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Alignment between national development priorities and climate change mitigation goals - analysis, modeling and implications for international climate negotiations

Articulation entre priorités de développement nationales et objectifs d'atténuation du changement climatique – analyse, modélisation et implications pour la négociation internationale sur le climat

Thèse de doctorat de l'université Paris-Saclay

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Spécialité de doctorat : Sciences économiques
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sous la direction de **Franck LECOCQ**, IGPEF (HDR)

Thèse soutenue à Nogent-sur-Marne, le 13 mai 2024, par

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Titre : Articulation entre priorités de développement nationales et objectifs d'atténuation du changement climatique – analyse, modélisation et implications pour la négociation internationale sur le climat

Mots clés : Atténuation du changement climatique ; Développement ; Objectifs de Développement Durable ; Modélisation macroéconomique ; Équité

Résumé : Objectifs d'atténuation du changement climatique et priorités de développement sont étroitement liés. Cependant, dans une certaine mesure, ces deux sujets restent traités dans des sphères séparées, à la fois au niveau des pays et à l'échelle internationale, où le développement est abordé dans le contexte des Objectifs de Développement Durable (ODDs), et l'atténuation via la Convention Cadre des Nations Unies sur les Changements Climatiques (CCNUCC). Dans ce contexte, les stratégies de développement des pays sont-elles alignées avec leurs objectifs d'atténuation du changement climatique ? Cette analyse peut-elle permettre de repenser le caractère équitable des contributions des pays à l'Accord de Paris ? Pour répondre à ces questions, y compris pour des pays pour lesquels données et analyses existantes sont limitées, ce travail de thèse construit et fournit des premières applications d'une méthodologie basée sur un modèle et peu intensive en données. Elle examine les conditions sous lesquelles les cibles d'atténuation, figurant dans les Contributions Déterminées au niveau National, et d'autres objectifs nationaux long-terme de développement, figurant dans des documents de planification nationale, sont compatibles.

Premièrement, en l'absence d'un recensement exhaustif des priorités de développement des pays, nous collectons et analysons les documents nationaux de développement à long-terme de 121 pays, pour en extraire leurs priorités de développement. Ce faisant, nous montrons que les ODDs constituent un cadre suffisamment exhaustif pour cartographier les priorités de développement.

Nous construisons ensuite une méthodologie utilisant le modèle d'équilibre général calculable (MEGC) KLEM, pour évaluer la compatibilité entre certaines des priorités de développement proposées dans les documents nationaux, et les cibles nationales d'atténuation. Nous montrons que l'évaluation des politiques climatiques par les MEGC est sensible aux choix de bouclage macroéconomique du modèle – un tel résultat n'existant pas encore, à notre connaissance, dans la littérature de modélisation climat – et incluons par conséquent des analyses de sensibilité autour de cette question dans notre méthode. Nous proposons de premières applications de la méthodologie au Malawi, à la Colombie et à l'Irak, et une discussion sur ses futurs développements. Troisièmement, nous passons en revue les outils utilisés pour évaluer le caractère équitable des cibles nationales d'atténuation : aucune ne permet à la fois d'inclure l'éventail complet de principes d'équité (parfois contradictoires) existant dans la littérature, et de systématiquement proposer un jugement concluant. Nous menons une première enquête par questionnaire pour collecter les opinions des citoyens Français et Américains sur l'équité dans le cadre international. Les résultats suggèrent qu'une extension de telles enquêtes à visée normative permettraient de légitimer l'utilisation d'un éventail plus restreint de principes, améliorant – sans toutefois le garantir – le caractère concluant des outils. Nous concluons cette thèse en exposant comment l'intégration d'autres priorités de développement dans ces discussions sur l'équité pourrait permettre de résoudre ces entraves.

Title : Alignment between national development priorities and climate change mitigation goals - analysis, modeling and implications for international climate negotiations

Keywords : Climate change mitigation; Development; Sustainable Development Goals; Macroeconomic modelling; Fairness

Abstract: Climate change mitigation goals and development priorities are closely linked. For the most part, however, they remain discussed in separate arenas, both within individual countries and at the international stage, where development is addressed in the context of the Sustainable Development Goals (SDGs) and mitigation is tackled by the UN Framework Convention on Climate Change (UNFCCC). In such a context, are countries' development strategies consistent with their climate mitigation targets? Can this assessment shed new light on how fair countries' contributions to the Paris Agreement are? To address these questions, including for countries in which existing data and analyses are limited, the present thesis builds and provides first applications of a model-based, data-sober methodology. Its aim is to examine the conditions under which climate mitigation targets, as expressed in Nationally Determined Contributions, and other long-term national development goals, as expressed in official development planning documents, are compatible.

In the absence of a comprehensive dataset on countries' development priorities, we first collect and analyse the long-term national development documents of 121 countries to extract stated development priorities. In doing so, we show that the SDGs are comprehensive enough to be a relevant framework to map development priorities.

We then build a flexible methodology based on the computable general equilibrium (CGE) model KLEM to assess the compatibility between some of the development priorities expressed in the development plans, and national mitigation targets. We demonstrate that CGE assessments of climate policies are sensitive to the choice of macroeconomic closure of the model – a point that, to our knowledge, had not been made in the climate modeling literature – and consequently include sensitivity analyses on this dimension in our methodology. We provide first applications of the methodology to Malawi, Colombia and Iraq, and discuss directions for future developments. Third, we review the tools currently used to assess the fairness of national mitigation targets: none would, at the same time, include the wide range of (sometimes contradictory) equity principles in the literature, while providing conclusive judgements. We build a survey collecting citizens' attitudes towards international equity in France and the US. Its results suggest that such surveys with a normative intent, if expanded, could legitimize the use of a narrower range of principles, thus improving – without fully reaching – the conclusiveness of these tools. We conclude by discussing how integrating other development priorities in the debates on fairness may help overcome this stumbling block.

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Introduction - Résumé en français

Atténuation du changement climatique et développement sont étroitement liés. Pourtant, les objectifs climatiques et les priorités de développement sont souvent traités dans des arènes politiques distinctes. La présente thèse a pour objectif d'explorer dans quelle mesure les objectifs nationaux d'atténuation sont alignés avec d'autres objectifs nationaux de développement, et à en comprendre les implications, au niveau national et pour la coopération internationale.

Cette introduction pose le cadre de notre démarche et détaille nos questions de recherche. Nous faisons d'abord un état des lieux sur la question de l'atténuation du changement climatique au niveau mondial, et rappelons à quel point des engagements plus ambitieux de la part des pays sont nécessaires, pour atteindre l'objectif de l'Accord de Paris de limiter le réchauffement climatique bien en dessous de 2°C (Section 1). Comme le souligne la littérature, une atténuation plus rapide et plus forte ne peut qu'avoir des interactions significatives avec d'autres priorités de développement, et l'incertitude concernant ces interactions constitue un obstacle majeur à une action renforcée (Section 2). Alors qu'au niveau international, le "développement" est maintenant entendu comme englobant l'atténuation (parmi d'autres objectifs de développement), ce cadre intégré ne se traduit pas nécessairement, au niveau national, par des objectifs d'atténuation et de développement cohérents entre eux (Section 3). Par conséquent, cette thèse développe une méthodologie pour évaluer dans quelle mesure les objectifs d'atténuation, tels qu'énoncés dans les Contributions Déterminées au niveau National, sont cohérents avec les priorités de développement, telles qu'énoncées dans les documents nationaux de planification à long terme. Elle examine ensuite comment ces résultats peuvent contribuer à débloquent les débats sur le caractère juste et ambitieux des efforts d'atténuation des pays (Section 4). La Section 5 conclut en donnant un aperçu de la structure de la thèse.

0.1 Négocier le changement climatique : une histoire d'équité liée au développement

Aperçu historique de la coopération internationale en matière de changement climatique : les débuts

Au niveau international, le changement climatique est mentionné pour la première fois avec d'autres questions environnementales dans le Plan d'action de Stockholm de 1972 (United Nations, 1972) adopté lors du premier Sommet de la Terre.¹ Au cours des deux décennies suivantes, des efforts concertés ont été déployés pour lutter contre le changement climatique. La question a été progressivement séparée des autres sujets liés à l'environnement et au développement, et des forums et institutions spécialisés ont été créés. Au sein de la communauté scientifique, la première conférence mondiale sur le changement climatique s'est tenue en février 1979. Au niveau international, le Groupe d'experts Intergouvernemental sur l'Evolution du Climat (GIEC), approuvé par l'ONU en 1988 (United Nations General Assembly, 1988), a été créé pour évaluer et synthétiser, de manière régulière, les connaissances scientifiques sur le sujet. Enfin, avec la signature de la Convention-Cadre des Nations Unies sur les Changements Climatiques (CCNUCC) lors du Sommet de la Terre de Rio en 1992 (United Nations, 1992) – qui a abordé séparément d'autres questions environnementales et de développement durable, donnant naissance à des conventions distinctes sur la Diversité Biologique (CDB) et sur la lutte contre la désertification (UNCCD), ainsi que l'Agenda 21, un plan d'action non contraignant visant à atteindre un développement durable au XXI^e siècle (United Nations Conference on Environment and Development, 1992).

La CCNUCC est un accord fondateur qui coordonne 198 Parties² et sert de base à une action coopérative pour lutter contre le changement climatique, avec l'objectif principal de parvenir à stabiliser les concentrations de gaz à effet de serre dans l'atmosphère "à un niveau qui empêche toute perturbation anthropique dangereuse du système climatique". (United Nations, 1992). Il mentionne explicitement la nécessité d'articuler changement climatique et développement, en déclarant qu' "*un tel niveau devrait être atteint dans un délai suffisant pour permettre aux écosystèmes de s'adapter*

¹Dans une section sur l'identification et le contrôle des polluants d'importance internationale, la Recommandation 70 recommande: "Governments be mindful of activities in which there is an appreciable risk of effects on climate" ["les gouvernements soient attentifs aux activités dans lesquelles il existe un risque appréciable d'effets sur le climat"].

²197 États et l'Union Européenne dans son ensemble.

naturellement au changement climatique, pour garantir que la production alimentaire ne soit pas menacée et pour permettre au développement économique de se poursuivre de manière durable". Au cours des décennies suivantes et sous son égide, la communauté internationale a été confrontée à la complexité de l'élaboration d'une réponse collective à un défi qui transcende les frontières et soulève de nombreuses questions de justice et d'équité.³

L'équité dans les négociations internationales sur le climat : des responsabilités communes mais différenciées

L'équité joue un rôle central dans la lutte contre le changement climatique à différentes échelles et niveaux. L'équité intergénérationnelle est importante, car les impacts et les réponses au changement climatique seront distribués entre les générations actuelles et futures (Meijers, 2023). L'équité importe au niveau procédural, par exemple dans les discussions sur l'inclusivité de la participation des parties prenantes aux prises de décisions liées au climat (Tomlinson, 2015). Au niveau intragénérationnel enfin, la manière dont les efforts, les coûts, les risques et les gains doivent être distribués entre les parties prenantes est une question cruciale pour l'action climatique, tant à l'intérieur des pays qu'entre eux (voir par exemple Méjean et al. (2015)). Sur ce dernier point, les différences de niveau de développement entre les pays planent sur de nombreux débats sur l'équité en lien avec l'atténuation (Heyward, 2007), et ce par trois aspects:

- Responsabilité historique du changement climatique : la plupart des pays développés ne sont pas seulement parmi les plus grands émetteurs d'aujourd'hui, mais l'ont été depuis le milieu du XIXe siècle (Botzen et al., 2008), en raison de leur développement historique.
- Vulnérabilité au changement climatique : les pays développés sont moins vulnérables au changement climatique, en partie en raison de leur forte préparation économique, gouvernementale et sociale à l'adaptation (Sarkodie and Strezov, 2019).
- Capacité à contribuer à l'atténuation du changement climatique : le coût de l'atténuation et l'éventail d'options d'atténuation dépendent du contexte de développement des pays (voir Chapitre 4). Les synergies et les compromis entre l'atténuation du changement climatique et les questions de développement économique et social varient également d'un pays à l'autre.

³En anglais, les mots *equity*, *justice* et *fairness* renvoient à des concepts légèrement différents mais très proches. Toutefois, les trois termes sont souvent utilisés de manière interchangeable (Grasso, 2007), comme ce sera le cas dans les chapitres de cette thèse.

Dans le contexte de la CCNUCC, l'équité apparaît donc comme un principe directeur, dont la compréhension et la mise en œuvre ont façonné les contours de la coopération climatique internationale telle que nous la connaissons aujourd'hui.

En ce qui concerne la justice distributive et l'atténuation du changement climatique, toutes les parties à la CCNUCC reconnaissent qu'il existe des inégalités entre les nations. L'Article 3 de la Convention stipule précisément qu' *"il incombe aux Parties de préserver le système climatique dans l'intérêt des générations présentes et futures, sur la base de l'équité et en fonction de leurs responsabilités communes mais différenciées et de leurs capacités respectives. Il appartient, en conséquence, aux pays développés parties d'être à l'avant-garde de la lutte contre les changements climatiques et leurs effets néfastes"*. (United Nations, 1992). D'un point de vue conceptuel, le principe des responsabilités communes mais différenciées (CBDR) fait référence au fait qu'il existe de grandes différences (*responsabilités différenciées*) entre les besoins de développement des nations, et leurs contributions à un problème qui affecte tous les pays dans une certaine mesure et ne peut être résolu sans une participation la plus large possible (*responsabilités communes*) (Cullet, 2021). La notion de CBDR (augmentée d'une mention des *capacités respectives*) est un compromis politique entre la demande des pays en développement de voir leurs circonstances nationales prises en compte, et l'opposition des pays développés à une mention directe de leurs émissions historiques (Deleuil, 2012), ce qui a rendu possible l'adoption de la CCNUCC.

Cependant, les responsabilités communes et différenciées ne sont pas nécessairement compatibles. Il n'y a donc guère eu d'accord sur la manière de mettre en œuvre ce principe, et son interprétation a varié selon les Parties et au cours du temps. Par conséquent, l'approche internationale de la coopération sur le changement climatique a considérablement évolué depuis la signature de la Convention (Heyward, 2007; Held and Roger, 2018), façonnée par les négociations sur la mise en œuvre des CBDR - et quelle(s) vision(s) de l'équité devrai(en)t la sous-tendre.

Du Protocole de Kyoto à la Conférence de Copenhague : essor et déclin d'une approche "top-down"

Dans le cadre de la CCNUCC, les pays développés Parties sont listés à l'Annexe I de la Convention. Dans ce cadre, ils ont des engagements spécifiques en matière d'atténuation qui sont détaillés à l'Article 4.2.

