offs from optimization modelling or socio-economic expertise;</li> <li>more broadly, develop a multidisciplinary approach.</li> </ul>                                                                              | <ul style="list-style-type: none"> <li>Regionalized/spatialized LCA</li> <li>Consequential LCA</li> <li>Transition LCA</li> <li>Optimization modelling</li> </ul> | <ul style="list-style-type: none"> <li>Attributional</li> <li>Consequential</li> <li>Hybrid</li> <li>Dynamic</li> <li>Prospective</li> </ul>  | <ul style="list-style-type: none"> <li>Large geographical scale (the one of the complex system).</li> <li>Studied: the complex system interacting with the product.</li> <li>Spatial/geographical properties focus. Phenomenon's timescale is varying from real-time to decades.</li> </ul>           | <ul style="list-style-type: none"> <li>Analysis perimeter challenges (i.e. which territory to consider?);</li> <li>causal model to choose (if consequential approach) and more broadly interaction modelling challenges;</li> <li>data collection and management challenges.</li> </ul>                                   | Design for Sustainability (Ceschin and Gazulusoy, 2019)                                                                                                                                               |
| <b>Archetype 5</b><br>Down-limiting                            | <ul style="list-style-type: none"> <li>Observe fair allocation methods (i.e. justice principles) and strictly define the service being studied;</li> <li>manage the data collection associated with the service (usually technoeconomically based);</li> <li>monitor methodological development (for product) from (AESA: Indicators, weighting).</li> </ul> | <ul style="list-style-type: none"> <li>Absolute (attributional) LCA</li> </ul>                                                                                    | <ul style="list-style-type: none"> <li>Prospective</li> <li>Transition</li> <li>Regionalized</li> <li>Dynamic</li> <li>Spatialized</li> </ul> | <ul style="list-style-type: none"> <li>Focused on services provided to humans, life cycle based on possible regional focus (national/sectorial).</li> </ul>                                                                                                                                           | <ul style="list-style-type: none"> <li>Scope and analysis is perimeter challenges (i.e. which human service/system to consider?);</li> <li>the functional unit is measured per unit of time (as an annual pressure on the environment);</li> <li>Specific characterization factors of the impact assessment.</li> </ul>   | Specific characterization factors (PB-LCA): (Ryberg et al., 2020; Winther, 2023)                                                                                                                      |

## A.8 Agrandissement (Article 2, Appendix 1, 1/3)

Appendix 1 - Selected characteristics of LCA modes potentially suitable for assessing one or several upscaling archetypes, adapted from (Guinée et al., 2018) and (Ventura, 2022a) (extracted from ARTICLE 2)