Lors de la troisième Conférence des Parties (COP) à la CCNUCC en 1997 (UNFCCC, 1997), des objectifs contraignants en matière d'émissions de gaz à effet de serre (GES) ont été négociés pour 38 Parties appartenant à l'Annexe I, dans le cadre du Protocole de Kyoto à la CCNUCC. Sous cette approche "top-down", les objectifs d'émissions étaient négociés en amont. Fixés pour la période 2008-2012 (communément appelée première période d'engagement), ils engageaient les pays industrialisés à réduire collectivement leurs émissions de 5,2% en moyenne par rapport à leurs niveaux de 1990, tandis que les pays en développement étaient encouragés, mais non tenus de prendre des mesures volontaires.⁴ Ils étaient ainsi libres de continuer à émettre davantage, selon leurs besoins de développement. Des tensions autour de cette opérationnalisation particulière du principe de CBDR ont rapidement émergé, comme le montre le refus des États-Unis de ratifier le Protocole de Kyoto, suite à la demande du Sénat américain, par le biais de la résolution Byrd, d'une participation contraignante pour les pays en développement (Lopez, 2003).

Bien que l'objectif agrégé d'atténuation fixé par le Protocole de Kyoto ait été atteint (Shishlov et al., 2016)⁵, ce dernier n'a eu qu'un impact limité sur les émissions mondiales. En effet, en l'absence des États-Unis et de tous les pays en développement, seule une fraction des émissions mondiales a finalement été couverte (Page, 2007). Les émissions mondiales de CO_2 ont augmenté de 59% entre 1990 et 2013, et de 14% au cours de la seule première période d'engagement (Rosen, 2015). Cela a mis en évidence la nécessité d'aborder les émissions provenant des pays en développement pour lutter contre le changement climatique, et a poussé les pays plus développés à plaider pour que l'accent soit moins mis sur la différenciation dans les processus internationaux ultérieurs.

Alors que l'amendement de Doha au protocole de Kyoto adopté en 2012 a établi une deuxième période d'engagement entrée en vigueur en 2020, un abandon de la division

⁴Trois mécanismes de marché ont été introduits pour permettre aux pays d'échanger des crédits d'émission, d'investir dans des projets de réduction des émissions dans les pays en développement grâce au mécanisme de développement propre et de collaborer à des projets de réduction des émissions grâce à la mise en œuvre conjointe.

⁵en tenant compte de la non-ratification des États-Unis et du retrait du Canada

Annexe I/non-Annexe I a ainsi été observé depuis le début de la préparation de la période post-2012. Lors de la 15^e Conférence des Parties (Copenhague, 2009), des tensions non résolues liées au principe de CBDR et à l'accent mis sur le traitement des émissions des pays en développement (tant les pays développés que les pays en développement maintenant leurs positions de longue date⁶) ont conduit à l'échec de l'adoption officielle d'un accord (Bodansky, 2010). Toutefois, la conférence de Copenhague a marqué une étape vers une approche plus "bottom-up", les principaux pays en développement s'étant engagés à intégrer leurs engagements nationaux en matière de réduction des émissions dans un instrument international et à fournir des rapports sur leurs efforts d'atténuation.

Ce changement a ouvert la voie à l'adoption de l'Accord de Paris lors de la 21^e conférence des parties en 2015 (UNFCCC, 2015), suivant lequel toutes les nations s'engagent à atténuer le changement climatique, mais chacune d'entre elles détermine sa propre contribution.

L'Accord de Paris : Une approche "bottom-up" avec des Contributions Déterminées au niveau National

L'Accord de Paris est un accord international historique adopté le 12 décembre 2015 (UNFCCC, 2015), entré en vigueur en 2016. Son principal objectif est de lutter contre le changement climatique en "*contenant l'élévation de la température moyenne de la planète nettement en dessous de 2 °C par rapport aux niveaux préindustriels et en poursuivant l'action menée pour limiter l'élévation de la température à 1,5 °C par rapport aux niveaux préindustriels*". L'Accord comporte également des objectifs généraux en matière d'adaptation au changement climatique⁷ et de flux financiers.⁸ Il met l'accent sur la transparence, la responsabilité, l'importance du soutien financier, les transferts de technologies et le renforcement des capacités pour les pays en développement, et reconnaît la nécessité de s'attaquer aux impacts du changement climatique qui ne

⁶Les pays développés insistant sur l'inclusion des émissions des principales économies développées et en développement, et faisant pression pour une plus grande uniformité dans les obligations des pays. Les pays en développement soulignant qu'ils n'ont aucune responsabilité historique dans le problème du changement climatique, qu'ils possèdent une capacité limitée pour y faire face et que, par conséquent, ils ne devraient pas être obligés de prendre des engagements internationaux spécifiques en matière de réduction des émissions (Pauw et al., 2014).

⁷"Renforçant les capacités d'adaptation aux effets néfastes des changements climatiques et en promouvant la résilience à ces changements et un développement à faible émission de gaz à effet de serre, d'une manière qui ne menace pas la production alimentaire."

⁸"Rendant les flux financiers compatibles avec un profil d'évolution vers un développement à faible émission de gaz à effet de serre et résilient aux changements climatiques"

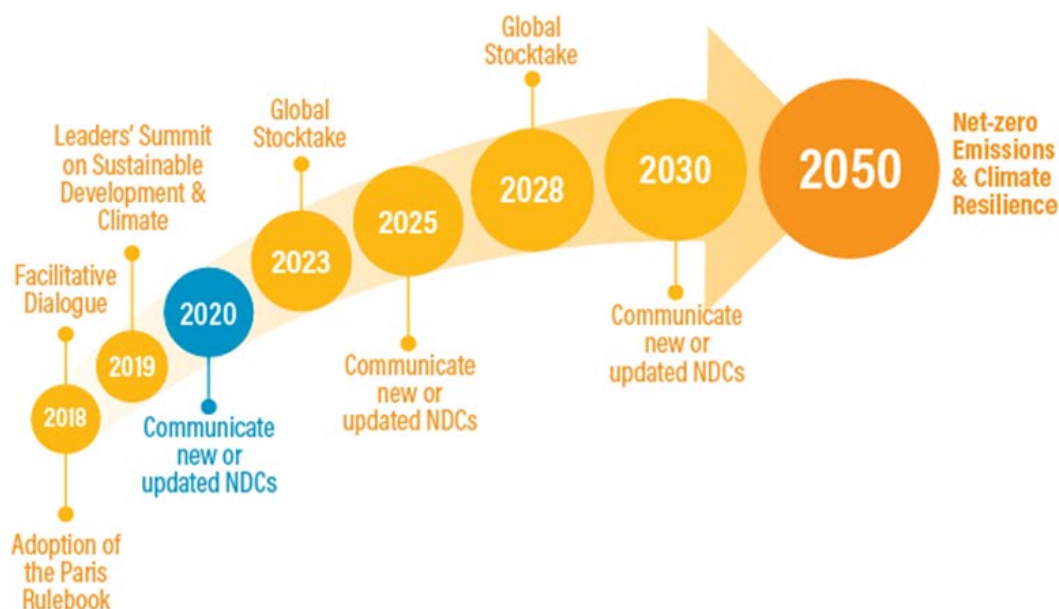
peuvent être atténués par des mécanismes d'adaptation, à travers le concept de pertes et dommages.

Alors que le protocole de Kyoto reposait sur une approche "top-down" de l'atténuation, l'Accord de Paris s'appuie sur une approche "bottom-up", qui prenait déjà forme lors de la COP de Copenhague en 2009 et représente une nouvelle vision du principe de CBDR.

Par rapport au protocole de Kyoto, cette dernière introduit une plus grande uniformité dans les obligations des Parties, puisque toutes les Parties, développées et en développement, sont légalement tenues de proposer des contributions pour atténuer le changement climatique et s'y adapter, à partir de 2020. Ces contributions sont présentées dans des documents appelés "Contributions Déterminées au Niveau National" (CDN), sont volontaires (non juridiquement contraignantes) et ne nécessitent pas l'approbation des autres Parties. Certains des objectifs énoncés dans les CDN des pays en développement sont également conditionnels à l'obtention d'un soutien financier. Enfin, les pays sont invités à justifier le caractère équitable de leur contribution (Winkler et al., 2018). Le mécanisme des CDN vise à prendre en compte la diversité des situations des pays et à garantir une participation plus large en évitant les considérations de répartition de l'effort (Falkner, 2016). Toutefois, les NDC étant fixées individuellement par chaque pays, il était clair dès le départ que leur impact agrégé sur les émissions ne suffirait pas à placer le monde sur une trajectoire compatible avec les objectifs de l'Accord de Paris. L'Accord établit donc un mécanisme dans lequel, à partir de 2023 et tous les cinq ans, un Bilan Mondial (en anglais, GST) évalue les progrès collectifs des Parties vers la réalisation de l'objectif mondial, et des NDCs avec une ambition renforcée sont communiquées. Le mécanisme, résumé dans la figure 0.1, vise à réaligner les efforts sur les objectifs de température à long terme.

Parallèlement, l'Accord encourage également la formulation de "*stratégies de développement à faible émission de gaz à effet de serre à long terme*" (LT-LEDS), généralement ayant pour horizon 2050.

Figure 0.1: Résumé du mécanisme d'ambition de l'Accord de Paris



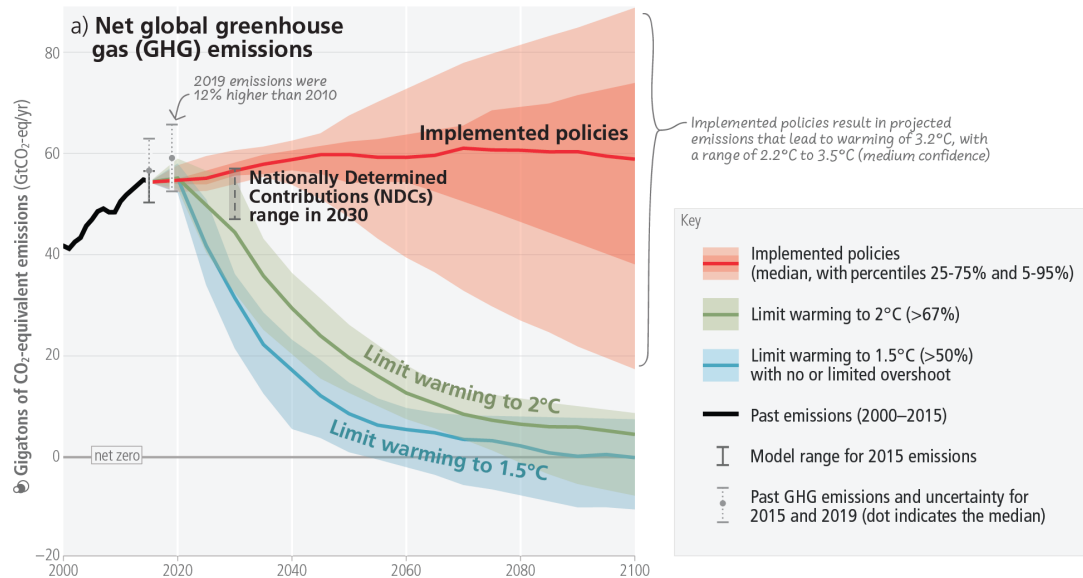
Source: World Resources Institute, <https://www.wri.org/research/enhancing-ndcs-2020-achieving-goals-paris-agreement>

Plus d'ambition est nécessaire, aux échelles mondiale et nationale

Au début de l'année 2024, 195 parties avaient soumis des CDN, certaines d'entre elles ayant déjà été mises à jour plusieurs fois. Les CDN sont diverses et hétérogènes en termes de secteurs ciblés, d'actions et d'horizons temporels. En outre, 68 Parties ont soumis des LT-LEDS (UNFCCC Secretariat, 2023a). L'année 2023 a marqué un tournant dans la mise en œuvre de l'Accord de Paris, car la COP 28 à Dubaï a vu les Parties accueillir un rapport technique sur le premier GST (UNFCCC Secretariat, 2023b), et décider d'une intensification de l'action climatique avant la fin de la décennie.

L'une des principales conclusions du rapport technique est, sans surprise, que les émissions mondiales actuelles n'atteignent pas des trajectoires qui seraient compatibles avec les objectifs d'atténuation mondiaux. Le rapport conclut que les émissions mondiales de GES devraient être réduites de 43% d'ici à 2030, et de 60% d'ici à 2035 par rapport aux niveaux de 2019 (et atteindre des émissions mondiales nettes de CO₂ nulles

Figure 0.2: Trajectoires d'émissions globales cohérentes avec les politiques et les stratégies d'atténuation mises en œuvre



Source: IPCC AR6 WGIII Résumé à l'intention des décideurs (Shukla et al., 2022), Figure SPM.5 panel (a). Légende adaptée : Cette figure montre l'évolution des émissions mondiales de GES dans les trajectoires modélisées. Les plages colorées indiquent les 5e à 95e percentiles des trajectoires mondiales modélisées entrant dans une catégorie donnée, comme décrit dans l'encadré SPM.1. Les fourchettes rouges décrivent les trajectoires d'émissions supposant que politiques mises en œuvre sont celles implémentées à la fin de l'année 2020. Les fourchettes des trajectoires modélisées qui limitent le réchauffement à 1,5 °C (>50 %) avec un dépassement nul ou limité du budget carbone sont indiquées en bleu clair (catégorie C1) et les trajectoires qui limitent le réchauffement à 2 °C (>67 %) sont indiquées en vert (catégorie C3). Les trajectoires d'émissions mondiales qui limiteraient le réchauffement à 1,5 °C (>50 %) avec un dépassement nul ou limité et qui atteindraient également l'objectif de zéro GES net dans la seconde moitié du siècle, le feraient entre 2070 et 2075.

d'ici à 2050). Comme confirmé par les résultats récents de la littérature académique (Benveniste et al., 2018; Iyer et al., 2022; Den Elzen et al., 2022), comme le soulignent le dernier rapport du GIEC (Shukla et al., 2022; Lecocq et al., 2022) et les rapports des Nations unies sur le "Gap" d'émissions (United Nations Environment Programme, 2023), et comme le résume la Figure 0.2, l'ambition agrégée des CDN en termes d'atténuation est loin d'être suffisante pour atteindre l'objectif de limiter le réchauffement climatique à 2°C. Il est également nécessaire d'intensifier les mesures d'adaptation et la prise en compte des pertes et dommages, ainsi que d'accroître le soutien à l'action climatique dans les pays en développement.

Ces résultats ne tiennent pas compte du fait que les CDN ne sont pas contraignantes : leur mise en œuvre n'est pas garantie (den Elzen et al., 2019; Roelfsema et al., 2020). Comme le montrent la Figure 0.2 et Lecocq et al. (2022), le GIEC fait état d'un écart estimé de 4 à 7 $GtCO_2eq$ en 2030, entre les "politiques actuellement mises en œuvre" et les scénarios des CDN conditionnelles et inconditionnelles.⁹ En outre, Pauw et al. (2020) montre que le coût global associé à la réalisation de tous les objectifs conditionnels des pays en développement dépasse les promesses existantes de soutien financier des pays développés - qui ont de plus tendance à surdéclarer l'aide climatique (Neumann Noel and Bayramoglu, 2022). Dans l'ensemble, des flux supplémentaires des pays développés vers les pays en développement seraient nécessaires dans la plupart des scénarios (Pachauri et al., 2022).