| LCA mode            | Definition                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Addressed question                                                                                                                                 | Scope                                                                                           |                                                      | ISO-standard covered | Considered expertise* and actors                                                                                                                                                                                | Databases or specific resources                                                                                                     | Associated references                                                                    |
|---------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|------------------------------------------------------|----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|
|                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                    | Reference flows or object in the foreground system                                              | Temporal                                             |                      |                                                                                                                                                                                                                 |                                                                                                                                     |                                                                                          |
| Attributional       | <ul style="list-style-type: none"> <li>• “The attributional approach attempts to provide information on what portion of global burdens can be associated with a product (and its life cycle).” (Sonnemann et al., 2011).</li> <li>• “Describe actual and/or forecasted specific and/or average life cycle of a studied object relatively to its functional unit into a static background system” (Ventura, 2022a).</li> </ul>                                                                                                                                                                                | What portion of global environmental impacts can be attributed to the studied object?                                                              | A product system (including the product's life-cycle), usually product and value chain focused. | Future or past-oriented.                             | Yes                  | Product and industrial engineering. Allocation rules.<br>One actor (in general).                                                                                                                                | Standard LCA data(bases), such as ecoinvent, GaBi, ILCD, USDA or Idenat                                                             | “ISO 14040,” 2006; Schaubroeck et al., 2021; Sonnemann et al., 2011                      |
|                     | <ul style="list-style-type: none"> <li>• “The consequential approach attempts to provide information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision (usually represented by changes in demand for a product).” (Sonnemann et al., 2011).</li> <li>• “Describe expected changes in response to possible decisions or to changes in demand for the functional unit into a dynamic background system” (Ventura, 2022a).</li> </ul>                                                                                                                             | How human activities or societies (socio-technical systems) react to an unusual event or request and what are the resulting environmental impacts? | Product systems they change due to a decision. (Multiple value chains).                         | Future-oriented.                                     | Yes                  | Technical and/or economic causal modelling expertise.<br>One actor (in general).                                                                                                                                | Standard LCA data(bases), such as ecoinvent.                                                                                        | “ISO 14040,” 2006; Sonnemann et al., 2011; Weidema et al., 2018                          |
| Prospective         | “Prospective LCA deals with technologies in the future, whereas retrospective studies deal with products in the past, regardless of other modelling approaches.” It is a scenario-based approach and can be motivated by predictive, exploratory or normative perspective (Arvidsson et al., 2018).                                                                                                                                                                                                                                                                                                          | What will/may or must be the environmental impacts of a studied object?                                                                            | A product system, already mature or not.                                                        | Future-oriented: predictive, exploratory, normative. | No                   | Scenario management expertise and socio-economic technological expertise.<br>If necessary, multiple actors (technical and technological experts, economists, social scientists, engineers, decision-makers...). | Software and computation resources: (Sacchi et al., 2023, 2022b; Steubing et al., 2020)<br>Sensitivity analysis: (Kim et al., 2022) | Arvidsson et al., 2018                                                                   |
| Ex-ante             | <ul style="list-style-type: none"> <li>• A particular case of prospective LCA. Describe the “environmental profile of an emerging technology on an industrial scale and use this information to steer further research efforts or compare an emerging technology with an incumbent technology on an industrial scale”. (Buyle et al., 2019).</li> <li>• “Ex-ante is defined as before a product or technology is commercially deployed at scale and information and insights on the topic under assessment are not (yet) readily available.” (Tecchio et al., 2016; van der Giesen et al., 2020).</li> </ul> | What will/may be the life cycle impacts associated with early-stage technology after its industrialization/commercialization?                      | An emerging/early-stage/prototype technology or product system. Rarely including EoL.           | Future-oriented: predictive, exploratory.            | No                   | Technology and extrapolating expertise. Multiple actors: LCA practitioners and technical experts (R&D actors) (Tsoy et al., 2020).                                                                              | Sensitivity analysis (Lacagnola et al., 2017)                                                                                       | Tecchio et al., 2016; van der Giesen et al., 2020; Buyle et al., 2019; Tsoy et al., 2020 |
| Classic, historical |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                    | Temporal focus                                                                                  |                                                      |                      |                                                                                                                                                                                                                 |                                                                                                                                     |                                                                                          |