L'Accord de Paris et l'atténuation : un défi de développement

La difficulté réside dans le fait que les scénarios de réduction des émissions de GES compatibles avec l'objectif de 2°C (et plus encore de 1,5°C) (Rogelj et al., 2016; Lecocq et al., 2022) exigent une stabilisation des émissions dès 2030, suivie d'une diminution très rapide et sans précédent des émissions à l'échelle mondiale. Comme l'indique le rapport technique du GST, *"la réduction à zéro des émissions nettes de CO₂ et de GES nécessite des transformations systémiques dans tous les secteurs et contextes, y compris l'augmentation d'échelle des énergies renouvelables, tout en éliminant progressivement toutes les énergies fossiles restantes, mettant fin à la déforestation, réduisant les émissions d'autres GES, et mettant en œuvre des mesures portant à la fois sur l'offre et la demande"* (traduction de l'auteurice, voir UNFCCC Secretariat (2023b)). De telles trajectoires ne peuvent être le résultat d'efforts "à la marge". Elles remettent en question les modes de consommation et de production dans leur ensemble, avec des implications de premier ordre pour les économies (Riahi et al., 2017) et une nécessité de réorienter les chemins de développement vers la durabilité (Winkler et al., 2022). Ce constat, vient confirmer que les politiques d'atténuation du changement climatique et de développement doivent être abordées de manière intégrée, une conclusion largement partagée dans la littérature.

⁹Comme indiqué précédemment, certains des engagements pris dans les CDN des pays en développement sont conditionnels à l'obtention d'une aide internationale pour lutter contre le changement climatique. Dans les scénarios des CDN conditionnelles, tous les objectifs des CDN sont censés être atteints. Dans les scénarios de CDN inconditionnelles, seuls les objectifs qui ne sont pas conditionnels sont atteints.

0.2 Changement climatique et développement : deux questions étroitement liées

Les liens entre le changement climatique et tous les aspects du développement sont reconnus depuis longtemps, car le changement climatique est causé par l'activité humaine et a un impact direct sur les sociétés, les économies et les installations humaines (Pörtner et al., 2022). En outre, l'atténuation et l'adaptation au changement climatique sont interdépendantes avec le développement : d'une part, les politiques climatiques ont des répercussions sur divers aspects des sociétés (Lecocq et al., 2022), et d'autre part, la réorientation des chemins de développement peut faciliter la résilience climatique (Pörtner et al., 2022) et accélérer la transition vers des sociétés à faibles émissions de carbone (Lecocq et al., 2022; Denton et al., 2023). L'articulation des politiques climatiques et de développement est donc une composante essentielle du paradigme du développement durable.

Le changement climatique a un impact direct sur les objectifs de développement

Le développement est un concept équivoque, pour lequel il est essentiel de reconnaître l'existence de modèles, cadres et interprétations alternatifs, mais qui est historiquement ancré dans une définition économique. Son paradigme dominant faisait initialement référence à la croissance économique et à l'industrialisation dans la théorie de la modernisation (Rostow, W.W., 1959) - en concurrence avec le structuralisme (Prebisch, 1950), et rapidement remis en question par d'autres visions économiques telles que les théories de la dépendance (Gunder Frank, 1967) ou du système monde (Wallerstein, 1974). La notion de développement a ensuite été étendue à des dimensions sociales telles que l'éducation, la santé ou le bien-être (Myrdal, 1974), et résumée dans le concept de Développement Humain proposé et popularisé par Amartya Sen et Mahbub ul Haq (Anand and Sen, 1994; United Nations Development Programme, 1990). L'idée en a encore été élargie au cours des dernières années, pour couvrir les questions liées à l'environnement et aux ressources naturelles, du concept d'éco-développement proposé par Ignacy Sachs (1977), à celui de "développement durable" issu du rapport Brundtland (Brundtland, 1987),¹⁰ actuellement incarné par les Objectifs de Développement Durable

¹⁰Le développement durable est défini par la commission Brundtland comme *"un processus de changement dans lequel l'exploitation des ressources, l'orientation des investissements, du développement technologique et les changements institutionnels sont tous en harmonie et améliorent le potentiel actuel et*

(présentés dans la section 4). La définition du développement a donc considérablement évolué dans le discours académique et politique au fil des ans, principalement en incluant davantage de dimensions. Le changement climatique a des répercussions sur chacune d'entre elles.

Le changement climatique crée des risques substantiels et variés pour l'économie mondiale, en partie en raison de l'augmentation de la fréquence et de la gravité des événements météorologiques extrêmes tels que les sécheresses, les incendies, les cyclones et les inondations (voir par exemple Felbermayr and Gröschl (2014); Hsiang and Jina (2014)). Ces événements perturbent les infrastructures clés liées à l'énergie, à l'alimentation, à l'eau, aux communications et au transport (Birkmann et al., 2016), en plus d'avoir un impact sur les chaînes d'approvisionnement et les systèmes agricoles. Au-delà des conséquences directes des événements extrêmes, la contribution du Groupe de travail sur les impacts, l'adaptation et la vulnérabilité au dernier rapport du GIEC (Pörtner et al., 2022) met en évidence les impacts de plus en plus évidents du changement climatique progressif sur les économies et les populations. Les coûts économiques qui en résultent sont particulièrement prononcés dans les pays en développement (voir par exemple Klomp and Valckx (2014)), affectant les régions appauvries et les populations vulnérables (Hallegatte and Rozenberg, 2017) et renforçant les inégalités. L'augmentation des températures, la montée du niveau des océans et les conséquences associées pour les cycles biogéochimiques ont un impact sur les rendements des cultures, la disponibilité de l'eau et la productivité du travail, contribuant tous aux défis économiques, sociaux et environnementaux (Pokhrel et al., 2021; Kalkuhl and Wenz, 2020; Burke and Tanutama, 2019; Lobell and Field, 2007). Par le biais des canaux précédents, le changement climatique affecte les personnes et le développement humain en intensifiant les menaces pesant sur la sécurité alimentaire et hydrique, la santé physique et mentale, influençant finalement les conflits sociaux, les schémas de migration (Beine and Parsons, 2017) et entraînant une augmentation de la mortalité (Carleton et al., 2022). Enfin, il a des impacts directs sur la biodiversité et les écosystèmes terrestres et marins (Burrell et al., 2020; Hughes et al., 2021), ce qui menace également le bien-être et les modes de vies humains.

futur de satisfaction des besoins et des aspirations humains" (traduction de l'auteurice). Il a été représenté par trois piliers interconnectés, économique, social et environnemental, auxquels ont été attribuées diverses origines (Purvis et al., 2019).

A l'inverse, l'activité humaine est la cause indéniable du changement climatique (Shukla et al., 2022) à travers les émissions de GES liées à la production et à l'utilisation d'énergie, à l'industrie, à l'agriculture, aux forêts et à l'utilisation des terres (AFOLU), aux transports et aux bâtiments. Les schémas de développement sont donc largement à l'origine du changement climatique.

Les politiques d'action climatique et de développement sont interdépendantes.

De la même manière que le changement climatique résulte du développement et l'impacte en retour, l'action climatique – atténuation et adaptation – est interconnectée avec les défis et politiques de développement.

Etant donné que l'adaptation vise à ajuster les systèmes humains et naturels aux effets du changement climatique, les politiques d'adaptation (telles que, entre autres, la conception et la rénovation des infrastructures, la gestion de l'eau et des cultures, l'adaptation des comportements alimentaires, l'urbanisme, la conservation des écosystèmes, la gestion des risques de catastrophe, les systèmes d'alerte précoce, les mécanismes d'éducation, d'assurance, de santé et de protection sociale) abordent des problèmes de développement. Les politiques d'adaptation ont en fait de nombreuses synergies positives avec d'autres objectifs de développement (Pörtner et al., 2022). Par exemple, adapter adéquatement les systèmes alimentaires au changement climatique aura un impact positif sur la sécurité alimentaire et la lutte contre la faim. De même, améliorer la résilience climatique des systèmes électriques aura un impact positif sur l'accès à l'énergie. Comparées aux politiques de développement traditionnelles, la principale spécificité des politiques d'adaptation est qu'elles se concentrent principalement sur l'atténuation des risques climatiques et sur les causes socio-environnementales de la vulnérabilité au changement climatique. Bien que souvent difficile à établir en pratique, la distinction est politiquement importante pour empêcher que les fonds liés à l'adaptation ne soient utilisés pour des projets de développement conventionnels (Agrawal and Carmen Lemos, 2015). En effet, simplement "requalifier" comme effort d'adaptation les projets de développement existants qui ciblent des secteurs sensibles au climat peut renforcer, redistribuer et créer des vulnérabilités (Eriksen et al., 2021).

En ce qui concerne l'atténuation, qui est le principal sujet de cette thèse, des trajectoires d'atténuation ambitieuses impliquent des changements économiques importants et parfois disruptifs.

Il existe trois principaux canaux par lesquels les objectifs d'atténuation peuvent avoir un impact (positif ou négatif) sur d'autres priorités de développement :

1. De nombreuses études au niveau des pays suggèrent des impacts négatifs des efforts d'atténuation sur le développement économique, en raison de l'utilisation réduite d'énergie fossile affectant les secteurs intensifs en GES, mais aussi des arbitrages d'investissement entre l'atténuation et les objectifs productifs (Lecocq et al., 2022). Plus généralement, la réduction des émissions de GES peut en effet nécessiter des ressources supplémentaires (capital, main-d'œuvre, matériaux, etc.) qui ne seraient alors pas disponibles pour d'autres priorités (*effet d'évincement*). Par exemple, les sources d'énergie peu émettrices de GES restent plus coûteuses que celles émettrices de GES dans de nombreuses parties du monde. Une conception de politique appropriée est essentielle pour limiter cet effet macroéconomique, qui tend également à s'affaiblir à plus long terme à mesure que les marchés s'ajustent et que des mécanismes tels que le progrès technique ont plus de temps pour jouer un rôle plus important.
2. La réduction des émissions de GES peut avoir des impacts plus négatifs pour certains groupes – par exemple, la suppression des subventions nationales aux combustibles fossiles pourrait affecter les utilisateurs pour lesquels il est plus difficile/impossible de passer à d'autres sources d'énergie – et ainsi affecter la distribution des ressources au sein des pays (*effet de distribution*). Les politiques d'atténuation peuvent avoir un impact sur l'emploi via des réallocations sectorielles d'emplois, avec création et destruction respectivement dans les secteurs à faible émission et les secteurs intensifs en émissions, ce qui pourrait affecter davantage les travailleurs peu qualifiés et renforcer les inégalités (Chateau et al., 2018). Les politiques d'atténuation telles que les taxes sur le carbone pourraient avoir des impacts de distribution négatifs en renforçant la pression socio-économique sur les ménages les plus pauvres, un effet qui peut être compensé par une conception appropriée des politiques (Ravigné et al., 2022). Dans les économies qui ne sont pas au meilleur de leur forme, l'atténuation peut cependant être une opportunité pour mieux allouer les ressources (par exemple, double dividende).
3. L'atténuation implique des transformations (en technologie, en offre, en demande, en institutions) qui peuvent affecter d'autres priorités de développement (*effet structurel*). Par exemple, il existe des compromis entre l'utilisation de l'énergie de la biomasse et la sécurité alimentaire par le biais de l'utilisation des terres, mais

il existe des synergies entre le passage aux énergies propres et la santé grâce à la qualité de l'air.

Certains soutiennent que les potentiels coûts nécessitent de faire des compromis entre l'atténuation et d'autres problèmes de développement, en particulier dans les pays en développement (Jakob et al., 2014). Cependant, la littérature démontre également les co-bénéfices substantiels des politiques d'atténuation sur divers aspects du développement, tels que : la diminution de la pollution de l'air et ses effets sur la santé, l'amélioration de la sécurité énergétique, la protection accrue de la biodiversité grâce à la réduction des menaces pesant sur les puits de carbone, le tout en plus des avantages à long terme liés à la réduction des effets du changement climatique (Karlsson et al., 2020; Denton et al., 2023). De plus, comme mentionné par le GIEC (Lecocq et al., 2022), les coûts liés à l'atténuation dépendent fortement des structures sous-jacentes de la société et des choix de développement effectués dans de nombreux secteurs.

Par conséquent, la réponse au changement climatique et le développement sont interdépendants à tout moment donné, mais il existe également un effet de dépendance au sentier : les options de développement futur dépendent de la réponse climatique actuelle et les options de réponse climatique future dépendent des choix de développement actuels. La Synthèse du Sixième Rapport d'évaluation du GIEC indique ainsi qu' *"une approche inclusive et équitable intégrant adaptation, atténuation développement peut faire progresser le développement durable à long terme (confiance élevée)"* et que *"les politiques qui orientent les trajectoires de développement vers une durabilité peuvent élargir l'éventail des réponses d'atténuation et d'adaptation disponibles (confiance moyenne)"* (traduction de l'autrice).¹¹ Dans la mesure où la lutte contre le changement climatique nécessite des transformations profondes des systèmes existants (voir par exemple Halsnæs and Garg (2011)), et des changements dans les trajectoires de développement, la lutte contre le changement climatique devrait être considérée comme une question de développement aux côtés des autres (Winkler et al., 2015).

¹¹Les trajectoires de développement se réfèrent à l'évolution des principales caractéristiques des sociétés et peuvent être comprises à différentes échelles, des récits mondiaux tels que les Shared Socio-economic Pathways (SSP) détaillés dans Riahi et al. (2017), à divers scénarios nationaux traduisant une vision de développement donnée, avec des priorités associées et des évolutions sociétales, comme celles développées dans les *LT-LDS* (Waisman et al., 2019).

0.3 Le développement au sein de l'ONU : vers une approche universelle et intégrée

Constater une interconnexion entre atténuation et développement ne signifie pas nécessairement que les décisions liées à l'atténuation et les décisions liées au développement sont prises de manière coordonnée. Cette section présente la manière dont le cadre de coopération onusien sur le développement a évolué pour étendre son programme à toutes les dimensions du développement durable, sous la forme des Objectifs de Développement Durable (ODDs). Bien que la présence de l'action climatique parmi les ODDs (ODD 13) soit un signe important d'intégration des deux problématiques, les paragraphes suivant discutent la manière dont elles sont, en pratique, articulées à l'échelle de l'ONU.

De la création de l'ONU aux Objectifs du Millénaire pour le Développement : des Décennies pour le Développement

Depuis sa création en 1945, le développement est un objectif central de l'ONU. En effet, la Charte des Nations Unies (United Nations, 1945) promeut *"le relèvement des niveaux de vie, le plein emploi et des conditions de progrès et de développement dans l'ordre économique et social; la solution des problèmes internationaux dans les domaines économique, social, de la santé publique et autres problèmes connexes, et la coopération internationale dans les domaines de la culture intellectuelle et de l'éducation; le respect universel et effectif des droits de l'homme et des libertés fondamentales pour tous, sans distinction de race, de sexe, de langue ou de religion"*. La Charte établit également le Conseil Economique et Social des Nations Unies (ECOSOC) comme une plate-forme clé pour la coopération économique internationale, qui était alors considérée comme un moyen de consolider la paix.¹²

Dès lors, le système des Nations Unies s'est largement saisi des questions de développement en fournissant une assistance technique, en contribuant à façonner les visions et les pratiques du développement, ainsi que par le biais de divers fonds et programmes, et un grand nombre d'agences spécialisées telles que l'Organisation des Nations Unies pour l'alimentation et l'agriculture (FAO), l'Organisation Internationale du Travail (OIT) ou l'Organisation Mondiale de la Santé (OMS). Certaines de ces

¹²L'article 55 de la Charte indique qu'il devrait être promu *"en vue de créer les conditions de stabilité et de bien-être nécessaires pour assurer entre les nations des relations pacifiques et amicales"*.

agences, la Banque Mondiale et le Fonds Monétaire International (FMI), datent en réalité de la conférence de Bretton Woods de 1944, précédant ainsi les Nations Unies. Bien qu'elles aient été rapidement intégrées au système onusien par le biais d'accords, elles disposent de mandats distincts en matière de développement économique (étant les principaux acteurs de l'aide financière) et sont traditionnellement considérées comme relativement indépendantes. En pratique, cela est dû au fait que les principes de vote différents entre les institutions des Nations Unies et les institutions de Bretton Woods ont conduit à des équilibres de pouvoir différents entre les pays (Singer, 1995). Plus précisément, les pays en développement ont plus d'influence dans le système des Nations Unies où chaque pays dispose d'une voix, tandis que les pouvoirs de vote dans les institutions de Bretton Woods favorisent les pays développés, car ils dépendent en partie de la position économique des pays. Cela a conduit, initialement, à la priorisation de différentes dimensions du développement, le système des Nations Unies accordant plus d'attention aux questions relatives au Développement Humain (Burley and Browne, 2015). Il est intéressant de noter, dans l'ensemble, que les visions du développement (Fukuda-Parr and Hulme, 2011) et les théories sous-jacentes au développement économique (Calcagno, 2021) prévalant dans les différentes institutions de ce système multilatéral n'ont pas toujours été alignées.

De 1960 à 1999, quatre "Décennies des Nations Unies pour le développement" se sont succédé, en proposant des objectifs économiques et sociaux pour les pays en développement. Une étape importante a été franchie avec la création, en 1965, du Programme des Nations Unies pour le Développement (PNUD), qui joue un rôle central dans la coordination des agences et la mise en œuvre de projets de développement à l'échelle mondiale. La publication du premier Rapport sur le Développement Humain (United Nations Development Programme, 1990) par le PNUD, mentionnée plus tôt dans cette introduction, a indiqué un changement progressif dans la compréhension du concept de développement, avec l'intégration de dimensions sociales et humaines au travers du bien-être et d'autres objectifs axés sur l'individu tels que les "choix" et la "liberté" (Linnér and Selin, 2013). La série des Rapports sur le Développement Humain propose l'Indice de Développement Humain (IDH) comme mesure alternative du développement, une évolution notable par rapport aux approches précédentes centrées uniquement sur le PIB.^{13,14}

¹³Voir paragraphe précédent sur la définition du développement

¹⁴Assez tôt, des premières critiques de l'IDH mentionnaient l'absence de considérations environnementales (Sagar and Najam, 1998)

Les Objectifs du Millénaire pour le Développement (OMDs) découlent de la Déclaration du millénaire (UN General Assembly, 2000), un document signé par 189 pays en septembre 2000 qui s'engage principalement à mettre fin à la pauvreté (Fukuda-Parr and Hulme, 2011; Hulme and Scott, 2010). Les OMDs comprenaient 8 objectifs pour l'année 2015, ainsi que 21 cibles et 60 indicateurs. Les 8 objectifs étaient : éliminer l'extrême pauvreté et la faim ; assurer l'éducation primaire pour tous ; promouvoir l'égalité des sexes et l'autonomisation des femmes ; réduire la mortalité infantile ; améliorer la santé maternelle ; combattre le VIH/SIDA, le paludisme et d'autres maladies ; préserver l'environnement ; mettre en place un partenariat mondial pour le développement. Ces objectifs n'étaient pas juridiquement contraignants et n'avaient aucun mécanisme formel de mise en œuvre : ils représentaient un engagement mondial, réunissant gouvernements, agences de développement et agences spécialisées de l'ONU (Hulme and Scott, 2010; Lomazzi et al., 2014). Ils étaient présentés comme un agenda Nord-Sud (De Jong and Vijge, 2021; Janus et al., 2015) : ils visaient les pays en développement, encouragés à adapter leurs stratégies à leur contexte national, tandis que les pays développés s'engageaient à fournir une assistance technique et financière via l'objectif 8. Dans l'ensemble, les OMDs sont largement considérés comme un processus guidé par les pays développés (Hulme and Scott, 2010).

La période couverte par les OMDs a vu des améliorations substantielles survenir en matière de développement humain, bien que des disparités subsistent par objectif et entre les régions du monde (United Nations, 2015). Ces améliorations ne sont pas dues aux seuls OMDs : en réalité, les pays où ils ont été le plus efficace étaient ceux dont les priorités nationales étaient déjà alignées sur les OMDs (Hickmann et al., 2023). Cependant, ce cadre a marqué une évolution de l'acception du terme "développement" sur la scène internationale, et a complété d'autres initiatives telles que l'*Initiative en faveur des pays pauvres très endettés*, menée par le FMI et la Banque Mondiale, qui conditionne une partie de l'aide au développement et de l'allègement de la dette à des réformes économiques. Les questions de durabilité environnementale et de changement climatique étaient alors relativement négligées dans les arènes internationales traitant du développement. Certains soutiennent ainsi que l'OMD 7 sur l'environnement était en réalité plus symbolique qu'autre chose (Pinter et al., 2015). Bien que des discussions sur les liens entre changement climatique et développement aient émergé à l'époque, elles étaient principalement contenues dans des arènes de coopération environnementale, telles que le Sommet de la Terre de Rio (1992) qui a vu l'adoption de la CCNUCC et de l'Agenda 21.

Les Objectifs de développement durable (ODDs) : un cadre pour intégrer toutes les dimensions du développement

S'appuyant sur les enseignements tirés des OMD (Sachs, 2012; Griggs et al., 2013), les Objectifs de développement durable (ODDs) ont été universellement adoptés en 2015 dans le cadre du Programme de développement durable à l'horizon 2030 (UN General Assembly, 2015b). Les ODDs mettent l'accent sur une approche holistique. Cela marque un changement de paradigme dans les réflexions au sein des arènes onusiennes de développement, vers une vision intégrée de toutes les dimensions du développement, y compris le changement climatique.

Figure 0.3: Les 17 Objectifs de développement durable



Source: Nations Unies

Les 17 Objectifs de Développement Durable pour 2030, présentés dans la Figure 0.3, sont associés à 169 cibles et ont été conçus pour créer un cadre universel pour réaliser le développement durable (Ki-Moon, 2019). Comme indiqué dans la résolution de l'ONU "Transformer notre monde : Le Programme de développement durable à l'horizon 2030" : *"Les objectifs et les cibles de développement durable sont*

intégrés et indissociables ; ils sont par essence globaux et applicables universellement, compte tenu des réalités, des capacités et des niveaux de développement des différents pays et dans le respect des priorités et politiques nationales." Ils diffèrent ainsi des OMDs sur plusieurs aspects. Premièrement, leur portée, car ils visent à couvrir le développement durable dans la plupart des aspects de la société. Par conséquent, les ODDs ciblent tous les pays, pas seulement les pays en développement, et pour les atteindre, tous les pays partagent des obligations similaires : ils sont "**universellement applicables**". Deuxièmement, le cadre des ODDs reconnaît que les différentes dimensions du développement sont interconnectées et doivent donc être visées ensemble : ils sont "**intégrés et indivisibles**". Troisièmement, contrairement aux OMDs – dont la formulation était pilotée par les pays développés –, les ODDs résultent d'un processus de formulation "bottom-up", consultatif et plus inclusif (Chasek et al., 2016).

Bien que les ODDs ne soient pas plus juridiquement contraignants que les OMDs, ils sont accompagnés d'un cadre de mise en œuvre, de suivi et de reporting plus formalisé. La résolution de l'ONU adoptant l'Agenda 2030 indique que : "*Si des cibles idéales sont définies à l'échelle mondiale, c'est à chaque État qu'il revient de fixer ses propres cibles au niveau national pour répondre aux ambitions mondiales tout en tenant compte de ses spécificités. Il appartient aussi à chaque État de décider de la manière dont ces aspirations et cibles devront être prises en compte par les mécanismes nationaux de planification et dans les politiques et stratégies nationales*". Les ODDs doivent être traduits en objectifs nationaux tenant compte du contexte et des défis de développement propres à chaque pays (Biermann et al., 2017; Kanie and Biermann, 2017; Vijge et al., 2020). Un cadre de suivi et de reporting est ensuite conçu pour suivre les progrès des pays vers la définition et la réalisation de leurs priorités de développement. Chaque année se tient un Forum politique de haut niveau (HLPF) qui agit comme un orchestrateur (Abbott and Bernstein, 2015), réunissant les gouvernements, la société civile et diverses parties prenantes telles que les institutions de développement et les agences spécialisées des Nations Unies. Les pays sont encouragés à préparer des Examens Nationaux Volontaires (ENV), qui sont des rapports sur leurs progrès qu'ils peuvent soumettre au HLPF sur une base volontaire. Les progrès vers la réalisation des ODDs à l'échelle mondiale sont également évalués régulièrement, conduisant à la rédaction d'un Rapport mondial sur le développement durable (Independent Group of Scientists appointed by the UN Secretary-General, 2023).

Depuis 2015, le cadre des ODDs est largement utilisé dans les discussions internationales, notamment pour cadrer les questions de développement dans les documents des Nations Unies et de ses agences spécialisées (UNDP, 2020), dans le travail d'organisations internationales telles que le GIEC (Denton et al., 2023) ou l'IPBES (Watson et al., 2019), dans le travail des organisations de recherche telles que Future Earth (Smith et al., 2018), ou les banques de développement internationales (World Bank, 2022b). Par exemple, le troisième groupe de travail du GIEC indique que *"Les Objectifs de développement durable (ODDs) adoptés dans le cadre du Programme 2030 pour le développement durable des Nations Unies peuvent être utilisés comme base pour évaluer l'action climatique dans le contexte du développement durable. (confiance élevée)"* (Shukla et al., 2022) (traduction de l'autrice). Cependant, les ODDs soulèvent encore des interrogations, et au-delà de leur narratif se pose la question cruciale, que nous abordons dans la section suivante, de savoir s'ils sont transformationnels ou non. Il n'est en effet pas acquis que les ODDs catalysent des changements fondamentaux dans les politiques, les pratiques et les mentalités, ou qu'ils s'articulent, en pratique, les uns avec les autres et avec les agendas nationaux.

Vers la réalisation des ODDs : impacts, progrès, limites

Les ODDs représentent une approche innovante de la gouvernance par le biais de la définition d'objectifs (Biermann et al., 2017), avec des limites et avantages liés à leur caractère non contraignant. L'un des principaux points d'attention vient de l'étendue de leur portée : leur objectif principal, qui est d'intégrer tous les aspects du développement, est pour le moins ambitieux. Naturellement, les ODDs présentent des synergies et des compromis entre eux,¹⁵ avec de nombreuses interrelations que la littérature a commencé à étudier (ICSU and ISSC, 2015; Nilsson et al., 2016; Le Blanc, 2015; McGowan et al., 2018; Nilsson et al., 2018; Independent Group of Scientists appointed by the UN Secretary-General, 2023), montrant qu'elles dépendent des contextes (Weitz et al., 2018; Mulugetta et al., 2022; Halsnæs et al., 2023). Certains soutiennent que les dimensions sociale et environnementale sont centrales dans le cadre (Arts, 2017), cependant des critiques ont rapidement souligné que les ODDs ne représentaient pas un changement majeur dans le discours international et la priorisation de la croissance économique par rapport aux préoccupations environnementales (Gupta and Vegelin, 2016; Briant Carant, 2017;

¹⁵Par exemple, il peut y avoir des synergies entre l'ODD 7 sur l'énergie et l'ODD 3 sur la santé à travers la qualité de l'air. Il peut y avoir des compromis entre l'ODD 7 ou l'ODD 13 sur le changement climatique et l'ODD 2 sur la sécurité alimentaire à travers l'utilisation des terres et la production de biocarburants (Halsnæs et al., 2023).

Eisenmenger et al., 2020). Sur le sujet spécifique du changement climatique, certains auteurs soutiennent que l'objectif de croissance qui accompagne l'ODD 8 pourrait ne pas être compatible avec les objectifs climatiques ou d'usage des ressources proposés dans les ODDs 12 et 13 (Stewart, 2015; Hickel, 2019). D'autres études montrent que les bénéfices liés à l'atténuation du changement climatique sont en réalité alignés avec les autres ODDs (Denton et al., 2023).

De plus, les ODDs sont, par construction, des aspirations globales qui doivent être adaptées aux réalités nationales et locales. L'efficacité des objectifs dépend alors du succès de leur traduction en priorités nationales et de leur mise en œuvre au niveau national (Allen et al., 2019). Dans le domaine du développement, la planification nationale et les institutions émergent donc comme des acteurs centraux, fait que nous discuterons plus en détail dans le Chapitre 1. La planification nationale de développement, qui est actuellement réinstaurée dans de nombreux pays (Munro, 2020), est souvent influencée par les cadres de coopération internationale. Cependant, des obstacles peuvent survenir lors de l'articulation entre la spécificité des priorités nationales et le caractère large des cadres de développement mondiaux. La littérature sur la planification nationale et les ODDs a commencé à fournir des outils pour analyser les cadres de développement nationaux à la lumière des ODDs (UNDP, 2017), mais elle ne se concentre que sur des pays spécifiques (Morita et al., 2020; Jönsson and Bexell, 2021; Horn and Grugel, 2018) ou des régions (CEPAL, nd). Les études systématiques et les méta-analyses sur l'alignement entre les cadres mondiaux et nationaux, évaluant l'effet transformationnel des ODDs, sont récentes et peu nombreuses (Allen et al., 2018; Biermann et al., 2022). Leurs conclusions suggèrent que, jusqu'à présent, les ODDs ont principalement eu des effets discursifs (dans la mesure où ils sont mentionnés dans les documents de politiques nationales), avec quelques cas de réformes normatives et institutionnelles pouvant leur être attribués. La plupart des pays ne sont pas avancés dans leur mise en œuvre, les gouvernements ayant tendance à faire du "cherry-picking" d'objectifs (Forestier and Kim, 2020) ou à simplement ré-étiqueter leurs priorités existantes (Tosun and Leininger, 2017). Même si plus de 170 pays ont présenté des ENV lors de l'un des HLPF, il existe peu de preuves de l'effet transformationnel des ODD à ce jour, certains suggérant que le reporting est performatif (Bexell and Jönsson, 2019), d'autres que peu de gouvernements expriment clairement la manière dont les ODDs sont institutionnalisés (Sarwar and Nicolai, 2018).