## A.9 Agrandissement (Article 2, Appendix 1, 2/3)

| Parametrized                    | A particular case of ex-ante LCA.<br>“The basic concept of the parametric life cycle assessment (PLCA) approach is combining the principles of parameterization with a general LCA method. [...] it helps to identify the eco-design as well as the effective parameters based on their effects on the entire life cycle through sensitivity analysis and scenario analysis.” (Kamalakkannan and Kulatunga, 2021)                                                                                                                                                                                                                                                                                                                                                                                                                                                 | What is the influence of design parameters on LCA results?                                                                                                                                                                                                                   | A future or current emerging/early-stage technology or product system. | Future-oriented: predictive, exploratory. | No  | Technology modelling, extrapolating and design expertise.<br>Multiple actors: LCA practitioner and technical experts (R&D actors) (Isoy et al., 2020). | /                                                                           | Kamalakkannan and Kulatunga, 2021                   |
|---------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|-------------------------------------------|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------|
| Anticipatory                    | <ul style="list-style-type: none"> <li>Describe future developments and “states that stakeholders should be included in the process to obtain more valuable results”. (van der Giesen et al., 2020). Based on anticipatory governance, “takes a forward-looking (not retrospective assessment) and engages stakeholders to inform critical modelling decisions and increase the credibility and relevance of results.</li> <li>Anticipatory LCA can be defined as “non-predictive and inclusive of uncertainty, which can be used to explore both reasonable and extreme-case scenarios of future environmental burdens associated with an emerging technology”. The aim is to identify the most relevant uncertainties and engaging research and development decision-makers to guide research and development and innovation” (Wender et al., 2014).</li> </ul> | <p>What may be the life cycle impacts associated with early-stage technology after its industrialization and what are the levels to lower them?</p> <p>OR</p> <p>What must be the life cycle impacts associated with early-stage technology after its industrialization?</p> | An early-stage technology/ product system.                             | Future-oriented: exploratory, normative.  | No  | Decision-sharing expertise. Multiple actors (LCA practitioner, technical experts, decision-makers).                                                    | /                                                                           | van der Giesen et al., 2020; Wender et al., 2014    |
| Ex-post/retrospective           | Describe the environmental profile of a product after it had been information and data are available from empirical experience” (van der Giesen et al., 2020).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | What was/is the environmental impacts of the studied object?                                                                                                                                                                                                                 | A commercially existing product system.                                | Past-oriented.                            | Yes | Data collection and management expertise, one actor (in general).                                                                                      | Standard LCA data(bases)                                                    | van der Giesen et al., 2020                         |
| Dynamic (Static)                | Dynamic LCA “assess the environmental impacts at different time steps, according to both different moments of emissions and kinetics of their effects inside the ecosystem”. “The dynamic approach is justified by the fact that the environmental impact of a pulsed emission is certainly different from that of the same quantity emitted but spread over time” (Ventura, 2022b).<br>Static : “LCA considers that all of the elementary flows in a product’s life cycle are emitted at the same time” (Ventura, 2022b).                                                                                                                                                                                                                                                                                                                                        | What are the effects of the time dependence of inventory and characterization on environmental impacts in LCA results? (Including cumulative effects)                                                                                                                        | A group of systems (fleet of products).                                | Future or past-oriented.                  | No  | Temporal variability expertise.<br>One actor (in general).                                                                                             | Brightway2 resources: (Cardellini et al., 2018; Cardellini and Murel, 2018) | Cardellini et al., 2018; Ventura, 2022b             |
| Regionalized (non-regionalized) | <p>Regionalization:</p> <ul style="list-style-type: none"> <li>Describe the environmental impacts with “assigned geographical location” (Frischknecht et al., 2019).</li> <li>A term used to describe the representativeness of the processes and phenomena of a given region (Patouillard et al., 2018).</li> </ul> <p>Spatial differentiation = regionalization of characterizing factors : site generic, site dependent and site specific (Porting and Hauschild, 2006).</p> <p>Non-regionalized: use aggregated/generic environmental</p>                                                                                                                                                                                                                                                                                                                     | What are the environmental impacts of a studied object with regard to its geographical location?                                                                                                                                                                             | A product system (including the product’s life-cycle).                 | Future or past-oriented.                  | Yes | Data collection and management expertise.<br>One actor (in general).                                                                                   | Brightway2 resources: (Murel, 2014; Murel and Louineau, 2021)               | Frischknecht et al., 2019; Patouillard et al., 2018 |
| Geographical focus              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                                                                                                                                                                                                                                                                              |                                                                        |                                           |     |                                                                                                                                                        |                                                                             |                                                     |