Enfin, l'une des principales limites des ODDs et de leur mise en œuvre actuelle est que, dans la pratique et même si l'objectif général était de fournir un cadre indivisible, les objectifs restent principalement traités en silo. À l'échelle internationale, certains soutiennent que les ODDs pourraient ne pas être capables de catalyser une coordination des diverses instances onusiennes, qui sont, comme nous l'avons vu précédemment, considérablement fragmentées (Kim, 2016). Le changement climatique reste traité séparément des autres objectifs de développement dans les sphères de l'ONU, à travers les mécanismes de la CCNUCC et de l'Accord de Paris. Même s'ils étaient plus intégrés dans les arènes internationales, au sein des pays, l'approche des ODDs est confrontée au fait que les décideurs politiques, les institutions et les structures fonctionnent également en silo (Nilsson et al., 2016; Allen et al., 2018). Souvent, les politiques climatiques et de développement sont abordées par des institutions et des ministères distincts, avec peu d'articulation, ce qui conduit à une fragmentation de leur traitement : ils sont situés dans différents documents de politiques publiques, avec différents échéanciers. Cela n'implique bien sûr pas automatiquement que les objectifs produits dans les deux contextes ne sont pas alignés, car les décideurs politiques pourraient être conscients des liens entre les questions. Cependant, même lorsqu'elle est abordée, l'articulation entre l'atténuation du changement climatique et les priorités de développement reste très généralement une question ouverte (voir par exemple UK Climate Change Committee (2022)).

0.4 Problématiques, objectifs et démarche

Comme développé dans les premières sections de cette introduction, une atténuation profonde est nécessaire à l'échelle mondiale pour maintenir le réchauffement en dessous de 2°C (plus encore pour 1,5°C). Il est nécessaire de réorienter les trajectoires de développement pour permettre des actions climatiques plus ambitieuses, ce qui ne peut avoir que des implications significatives sur la réalisation d'autres priorités de développement. Bien sûr, le lien entre les objectifs mondiaux et nationaux, qu'il s'agisse des ODDs et des priorités nationales de développement, ou entre les objectifs de l'Accord de Paris et leur déclinaison au niveau national, n'est pas immédiat. Les capacités d'atténuation et les contributions varient d'un pays à l'autre, mais la nécessité de réorienter les trajectoires de développement existe au niveau national, quel que soit le pays. Évaluer les synergies et les tensions entre les objectifs de développement et d'atténuation, à ce niveau, comme proposé dans cette thèse, constitue une première étape dans cette direction.

En effet, les pays élaborent souvent des objectifs d'atténuation et de développement dans des cadres distincts. Cela soulève la question de savoir si les pays communiquent à la CCNUCC des objectifs climatiques compatibles avec leurs objectifs de développement, ce qui est le principal objectif de cette thèse. Il s'agit d'une question positive, qui peut être résumée comme suit : *Comment les pays alignent-ils leurs stratégies de développement et leurs objectifs d'atténuation ?*

Une première étape consiste à recueillir les objectifs nationaux d'atténuation et de développement. Les premiers figurent dans les CDN, et sont facilement accessibles. Cependant, en débutant ce travail de thèse, nous n'avons trouvé aucune liste systématique des priorités nationales de développement à long terme (quantitatives ou qualitatives). Nous avons donc construit une base de données des priorités nationales de développement à partir de matériel brut (c'est-à-dire des documents nationaux de développement à long terme). Ce travail est détaillé dans la Partie I (Chapitre 1), dans laquelle nous utilisons l'analyse effectuée pour construire la base de données pour également relier les priorités nationales et le cadre mondial des ODDs, en discutant de son universalité et de son indivisibilité.

Dans la Partie II, nous proposons une méthodologie pour discuter dans quelle mesure les objectifs d'atténuation et de développement sont alignés (Chapitre 4). Elle est basée sur le modèle d'équilibre général calculable (MEGC) KLEM, que nous présentons d'abord dans le Chapitre 2. En effet, pour représenter les synergies et les tensions entre les futures politiques d'atténuation et de développement, les modèles CGE sont un outil de choix. Ils fournissent une vision globale des implications économiques de l'atténuation. Ils sont particulièrement pertinents pour fournir des informations sur les effets de différentes politiques sur certains objectifs de développement (comme la croissance, la pauvreté, l'emploi). Ils sont donc adaptés pour étudier les effets d'évincement et peuvent être élargis pour discuter des effets distributifs et structurels. Il est toutefois essentiel de qualifier la robustesse de notre évaluation. Comme le montre la littérature générale en modélisation CGE, l'évaluation économique des politiques dépend fortement du choix de "bouclage macroéconomique" du modèle,¹⁶. Nous avons donc réalisé une analyse approfondie de la sensibilité du modèle aux options de bouclage, qui est détaillée dans le Chapitre 3. Elle informe l'utilisation du modèle KLEM dans la méthodologie proposée dans le Chapitre 4. Les interactions entre les objectifs nationaux d'atténuation et de développement sont relativement bien étudiées pour les grands émetteurs (Dubash et al.,

¹⁶c'est-à-dire, comme détaillé dans le Chapitre 3, le choix de modélisation qui permet d'équilibrer le nombre d'équations et de variables d'un MEGC, ce qui a un impact sur sa structure causale.

2018; Gupta et al., 2020; Su et al., 2022). En revanche, la plupart des émetteurs de taille moyenne à petite restent peu étudiés. Les études existantes sont soit détaillées mais se concentrent sur un seul pays, soit couvrent un grand nombre de pays mais sans possibilité de traduire les contextes spécifiques à chaque pays (différents échéanciers, priorités de développement, données disponibles et objectifs quantifiés). Nous proposons ici une méthodologie intermédiaire - suffisamment générale pour inclure autant de pays que possible, mais permettant des flexibilités dans la représentation des objectifs nationaux.

Enfin, cette discussion vise à informer l'élaboration des politiques des pays, mais a également des implications pour la coopération internationale en matière de changement climatique. En effet, si des incohérences entre les objectifs climatiques et de développement sont révélées au niveau national, et étant donné que les politiques nationales d'atténuation ont automatiquement un impact sur le changement climatique global, la solution proposée dépendrait, dans une large mesure, de considérations d'équité. Que disent l'existence d'incohérences sur les objectifs eux-mêmes, et sur leur ambition ? Dans le contexte de l'Accord de Paris, où la déclinaison des objectifs mondiaux d'atténuation n'est pas automatique, conclure sur le niveau d'ambition des pays n'est pas évident. Nous complétons donc la discussion positive sur l'alignement des objectifs nationaux de développement et d'atténuation, par une discussion normative sur le caractère équitable des contributions d'atténuation des pays, qui peut être résumée comme suit : ***Comment le caractère équitable des contributions d'atténuation des pays peut-il être réévalué, en tenant compte du contexte de l'Accord de Paris et de la gamme plus large des ODD ?*** Dans la Partie III, nous passons d'abord en revue les outils actuels d'évaluation de l'équité, qui rencontrent des obstacles liés à l'absence d'une vision unique et acceptée de ce qu'une CDN équitable serait (Chapitre 5). Nous avons l'intention d'améliorer les outils existants en utilisant les opinions des citoyens pour légitimer les jugements collectifs. Dans le Chapitre 6, nous proposons les enquêtes comme moyen d'observer leurs jugements. Nous ouvrons également, dans la conclusion de cette thèse, la discussion sur le recadrage du débat sur l'équité pour prendre en compte d'autres objectifs de développement et le contexte plus large des ODDs.

Méthodologies et résultats

Cette thèse s'appuie sur trois principaux courants de littérature, sur la planification de développement et les ODDs, sur la modélisation en équilibre général calculable appliquée aux questions liées au climat, ainsi que la littérature sur les principes d'équité, le choix social empirique et les enquêtes par questionnaire.

Nous utilisons une large gamme de méthodologies, de l'analyse qualitative des plans de développement pour collecter des données, à la modélisation en équilibre général calculable. Nous menons également une enquête pour recueillir les jugements de la population générale. Une contribution majeure est la base de données cartographiant les priorités nationales de développement, accompagnée d'un outil de visualisation, qui, à notre connaissance, sont entièrement nouveaux. Nous proposons également des innovations méthodologiques, en utilisant des modèles KLEM pour discuter de la compatibilité des objectifs d'atténuation et de développement dans des pays disposant de données limitées, mais aussi en utilisant le choix social empirique pour construire une enquête et tirer des conclusions normatives des opinions des citoyens. Enfin, nous mettons en lumière, dans un contexte de modélisation énergie-économie-environnement, un débat autour de la notion de bouclage macroéconomique qui provient de la communauté de modélisation CGE en économie du développement.

Structure de la thèse

PARTIE I – Des priorités nationales de développement, et de la pertinence de l'utilisation du cadre des ODDs pour les analyser

Chapitre 1 - Cartographie des priorités nationales de développement dans le cadre des Objectifs de Développement Durable – une analyse systématique (Auriane Meilland, Franck Lecocq)

Notre travail initial consiste à collecter systématiquement des données sur les priorités nationales de développement à long terme de 121 pays, et à les relier au cadre des Objectifs de Développement Durable (ODDs). Ce cadre, considéré comme "universel" et "indivisible", est aujourd'hui dominant pour aborder les questions de développement à l'échelle mondiale. Ce chapitre vise donc à obtenir des informations pour déterminer si les ODDs fournissent une bonne cartographie des priorités de développement telles qu'exprimées par les pays. Nous catégorisons ainsi chaque priorité nationale, extraite

des documents nationaux de développement, selon son/ses ODD(s) associés, et créons une typologie des documents, ainsi qu'un outil de visualisation qui montre comment les ODDs sont priorisés parmi les pays. Nous montrons que seules quelques priorités ne rentrent pas dans le cadre global, notamment celles liées à la défense et à la croissance démographique. De plus, certains ODDs sont largement plus priorisés, et de nombreux documents ne contiennent pas tous les ODDs. L'outil et la base de données pourraient permettre d'informer de nombreuses questions de recherche liées au développement - ici, en nous permettant de discuter de la pertinence et de l'universalité supposées des ODDs à la lumière de leurs liens avec les priorités nationales de développement.

PARTIE II – Modéliser l'alignement entre les priorités de développement et les objectifs climatiques

Chapitre 2 – Utilisation de la modélisation en EGC pour étudier les objectifs de développement et de climat – présentation du cadre de modélisation KLEM (Auriane Meilland)

Dans ce chapitre, nous introduisons la modélisation en équilibre général calculable, et sa pertinence politique dans le contexte de ce travail de thèse. Nous présentons le cadre de modélisation KLEM (Capital-Travail-Energie-Matériaux), qui est à la base des deux modèles qui seront utilisés dans les Chapitres 3 et 4. Nous fournissons une description analytique des modèles, mettant en évidence les différences entre le cadre de modélisation en statique comparative utilisé dans le Chapitre 3 et le cadre de modélisation dynamique utilisé dans le Chapitre 4. Nous introduisons également les variantes du modèle liées aux différentes façons de "boucler" le modèle, dont les conséquences seront étudiées plus en détail dans le Chapitre 3. Nous présentons enfin les procédures de calibration génériques des modèles.

Chapitre 3 - Boucler des modèles, ouvrir des débats : incertitude théorique et transition bas carbone (Frédéric Ghersi, Louis Daumas, Auriane Meilland, Soline Ralite, Julien Lefèvre, Gaëlle Le Treut)

Ce chapitre s'appuie sur l'observation selon laquelle la littérature Énergie-Économie-Environnement (E3) a largement laissé de côté les questions des options de "bouclage" des modèles, et des théories économiques sous-jacentes lors de la construction des modèles ou modules macroéconomiques. Le fait est d'autant plus surprenant que les communautés MEGC d'autres domaines de l'économie se sont depuis longtemps intéressées à de telles questions. Depuis l'article fondateur d'Amartya Sen en 1963, la question des effets des

"bouclages", c'est-à-dire des manières de déterminer la structure causale d'un MEGC donné, a en effet suscité d'intenses discussions. L'objectif du travail suivant est de réunir ces deux littératures afin de donner un aperçu de l'effet des options de "bouclage" sur le comportement des modèles E3. Pour ce faire, nous implémentons le MEGC stylisé Capital-Travail-Énergie-Matériaux (KLEM) et testons un éventail d'objectifs de réduction de la consommation d'énergie, en utilisant différentes structures de causalité. Nos résultats montrent que les sorties du modèle dépendent fortement de la manière dont KLEM est bouclé. Cela nous conduit à conclure que s'appuyer quasi-exclusivement sur un seul ensemble d'hypothèses peut proposer une image artificiellement unifiée des possibilités de transition, et que d'autres bouclages de modèles devraient être davantage explorés dans le cadre des études E3.

Chapitre 4 - Les objectifs nationaux à long terme en matière d'atténuation du changement climatique et de développement économique sont-ils compatibles ? Exemple et modélisation sur le Malawi, la Colombie et l'Irak (Auriane Meilland, Franck Lecocq)

L'atténuation du changement climatique et le développement sont étroitement liés. En pratique, cependant, à l'échelle nationale, les objectifs climatiques et de développement sont généralement établis dans des documents distincts, parfois émis par des institutions ou ministères distincts, selon des échéanciers séparés. De plus, même lorsque les cadres sont intégrés, leur compatibilité fait encore l'objet de débats. Les objectifs de développement à long terme des pays sont-ils cohérents avec leurs engagements climatiques à court et moyen terme ? Dans ce chapitre, nous proposons une méthode par étapes basée sur le MEGC compac à deux secteurs KLEM, pour aider à discuter de la compatibilité entre les objectifs climatiques et certains objectifs de développement économique, dans différents pays. Notre intention est de fournir des premières réponses à la question, en particulier dans le cas des pays pour lesquels il n'existe pas de cadre de modélisation national détaillé et peu de données disponibles. Nous utilisons le secteur de l'énergie entièrement exogène, et d'autres drivers exogènes du modèle KLEM pour traduire les objectifs d'atténuation et les objectifs macroéconomiques tels que décrits dans les documents climatiques et de développement du pays, puis ajustons certains autres paramètres pour reproduire son objectif de croissance du PIB. La mesure dans laquelle cette trajectoire peut être reproduite avec des valeurs réalistes pour ces paramètres fournit une base de discussion sur la compatibilité. Nous appliquons la méthodologie à des études de cas sur le Malawi, l'Irak et la Colombie - des pays qui représentent une diversité de priorités de développement et affichent des objectifs de développement à long terme quantifiés. Pour les deux premiers

pays, elle montre un large alignement entre les deux cadres, pour l'Irak, elle indique de possibles incohérences au sein des objectifs de développement. Nous proposons finalement des pistes d'amélioration de la méthodologie, en gardant à l'esprit que chaque complexification du modèle serait associée à un besoin accru de données.

PARTIE III – Mettre à jour les considérations d'équité climatique dans les contextes récents du climat et du développement

Chapitre 5 – Qui en fait assez ? Une revue des règles d'équité et des outils d'évaluation des objectifs climatiques des pays (Auriane Meilland, Yann Kervinio, Aurélie Méjean)

Depuis la signature de la CCNUCC, de nombreuses approches de partage de l'effort ont été élaborées pour opérationnaliser le principe de "responsabilités communes mais différenciées - capacités respectives", qui lie développement et équité dans le contexte de l'atténuation du changement climatique. Beaucoup sont basées sur des règles d'allocation, qui consistent à identifier un budget carbone mondial pour une année donnée puis à le partager équitablement entre les pays. Ce chapitre propose un cadre pour présenter, de manière formalisée et harmonisée, les règles d'allocation existantes qui opérationnalisent la distribution d'un budget climatique donné. Cependant, dans l'approche "bottom-up" de l'Accord de Paris, aucune règle d'allocation unique n'a été convenue ex-ante par les Parties. Toute évaluation de l'effort d'un pays implique pourtant d'avoir une vision de ce qui constituerait une contribution ambitieuse pour ce pays. Nous proposons alors un nouveau cadre pour répertorier et évaluer les outils évaluant le caractère équitable des Contributions Déterminées au niveau National. Nous les classons en trois catégories et comparons leur pertinence pratique dans le contexte actuel. Nous montrons qu'ils font tous un compromis entre la multiplication des points de vue sur l'équité (car il n'y a pas de raison théorique de préférer une règle) et le besoin d'avoir une évaluation conclusive. Nous discutons de leurs limites, en relation avec l'inclusion d'autres objectifs de développement des pays.

Chapitre 6 - Justice climatique internationale : ce que pensent les gens. (Auriane Meilland, Yann Kervinio, Aurélie Méjean)

L'un des objectifs de la thèse est de reconsidérer les considérations d'équité dans la coopération climatique internationale, en les adaptant aux contextes récents de l'Accord de Paris et des Objectifs de Développement Durable. Tout d'abord, le passage de l'Accord de Paris à des engagements volontaires n'a pas mis de côté les discussions sur l'équité. Dans quelle mesure les pays proposent-ils des contributions climatiques équitables dans le cadre de l'Accord de Paris ? La réponse à cette question centrale peut reposer sur l'existence de points de vue explicites et partagés sur l'équité. Pourtant, les études sur les opinions existantes en matière d'équité sont rares et ont souvent une portée pratique limitée. Dans cet article, nous discutons de la manière dont l'utilisation des jugements des citoyens peut être justifiée pour discriminer parmi le grand ensemble de points de vue raisonnables qui peuvent définir la justice climatique internationale. Nous concevons et administrons une enquête par questionnaire pour collecter des jugements pertinents parmi les citoyens Français et Américains. Nous constatons que dans les deux pays, la plupart des répondants pensent que les principes de justice climatique devraient être fixés au niveau international même s'ils vont à l'encontre des intérêts de certains pays, et expriment une préférence pour des responsabilités communes (plutôt que différenciées) - d'autant plus lorsqu'ils sont préoccupés par le changement climatique. Nous observons un soutien envers deux règles de partage de l'effort : une convergence vers des émissions égales par habitant, et une version opérationnalisée de la clause d'antériorité. Notre enquête montre également des incohérences dans les jugements sur l'équité, et que les citoyens ont des difficultés à se coordonner sur des jugements simples concernant les CDN existantes. Ces résultats appellent au développement d'enquêtes standardisées sur ces questions.

Enfin, la conclusion de cette thèse résume ses principales conclusions et les pistes de recherche qu'elle ouvre, notamment sur l'équité et les démarches visant à repenser, à la lumière de nos discussions, le cadre de justice climatique comme un cadre intégrant d'autres objectifs de développement.

Introduction

Climate change mitigation and development are intricately linked. Yet, climate objectives and development priorities are still often addressed in separate arenas. The present thesis aims to explore the extent to which national climate mitigation targets align with other national development objectives, and to draw implications at country level and for international cooperation.

The present introduction sets the stage for our endeavour, and details our research questions. We first recall where we stand on climate mitigation at the global level, and how more ambitious commitments by countries are necessary to meet the Paris Agreement Goal of limiting global warming well below 2°C (Section 1). As is well-known in the literature, faster and deeper mitigation cannot but have significant interactions with other development priorities, and uncertainty about these interactions is a major impediment to enhanced action (Section 2). While at the international level, "development" is now understood to encompass climate mitigation (amongst other goals), this integrated framework does not necessarily translate, at the national level, into mitigation and development objectives that are consistent with each other (Section 3). Hence, this thesis develops a methodology to assess the degree to which mitigation objectives, as stated in Nationally Determined Contributions, are consistent with development priorities, as stated in national long-term planning documents. It then discusses how these results may help unlock debates on the fairness of countries' mitigation efforts (Section 4). Section 5 concludes by providing an overview of the structure of the thesis.

0.1 Negotiating on climate change: a story of equity linked to development

Historical Overview of International Cooperation on Climate Change: the Beginnings

At the international level, climate change is first mentioned alongside other environmental issues in the 1972 Stockholm Action Plan (United Nations, 1972) adopted during the First Earth Summit.¹⁷ As concerted efforts to address climate change emerged over the next two decades, the issue became gradually separated from other environment and development subjects and dedicated forums and institutions were created. Within the scientific community, the first global conference on climate change was held in February 1979. At the international level, the Intergovernmental Panel on Climate Change (IPCC) – endorsed by the United Nations in 1988 (United Nations General Assembly, 1988) – was created to regularly assess and synthesize scientific knowledge on the subject. Finally, with the signature of the United Nations Framework Convention on Climate Change (UNFCCC) at the Rio Earth Summit in 1992 (United Nations, 1992) – which separately addressed other environmental issues and sustainable development, leading to the creation of distinct Conventions on Biological Diversity (CBD) and to Combat Desertification (UNCCD), and of Agenda 21, a non-binding action plan aiming to achieve sustainable development by the twenty-first century (United Nations Conference on Environment and Development, 1992).

The UNFCCC is a seminal agreement, which coordinates 198 Parties¹⁸ and serves as a foundation for cooperative action to fight climate change, with the overarching objective of achieving *"stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system"* (United Nations, 1992). It explicitly mentions the need to articulate climate change and development, by stating that *"such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner"*. Over the subsequent decades and under its aegis, the international

¹⁷In a section on the identification and control of pollutants of broad international significance, Recommendation 70 recommends that "Governments be mindful of activities in which there is an appreciable risk of effects on climate".

¹⁸197 States as well as the European Union as a whole

community grappled with the complexities of forging a collective response to a challenge that transcends borders, and raises many questions about fairness and equity.¹⁹

Fairness in International Climate Negotiations: Common but Differentiated Responsibilities

Equity plays a central role in addressing climate change across various scales and levels. Intergenerational equity is important, as climate impacts and responses will be distributed amongst present and future generations (Meijers, 2023). Equity matters at a procedural level, for example with discussions about the inclusiveness of the participation of stakeholders in decision-making related to mitigation and adaptation (Tomlinson, 2015). Finally, at the intra-generational level, how efforts, costs, risks, and gains should be allocated amongst stakeholders is a crucial issue for climate action, both within and across countries (see for example Méjean et al. (2015)). On the latter, differences in levels of development across nations loom large in many debates on equity related to climate change mitigation (Heyward, 2007), through at least three channels:

- Historical responsibility for climate change: most developed countries are not only among the largest emitters today, but have been so since the middle of the 19th century (Botzen et al., 2008), because of their early development.
- Vulnerability to climate change: developed countries are less vulnerable to climate change, partly due to strong economic, governance and social adaptation readiness (Sarkodie and Strezov, 2019).
- Capacity to contribute to climate change mitigation: the cost of mitigation and the breadth of mitigation options depend on countries' development context (see Chapter 4). The synergies and trade-offs between climate mitigation and economic and social development issues also vary across countries.

In the context of the UNFCCC, fairness thus emerges as a guiding principle, and its understanding and operationalization has shaped the contours of international climate cooperation as we know it today.

¹⁹The words equity, justice and fairness refer to slightly different but very neighbouring concepts. As Grasso (2007) puts it, "*principles of justice [...] exist independently before any process of judgment or interpersonal comparison has begun. 'Equity' instead refers to normative criteria used to orient the implementation of principle(s)/theory(s) of justice, whilst 'fairness' pertains to the individual's perception arising from a judgmental process*". However, the three terms are often used interchangeably (Grasso, 2007), as will be the case in the following chapters.

When it comes to distributive justice and climate change mitigation, all Parties to the UNFCCC recognize that there are inequalities among nations. Precisely, Article 3 of the Convention indeed states that *"The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof"* (United Nations, 1992). Conceptually, the common but differentiated responsibilities (CBDR) principle refers to the fact that there are large differences (*differentiated responsibilities*) in nations' development needs and contributions to a problem that affects all countries to some extent, and cannot be solved without a widest possible participation (*common responsibilities*) (Cullet, 2021). The notion of CBDR (augmented by a mention of *respective capabilities*) is a political compromise between the demand of developing countries to see national circumstances be taken into account, and the opposition of developed countries to a direct mention of their historical emissions (Deleuil, 2012), which made the adoption of the UNFCCC possible.

However, common and differentiated responsibilities are not necessarily compatible. There has thus been little agreement on how to operationalize this principle, and its interpretation has varied across Parties and time periods. Consequently, the international approach of cooperation on climate change has significantly evolved since the signature of the Convention (Heyward, 2007; Held and Roger, 2018), shaped by negotiations on how to implement CBDR – and which vision(s) of equity should underlie this implementation.

From the Kyoto Protocol to the Copenhagen Conference: Rise and Death of a top-down approach

In the UNFCCC, developed country Parties are listed in the Annex I to the Convention. Under the Convention, they have specific mitigation commitments which are detailed in Article 4.2.

At the third Conference of Parties (COP) to the UNFCCC in 1997 (UNFCCC, 1997), binding greenhouse gases (GHG) emissions targets were negotiated for 38 Parties belonging to Annex I, under the Kyoto Protocol to the UNFCCC. In this top-down approach, the targets were negotiated upfront. Set for the period 2008-2012 (commonly known as the first commitment period), they committed industrialized countries to a

collective reduction of emissions by an average of 5.2% below 1990 levels, while developing countries were encouraged but not committed to take voluntary actions.²⁰ They would then have freedom to continue emitting more according to their development needs. Tensions around this particular operationalization of the CBDR principle were clearly on display, as with the refusal of the United States to ratify the Kyoto Protocol, following the demand of the U.S. Senate, through the Byrd resolution, of a binding participation of developing countries (Lopez, 2003).

Even though the aggregate mitigation goal of the Kyoto Protocol was met (Shishlov et al., 2016)²¹, it had a limited impact on global emissions since, with the absence of the United States and of all developing countries, only a fraction of the World's emissions were ultimately covered (Page, 2007). The global CO_2 emissions increased by 59% between 1990 and 2013, and by 14% during the first commitment period alone (Rosen, 2015). This highlighted the necessity to tackle emissions originating from developing nations to address climate change, and pushed more developed countries to advocate for less emphasis on differentiation in subsequent international processes.

While the Doha Amendment to the Kyoto Protocol adopted in 2012 established a second commitment period which entered into force in 2020, a shift away from the Annex I/non-Annex I divide had thus been observed since the beginning of the preparation of the post-2012 period. The 15th Conference of the Parties (Copenhagen, 2009) saw unresolved tensions related to the CBDR principle and the increased emphasis on addressing emissions from developing countries (both developed and developing countries maintaining their longstanding positions²²), ultimately leading to the failure to officially adopt an agreement (Bodansky, 2010). However, the Copenhagen Conference marked a step towards a more bottom-up approach, as major developing countries committed to incorporate their national emissions reduction commitments into an international instrument and to provide reports on their mitigation efforts.

²⁰Three market-based mechanisms were introduced to allow countries to trade emissions credits, invest in emissions reduction projects in developing nations through the Clean Development Mechanism, and collaborate on emission reduction projects through Joint Implementation

²¹accounting for the non-ratification of the United States and withdrawal of Canada

²²Developed countries emphasize the inclusion of emissions from both major developed and developing economies and push for more uniformity in countries' obligations. Developing countries emphasize that they bear no historical responsibility for the climate change issue, possess limited capacity to address it, and, consequently, should not be obliged to undertake specific international commitments for emission reductions (Pauw et al., 2014)

This shift paved the way to the adoption of the Paris Agreement at the 21st Conference of Parties in 2015 (UNFCCC, 2015), according to which all nations take commitments to mitigate climate change, but each one determines its own contribution.

The Paris Agreement: A bottom-up approach with Nationally Determined Contributions

The Paris Agreement is a landmark international accord adopted on December 12, 2015 (UNFCCC, 2015), that entered into force in 2016. Its primary goal is to address climate change by " *Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels* ". The agreement also features overall goals on adaptation to climate change²³ and finance.²⁴ It emphasizes transparency, accountability, the importance of financial support, technology transfer and capacity building for developing countries, and recognizes the need to tackle climate change impacts that can not be mitigated by adaptation mechanisms, through the concept of loss and damage.

While the Kyoto Protocol was based on a top-down approach to mitigation, the Paris Agreement relies on a bottom-up approach, that was already taking shape at the 2009 Copenhagen Conference of Parties and represents a new vision of the CBDR principle.

Compared to the Kyoto Protocol, it introduces more uniformity in the Parties' obligations, as all Parties, developed and developing, are legally bound to propose contributions to mitigate and adapt to climate change from 2020 on. These contributions are outlined in documents called Nationally Determined Contributions (NDCs), are voluntary (not legally binding) and do not require an approval of other Parties. Some of the goals stated in developing countries' NDCs are also conditional on financial support. Finally, countries are invited to justify the fairness of their contribution (Winkler et al., 2018). The NDC mechanism aims at accommodating the diverse circumstances of countries, and at ensuring broader participation by sidestepping distributional considerations (Falkner, 2016). However, because NDCs are individually set by each country, it was clear from the onset that their aggregated impact on emissions would not be sufficient to put the world on a pathway compatible with the goals of the

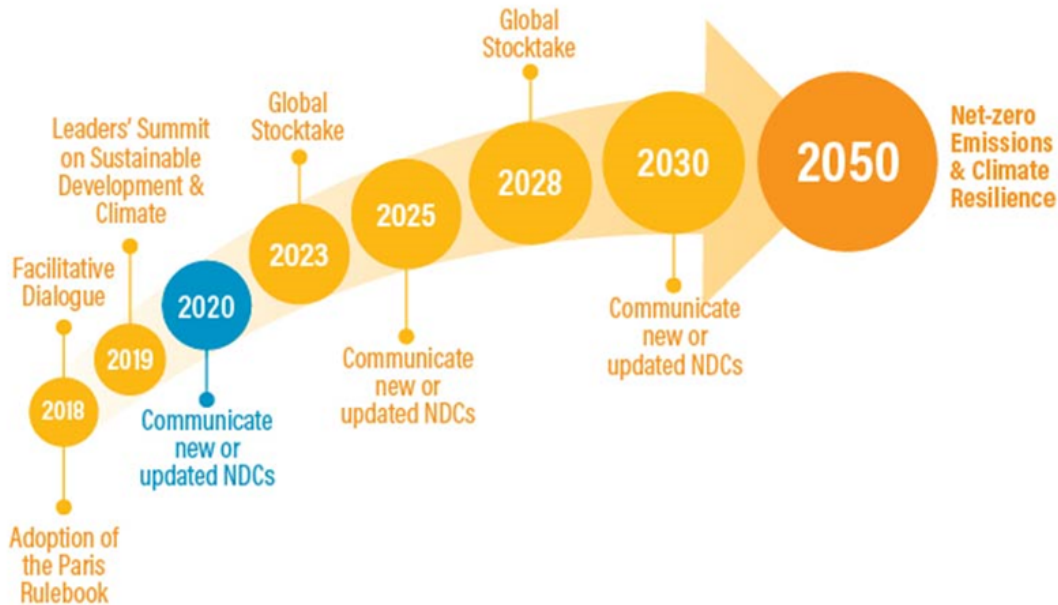
²³ "*Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production.*"

²⁴ "*Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.*"

Paris Agreement. The agreement thus establishes a ratcheting mechanism, in which, starting from 2023 and every five years onward, a Global Stocktake assesses the collective progress of Parties towards meeting the global goal, and new or updated NDCs with enhanced ambition are communicated. The mechanism, which is summarized in Figure 0.4, aims at realigning efforts with long-term temperature goals.