## A.10 Agrandissement (Article 2, Appendix 1, 3/3)

|                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                           |                                                                                                                                                       |                          |    |                                                                                                                                                         |                                                                                                        |                                                                                     |
|---------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------|----|---------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
|                     | Impacts without spatial differentiation.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Type A: What are the environmental impacts of a studied object with regard to its interactions with a considered territory?<br>Type B: What are the environmental impacts associated with functions and services provided by a territory? | Type A: One product system produced in a territory.<br>Type B: A territory ("several products produced or consumed in a territory" (Ventura, 2022a)). | Future or past-oriented. | No | Geographer's expertise.<br>Type A: Possibly involving "several actors in the territory".<br>Type B: "several actors in the territory" (Ventura, 2022a). | /                                                                                                      | Loiseau et al., 2018                                                                |
| Territorialized     | A particular case of regionalized LCA. Territorial LCAs have been divided into two types: type A and type B (Loiseau et al., 2018).<br>Type A: study a technology anchored in a known territory of which functions may vary according to that territory, and type B study one territory with all its functions and related activities. In both methods, the foreground system is inside the considered territory. [...]<br>Territorial LCAs (type A) assess environmental impacts relatively to a unitary functional unit, but it may include several actors if these are located inside the considered territory.<br>Territorial LCAs (type B) assess environmental impacts relatively to the total numbers of products that are produced and consumed inside the considered territory and thus all concerned actors inside this territory. (Loiseau et al., 2018; Ventura, 2022a) |                                                                                                                                                                                                                                           |                                                                                                                                                       |                          |    |                                                                                                                                                         |                                                                                                        |                                                                                     |
| Spatialized         | Spatialization: act of assigning a location to something, e.g. a flow (Patouillard et al., 2018). A term used to describe the variability of processes and phenomena depending on geography.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | What is the geographical distribution of environmental impacts associated with LCA results?                                                                                                                                               | A large area system.                                                                                                                                  | Past-oriented.           | No | Geographical variability expertise, geographical information system (GIS) data collection.<br>One actor (in general).                                   | Brightway2 resources (Mutel, 2014)                                                                     | Patouillard et al., 2018                                                            |
| Transition (Hybrid) | A particular case of hybrid LCA, using consequential and spatialized attributional LCA frameworks. "Describe expected changes in response to possible decisions or to changes generated by transition solutions into a dynamic background system" (Ventura, 2022a).<br>Hybrid: use methodological elements of LCA (e.g. environmental indicators, models, characterization factors).<br>A particular case of hybrid LCA: "Describe macroscale changes in response to possible decisions or changes in a given economic sector" (Ventura, 2022a).                                                                                                                                                                                                                                                                                                                                    | What are the expected changes in a given territory in response to the implementation of "transition solutions"?                                                                                                                           | Territory, including the human activities                                                                                                             | Future-oriented.         | No | "Several actors, several products, all involved in existing and substitution territorial scenarios" (Ventura, 2022a).                                   | /                                                                                                      | Ventura, 2022a                                                                      |
| Input/Output (IO)   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | What are the global life-cycle impacts associated with the evolution of an economic sector?                                                                                                                                               | An economic sector (multiple product systems or economic sectors).                                                                                    | Future or past-oriented. | No | Economic expertise, A Multiple actors (industrials, economists).                                                                                        | Examples of model/database: EXIOBASE: (Agez, 2022; Agez and Majeau-Bettez, 2020; Stadler et al., 2018) | Ventura, 2022a                                                                      |
| Absolute (AESA)     | A particular case of hybrid LCA, using the attributional LCA framework and completes it by comparing resulting impacts with an external list of environmental carrying capacities. It implies that for a given functional unit, no technical solution may be environmentally sustainable (Bjorn et al., 2020a).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Are the environmental impacts of the studied object lower than environmental limits/ sustainability levels normatively defined?                                                                                                           | Product system, industrial or economic sector, human activities.                                                                                      | Future or past-oriented. | No | Allocative, economic, social expertise.<br>One actor (in general).                                                                                      | Specific characterization factors. Available from (Winther, 2023)                                      | Bjorn et al., 2016; Bjorn et al., 2020b; Heijungs et al., 2014; Ryberg et al., 2020 |
| Hybrid, combined    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                                                                                                                                                                                           |                                                                                                                                                       |                          |    |                                                                                                                                                         |                                                                                                        |                                                                                     |



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# Liste des Travaux

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- Conférence 1**, L. RIONDET, M. RIO, V. PERROT-BERNARDET et P. ZWOLINSKI, « For an upscaling assessment integration in product design, » *Procedia CIRP*, 32nd CIRP Design Conference (CIRP Design 2022) - Design in a changing world, t. 109, p. 89-94, 2022. adresse : <https://doi.org/10.1016/j.procir.2022.05.219>.
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- Article 2**, L. RIONDET, M. RIO, V. PERROT-BERNARDET et P. ZWOLINSKI, « Emerging technologies upscaling : a framework for matching LCA practices with upscaling

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**Article B**, V. GIRARD, L. RIONDET, L. FANG et M. RIO, « Sharing principles in AESA : help designers get a foot on the ladder, » *In progress*,



*Good morning, and in case I don't see ya :*  
*Good afternoon, good evening, and good night !*  
**Truman**