In parallel, the agreement also encourages the formulation of "*long-term low greenhouse gas emission development strategies*" (LT-LEDS), usually with a 2050 horizon.

Figure 0.4: Summary of the Paris Ambition mechanism



Source: World Resources Institute, <https://www.wri.org/research/enhancing-ndcs-2020-achieving-goals-paris-agreement>

More ambition is needed at the global and national levels

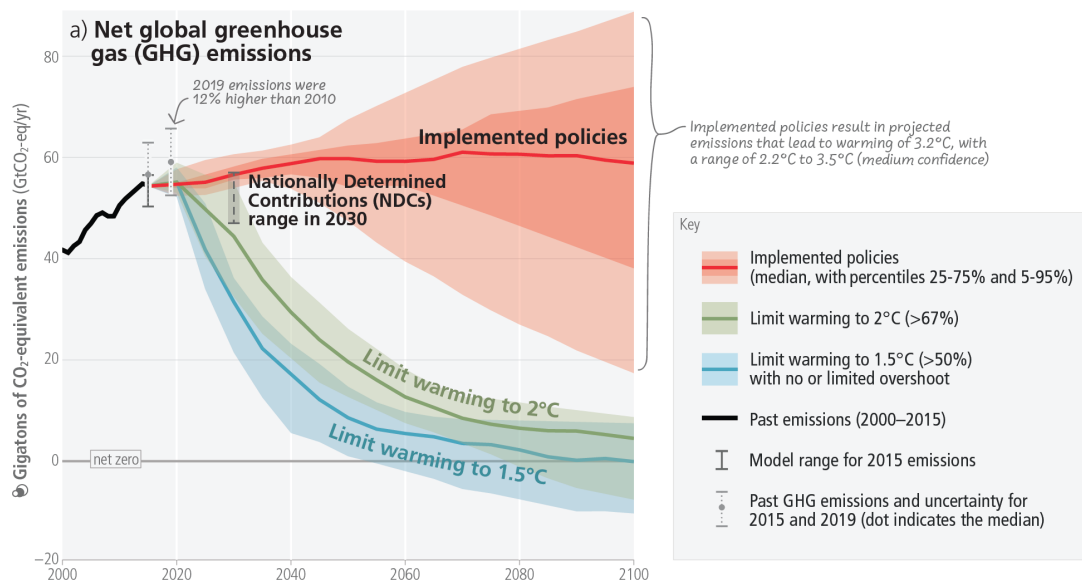
As of the beginning of 2024, 195 Parties had submitted NDCs, some of them having already been updated several times. NDCs are diverse and heterogeneous in terms of targeted sectors, actions and horizons. Additionally, 68 Parties had submitted long-term low-emission development strategies (UNFCCC Secretariat, 2023a). 2023 was an landmark in the implementation of the Paris Agreement, as COP 28 in Dubai saw Parties welcome a technical report on the first Global Stocktake (UNFCCC Secretariat, 2023b), and decide on the ratcheting up of climate action before the end of the decade.

Among the key findings of the Global Stocktake technical report, rather unsurprisingly, is that current global emissions fail to meet pathways that would be consistent with the global mitigation targets. The report concludes that global GHG emissions should be reduced *"by 43 per cent by 2030 and further by 60 per cent by 2035 compared with 2019 levels and reach net zero CO₂ emissions by 2050 globally"*. Consistently with recent results in the academic literature (Benveniste et al., 2018; Iyer et al., 2022; Den Elzen et al., 2022), as highlighted in the latest IPCC (Shukla et al., 2022; Lecocq et al., 2022) and UN Emissions Gap reports (United Nations Environment Programme, 2023) and summarized in Figure 0.5, the aggregated ambition of NDCs in terms of mitigation is far from sufficient to achieve the goal of limiting global warming to 2°C. An increased adaptation action and loss and damage tackling, as well as an increased support for climate action in developing countries are also called for.

This, of course, does not take into account the fact that NDCs are non-binding: their implementation is not a given (den Elzen et al., 2019; Roelfsema et al., 2020). As shown in Figure 0.5 and in Lecocq et al. (2022), the IPCC reports an estimated 4 to 7 *GtCO₂eq* gap in 2030, between the 'current implemented policies' and respectively conditional and unconditional NDCs scenarios.²⁵ Moreover, Pauw et al. (2020) show that the aggregate cost associated with aiming for all developing countries' conditional targets exceeds the existing promises of financial support from developed countries – which tend to over-report on climate aid (Neumann Noel and Bayramoglu, 2022). Overall, additional flows from developed countries to developing countries would be needed in most scenarios (Pachauri et al., 2022).

²⁵As stated earlier, some of the commitments in developing countries' NDCs are conditional to receiving international climate aid. In the conditional NDCs scenarios, all NDC targets are supposed to be met. In the unconditional NDCs scenarios, only the targets that are not conditional are met.

Figure 0.5: Global emissions pathways consistent with implemented policies and mitigation strategies



Source: IPCC AR6 WGIII Summary for policymakers (Shukla et al., 2022), Figure SPM.5 panel (a). Adapted legend: This figure shows the development of global GHG emissions in modelled pathways. Coloured ranges denote the 5th to 95th percentile across the global modelled pathways falling within a given category as described in Box SPM.1. The red ranges depict emissions pathways assuming policies that were implemented by the end of 2020. Ranges of modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are shown in light blue (category C1) and pathways that limit warming to 2°C (>67%) are shown in green (category C3). Global emission pathways that would limit warming to 1.5°C (>50%) with no or limited overshoot and also reach net zero GHG in the second half of the century do so between 2070-2075.

The difficulty is that greenhouse gases emission reduction scenarios compatible with 2°C (and even more so 1.5°C) targets (Rogelj et al., 2016; Lecocq et al., 2022) require a stabilization of emissions as early as 2030, followed by a very rapid and unprecedented decrease in emissions globally. As stated by the Global Stocktake technical report, *"achieving net zero CO₂ and GHG emissions requires systems transformations across all sectors and contexts, including scaling up renewable energy while phasing out all unabated fossil fuels, ending deforestation, reducing non-CO₂ emissions, and implementing both supply- and demand-side measures"* (UNFCCC Secretariat, 2023b). Such trajectories cannot be the result of efforts "at the margin". They question consumption and production patterns as a whole, with first-order implications for economies (Riahi et al., 2017) and a need to shift development pathways towards sustainability (Winkler et al., 2022). This comes to support the fact that climate change mitigation and development policies should be tackled in an integrated manner, as is now well known in the literature.

0.2 Climate change and Development: two intertwined issues

The links between climate change and all aspects of development have long been recognized, as climate change is caused by human activity and has a direct impact on societies, economies and settlements (Pörtner et al., 2022). In addition, climate change mitigation and adaptation are interdependent with development: on the one hand, climate change policies have implications for various aspects of societies (Lecocq et al., 2022), and on the other hand, shifting development pathways can facilitate climate resilience (Pörtner et al., 2022) and accelerate the transition to low-carbon societies (Lecocq et al., 2022; Denton et al., 2023). Integrating climate change and development policies is thus a core component of the sustainable development paradigm.

Climate change has a direct impact on development objectives

Development is an equivocal concept, for which it is essential to acknowledge the existence of various alternative models, frameworks and interpretations, but that is historically rooted in economic terms. Its dominant paradigm initially referred to economic growth and industrialization in the Modernization Theory (Rostow, W.W., 1959) – competing with structuralism (Prebisch, 1950), and also rapidly challenged by other economic visions such as the Dependency (Gunder Frank, 1967) or World-Systems theories (Wallerstein, 1974). The notion of development was later expanded

to social dimensions such as education, healthcare or well-being (Myrdal, 1974), and encapsulated within the concept of Human Development that was proposed and popularized by Amartya Sen and Mahbub ul Haq (Anand and Sen, 1994; United Nations Development Programme, 1990). The idea has been further enlarged in recent years to cover issues related to the environment and to natural resources, from the concept of eco-development proposed by Ignacy Sachs (1977), to one of "sustainable development" following the Bruntland report (Brundtland, 1987)²⁶, currently embodied by the Sustainable Development Goals (presented in Section 4). The definition of development has thus significantly evolved within the academic and political discourse over the years, mostly to include more dimensions. Climate change has impacts on all of them.

Climate change creates substantial and varied risks to the global economy, partly due to the increasing occurrence and severity of extreme weather events such as droughts, wildfires, cyclones, and floods (see for example Felbermayr and Gröschl (2014); Hsiang and Jina (2014)). These events disrupt key infrastructure related to energy, food, water, communications and transportation (Birkmann et al., 2016), in addition to impacting supply chains and agricultural systems. Beyond the direct consequences of extreme events, the contribution of the Working Group on Impacts, Adaptation, and Vulnerability to the latest IPCC report (Pörtner et al., 2022) highlights the increasingly evident adverse impacts of gradual climate change on economies and populations. The resulting economic costs are particularly pronounced in developing countries (see for example Klomp and Valckx (2014)), affecting impoverished regions and vulnerable populations (Hallegatte and Rozenberg, 2017) and reinforcing inequalities. Rising temperatures, sea-level rise, and associated consequences for biogeochemical cycles impact on crop yields, water availability, and labor productivity, all contributing to economic, social and environmental challenges (Pokhrel et al., 2021; Kalkuhl and Wenz, 2020; Burke and Tanutama, 2019; Lobell and Field, 2007). Through the previous channels, climate change affects people and human development by heightening threats to food and water security, human physical and mental health, ultimately influencing social conflict, migration patterns (Beine and Parsons, 2017) and resulting in an increase in mortality (Carleton et al., 2022). Finally, it has direct impacts on biodiversity and

²⁶Sustainable development is defined by the Bruntland commission as *"a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations"*. It has been represented by three interconnected pillars, economic, social and environmental, which have been attributed to various origins (Purvis et al., 2019).

terrestrial and marine ecosystems (Burrell et al., 2020; Hughes et al., 2021), which in turn also threatens well-being and livelihoods.

Conversely, human activity is the unequivocal cause of climate change (Shukla et al., 2022) through the GHG emissions of energy production and use, industry, agriculture, forestry and other land-use (AFOLU), transports and buildings. To a large part, development patterns thus drive climate change.

Climate action and development policies are interdependent

Just as climate change results from and impacts on development, climate change action – mitigation and adaptation – is interlinked with development challenges and policies.

Because adaptation aims to adjust human and natural systems to the effects of climate change, adaptation policies (such as, inter alia, infrastructure design and retrofitting, water and crop management, food diet adaptation, urban planning, ecosystem conservation, disaster risk management, early warning systems, education, insurance, health and social protection mechanisms) do tackle development issues. Adaptation policies have in fact many positive synergies with other development goals (Pörtner et al., 2022). For example, adequately adapting food systems to climate change will have a positive impact on food security and hunger. Similarly, improving the climate-resilience of power systems will have a positive impact on the access to energy. Compared to traditional development policies, the main specificity of adaptation policies is that they primarily focus on mitigating climate risks and socio-environmental causes of vulnerability to climate change. While often difficult to establish in practice, the distinction is politically important to prevent adaptation-related funds to go towards conventional development projects (Agrawal and Carmen Lemos, 2015). Indeed, simply 'rebranding' existing development projects that target climate-sensitive sectors as adaptation efforts can reinforce, redistribute and create vulnerability (Eriksen et al., 2021).

When it comes to climate change mitigation, which is the main focus of this thesis, ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure. There are three main channels through which mitigation objectives may have an impact (positive, or negative) on other development priorities:

1. Many country-level studies suggest negative impacts of mitigation efforts on economic development, because of the reduced use of fossil energy affecting GHG-intensive sectors, but also investment trade-offs between mitigation and productive

purposes (Lecocq et al., 2022). More generally, reducing GHG emissions can indeed require additional resources (capital, labor, materials, etc.) that would then not be available for other priorities (*crowding out effect*). For example, GHG-efficient energy sources remain more costly than GHG-intensive ones in many parts of the World. Proper policy design is instrumental in limiting this macroeconomic effect, which also tends to weaken in the longer-term as markets adjust and mechanisms like technical change have time to play a more important role.

2. Reducing GHG emissions can have more negative impacts for some groups – e.g., removing domestic subsidies to fossil fuels might affect users for which it is harder/not possible to switch to other energy sources – and thus affect the distribution of resources within countries (*distributional effect*). Mitigation policies can impact employment via sectoral reallocations of jobs, with creation and destruction in respectively low-emission sectors and emission-intensive sectors, which might affect low-skilled workers more and reinforce inequalities (Chateau et al., 2018). Mitigation policies such as carbon taxes might have negative distributional impacts by reinforcing the socio-economic pressure on poorer households, an effect that can be offset by adequate policy design (Ravigné et al., 2022). In economies that are not at their first best, mitigation may however be an opportunity to better allocate resources (e.g., double dividend).
3. Mitigation involves transformations (in technology, supply, demand, institutions) that may affect other development priorities (*structural effect*). For example, there are trade-offs between the use of biomass energy and food security through land use, but there are synergies between the switch to clean energies and health through air quality.

Some argue that the potential costs call for trade-offs between mitigation and other development issues, especially in developing countries (Jakob et al., 2014). However, the literature also demonstrates the substantial positive co-benefits of climate mitigation policies on various dimensions of development, such as decreased air pollution and related health effects, improved energy security, improved biodiversity protection via the decrease of threats to greenhouse gases sinks, in addition to the long-term benefits linked to the reduced effects of climate change (Karlsson et al., 2020; Denton et al., 2023). Additionally and as mentioned by the IPCC (Lecocq et al., 2022), these very costs linked to mitigation highly depend on underlying structures of society, and what development choices are made across many sectors.

Consequently, climate change response and development are interdependent, at a given time, but there is also a dimension of path-dependency, as future development options depend on current climate response and future climate response options depend on current development choices. The Synthesis of the IPCC's Sixth Assessment Report thus states that *"An inclusive, equitable approach to integrating adaptation, mitigation and development can advance sustainable development in the long term (high confidence)"* and that *"Policies that shift development pathways towards sustainability can broaden the portfolio of available mitigation and adaptation responses (medium confidence)".*²⁷ To the extent that tackling climate change calls for deep transformations in existing systems (see for example Halsnæs and Garg (2011)), and for shifts in development pathways, tackling climate change should be understood as a development issue alongside others (Winkler et al., 2015).

0.3 Development in the UN: towards a universal, integrated approach

Because mitigation and development are interlinked does not mean that decisions related to mitigation and decisions related to development are coordinated. This section presents how the UN development framework expanded to align its agenda to all dimensions of sustainable development, in the form of the Sustainable Development Goals (SDGs). While the presence of climate action as one of the SDGs (SDG13) is an important sign of integration of the two issues, the following also discusses how they are, in practice, articulated at the UN level.

From the UN creation to the Millenium Development Goals: decades of human development

Development is a central goal of the UN since its foundation in 1945. In fact, the United Nations Charter (United Nations, 1945) promotes *"higher standards of living, full employment, and conditions of economic and social progress and development; solutions of international economic, social, health, and related problems; and international cultural*

²⁷Development pathways refer to the evolution of societies' main characteristics and can be understood at various scales, from global narratives such as the Shared Socio-economic Pathways (SSPs) detailed in Riahi et al. (2017), to various national scenarios translating a given development vision, with associated priorities and societal evolutions, such as the ones developed in the national *low greenhouse gas emission development strategies* (Waisman et al., 2019).

and educational cooperation; and universal respect for, and observance of, human rights and fundamental freedoms for all without distinction as to race, sex, language, or religion". The Charter also establishes the UN Economic and Social Council (ECOSOC) as a key platform for international economic cooperation, which was then seen as a way to consolidate peace.²⁸

From then on, the UN system has been extensively involved in development issues by providing technical assistance, contributing to shaping the visions and practices of development, as well as through various funds and programs, and a large number of Specialized Agencies such as the Food and Agriculture Organization (FAO), the International Labour Organization (ILO), or the World Health Organization (WHO). Some of these agencies, the World Bank and the International Monetary Fund (IMF), actually date back to the 1944 Bretton-Woods conference, thus pre-existing the United Nations. While they were rapidly attached to the UN system as Specialized Agencies through agreements, they have separate mandates on economic development (being the major actors in financial assistance), and are traditionally considered relatively independent. In practice, this is due to the fact that different voting principles between the UN institutions and the Bretton-Woods institutions led to different power balances between countries (Singer, 1995). More specifically, developing countries are more influent in the UN system where each country has one vote, whereas voting powers in the Bretton-Woods institutions favour developed countries, as they partly depend on the countries' economic positions. This, at the time, led to the prioritization of different dimensions of development, with the UN system bringing more attention to issues relating to what is now called human development (Burley and Browne, 2015). It is interesting to note, overall, that the visions of development (Fukuda-Parr and Hulme, 2011) and theories underlying economic development (Calcagno, 2021) prevailing in the different institutions of this multilateral system have not always been aligned.

From 1960 to 1999, four "United Nations Decades of Development" succeeded each other, proposing economic and social goals for developing countries. A significant milestone occurred with the creation, in 1965, of the United Nations Development Programme (UNDP) which plays a pivotal role in coordinating agencies and implementing development projects globally. The release of the first Human Development Report (United Nations Development Programme, 1990) by the UNDP, as mentioned earlier, manifested the progressive change in the main understanding of

²⁸Article 55 in the UN indicates that it should be promoted *"With a view to the creation of conditions of stability and well-being which are necessary for peaceful and friendly relations among nations"*

what development referred to, with the integration of social and human dimensions of development through well-being and other individual-focused goals such as "choices" and "freedom" (Linnér and Selin, 2013). The series of Human Development Reports proposed the Human Development Index (HDI) as an alternative measure of development, a notable evolution compared to previous approaches centered uniquely around the GDP.^{29,30}

The Millenium Development Goals (MDGs) derive from the Millenium Declaration (UN General Assembly, 2000), a document that was signed by 189 countries in September 2000, and mainly commits to ending poverty (Fukuda-Parr and Hulme, 2011; Hulme and Scott, 2010). The MDGs included 8 Goals for the year 2015, along with 21 targets and 60 indicators. The 8 Goals were: to eradicate extreme poverty and hunger; to achieve universal primary education; to promote gender equality and empower women; to reduce child mortality; to improve maternal health; to combat HIV/AIDS, malaria, and other diseases; to ensure environmental sustainability; to develop a global partnership for development. These Goals were not legally binding and had no formal mechanism for enforcement: they represented a global commitment, bringing together governments, development agencies and UN specialized agencies (Hulme and Scott, 2010; Lomazzi et al., 2014). They were framed as a North-South Agenda (De Jong and Vijge, 2021; Janus et al., 2015): they targeted developing countries, which were encouraged to adapt their strategies to their national context, while developed countries committed to provide development and financial assistance through Goal 8. For the most part, the MDGs are seen as a process driven by developed countries (Hulme and Scott, 2010).

The period covered by the MDGs saw substantial improvements in human development, although with disparities across goals and regions of the world (United Nations, 2015). These improvements are not due to the MDGs alone: in fact, the countries in which they were most effective already had national priorities aligned with the MDGs (Hickmann et al., 2023). However, they marked an evolution of the understanding of development on the international stage, and came to complement other initiatives such as the *Heavily indebted poor countries initiative* led by the IMF and World Bank, which conditions some development aid and debt relief to economic reforms for specific countries. However, environmental sustainability and notably climate change were mostly overlooked in the international arenas tackling development at the

²⁹See earlier paragraph on the definition of development

³⁰Early critics of the HDI already mentioned the absence of environmental considerations (Sagar and Najam, 1998)

time. Some argue that the MDG 7 on the environment is in fact more symbolic than anything else (Pinter et al., 2015). Discussions on the links between climate change and development arose but were mostly contained to environmental arenas such as the 1992 Rio Earth Summit that saw the adoption of the UNFCCC and Agenda 21.

The Sustainable Development Goals: a framework to integrate all dimensions of development

Building on lessons from the MDGs (Sachs, 2012; Griggs et al., 2013), the Sustainable Development Goals (SDGs) were universally adopted in 2015 as a part of the 2030 Agenda for Sustainable Development (UN General Assembly, 2015b). The SDGs emphasize a holistic approach. This marks a paradigm shift in the thinking within UN development spheres towards an integrated vision of all the issues related to development, including climate change.

Figure 0.6: The 17 Sustainable Development Goals



Source: United Nations

The 17 SDGs for 2030, displayed in Figure 6.10, are associated with 169 targets, and were designed to create a universal framework for achieving sustainable development (Ki-Moon, 2019). As stated in the UN resolution “Transforming our world: the 2030 Agenda for Sustainable Development”: “*The Sustainable Development Goals and targets are integrated and indivisible, global in nature and universally applicable, taking into account different national realities, capacities and levels of development and respecting national policies and priorities.*” They thus differ from the MDGs on several aspects. First, their scope, as they intend to cover sustainable development in most aspects of society. Consequently, the SDGs target all countries, not just developing countries, and all countries share similar obligations while being expected to work towards achieving them: they are “**universally applicable**”. Second, the SDG framework recognizes that the different dimensions of development are interlinked, and should thus be pursued together: they are “**integrated and indivisible**”. Third, unlike the MDGs – the formulation of which was driven by developed countries –, the SDGs result from a bottom-up, consultative and more inclusive formulation process (Chasek et al., 2016).

While the SDGs are no more legally binding than the MDGs, they are accompanied by a more formalized implementation, monitoring and reporting framework. The UN resolution adopting the 2030 Agenda states that: “*Targets are defined as aspirational and global, with each Government setting its own national targets guided by the global level of ambition but taking into account national circumstances. Each Government will also decide how these aspirational and global targets should be incorporated into national planning processes, policies and strategies*”. SDGs are to be translated into national targets taking into account the countries’ own development context and challenges (Biermann et al., 2017; Kanie and Biermann, 2017; Vijge et al., 2020). A reporting and monitoring framework is then designed to track progress of countries towards setting and working to achieve their development priorities. Each year, a High-Level Political Forum (HLPF) takes place, which acts as an orchestrator (Abbott and Bernstein, 2015), bringing together governments, civil society, and various stakeholders such as development institutions and UN specialized agencies. Countries are encouraged to prepare so-called Voluntary National Reviews (VNR), which are reports on their progress that they can submit to the HLPF on a voluntary basis. Global progress towards the achievement of the SDGs is also assessed on a regular basis, leading to the writing of a Global Sustainable Development Report (Independent Group of Scientists appointed by the UN Secretary-General, 2023).

Since 2015, the SDG framework has become widely used in international conversations, including to frame development matters in documents from the United Nations and its subsidiary agencies (UNDP, 2020), in the work of international bodies such as the IPCC (Denton et al., 2023) or IPBES (Watson et al., 2019), in the work of international research organizations such as Future Earth (Smith et al., 2018), or international development banks (World Bank, 2022b). For example, the IPCC’s third working group states that “*The Sustainable Development Goals (SDGs) adopted under the UN 2030 Agenda for Sustainable Development can be used as a basis for evaluating climate action in the context of sustainable development. (high confidence)*” (Shukla et al., 2022). However, the SDGs still raise questions, and beyond the narratives also lies the critical question of whether they are transformative or not, which we discuss in the next Section. It is indeed not a given that the SDGs would catalyze fundamental shifts in policies, practices, and mindsets, or that they would, in practice, connect with each other and with national agendas.

Towards achieving the SDGs: impacts, progress, limits

The SDGs represent a rather novel approach of governance through goal-setting (Biermann et al., 2017), with the limitations and advantages attached to the non-binding character of the Goals. One of the main attention points comes with the wideness of their scope: their global intent, which is to integrate all aspects of development, is, to say the least, somewhat ambitious. Quite naturally, SDGs present synergies and trade-offs between one another,³¹ with numerous interrelations that the literature has started to study (ICSU and ISSC, 2015; Nilsson et al., 2016; Le Blanc, 2015; McGowan et al., 2018; Nilsson et al., 2018; Independent Group of Scientists appointed by the UN Secretary-General, 2023), showing that they are context-specific (Weitz et al., 2018; Mulugetta et al., 2022; Halsnæs et al., 2023). While some argue that the social and environmental dimensions are central to the framework (Arts, 2017), early critics have underlined that the SDGs did not represent a major change in the international discourse and prioritization of economic growth over environmental concerns (Gupta and Vegelin, 2016; Briant Carant, 2017; Eisenmenger et al., 2020). On the specific topic of climate change, some authors argue that the growth target that come with SDG 8 might not be compatible with the global climate or resource use targets that are implied by SDGs

³¹For example, there might be synergies between SDG 7 on clean energy and SDG 3 on health through air quality. There might be trade-offs between SDG 7 or 13 on climate change and SDG 2 on food security through land use and biofuels production (Halsnæs et al., 2023).

12 and 13 (Stewart, 2015; Hickel, 2019), while other studies show that the benefits of climate change mitigation ultimately aligns with the other SDGs (Denton et al., 2023).

Moreover, SDGs are, by construction, global aspirations that need to be adapted to national and local realities. The effectiveness of the Goals then depends on the success of their translation to national priorities and of their implementation at the national level (Allen et al., 2019). Within the realm of development, national planning and institutions thus emerge as pivotal players, which we will discuss further in Chapter 1. National development planning, which is being re-instated in many countries (Munro, 2020), is often influenced by UN frameworks. However, the integration is not always seamless, and challenges may arise in aligning the specificity of national priorities with the broad mandates of global development frameworks. The literature on national development planning and the SDGs has started to provide tools for analysing national development frameworks in light of the SDGs (UNDP, 2017) but it only focuses on specific countries (Morita et al., 2020; Jönsson and Bexell, 2021; Horn and Grugel, 2018) or regions (CEPAL, nd). Systematic studies and meta-reviews on the alignment between the global and national frameworks, thus evaluating the transformative power of SDGs, are only recent and few (Allen et al., 2018; Biermann et al., 2022). Their findings suggest that, so far, the SDGs have mainly had discursive effects (in that they are mentioned in national documents), with some isolated normative and institutional reforms that can be attached to them. Most countries are not advanced in their implementation, with governments having a tendency to "cherry-pick" Goals (Forestier and Kim, 2020) or rebrand existing priorities (Tosun and Leininger, 2017). Even though more than 170 countries have presented VNRs at a HLPF, there is limited evidence of the transformative impact of SDGs as of yet, as some suggest the reporting is performative (Bexell and Jönsson, 2019) but few governments articulate how the SDGs are institutionalized (Sarwar and Nicolai, 2018).

Finally, one of the main issues with SDGs and their current implementation is that in practice, and even though the overarching goal is to provide an indivisible framework, the Goals remain mostly treated in silos. At the international scale, some argue that SDGs might not be able to orchestrate the institutions of the UN framework, that is, as seen earlier, considerably fragmented (Kim, 2016). Climate change is still mainly treated separately from other development goals in the UN spheres, through the mechanisms of the UNFCCC and the Paris Agreement. Even if they were more integrated, within countries, the approach of SDGs is confronted to the fact that policymakers, institutions and structures are in silo as well (Nilsson et al., 2016; Allen et al., 2018). Often, distinct

institutions and ministries still tackle climate and development issues with little policy integration, leading to a fragmentation in their treatment: they can be found in different policy documents, with different timelines. This, of course, does not automatically imply that the targets produced within both contexts are not aligned, as policy makers might be well-aware of interlinkages between the issues. However, even when discussed, the alignment between climate mitigation and development priorities is very much an open question (see for example UK Climate Change Committee (2022)).

0.4 Research questions, objectives and endeavour

As developed in the first sections of this introduction, deep mitigation is needed at global scale, to keep warming below 2°C (let alone 1.5°C). There is a need to shift development pathways to allow for more ambitious climate action, and this cannot but have significant implications for the achievement of other development priorities. Of course, the link between global and country-level targets, be it between SDGs and national development priorities, or between the Paris Agreement goals and their downscaling at the national level, is not immediate. Mitigation capacities and pledges vary across countries, but the need for shifting development pathways arises no matter what at country level. Assessing the synergies and tensions between development and climate objectives at this level, which is the aim of this thesis, is a first step in this direction.

Indeed, countries often produce climate and development targets within separate frameworks. This raises the question of whether countries communicate climate targets to the UNFCCC that are consistent with their development targets, which is the main focus of this thesis. This is a positive question, which can be summarized as follows: ***How do countries align their development strategies and their climate mitigation targets?***

A first step is to collect national mitigation and development objectives. The former are encapsulated in NDCs, and are easily accessible. As we delved into this thesis, however, we found no systematic list of national (quantitative or qualitative) long-term development priorities. We thus built a database of national development priorities starting from raw material (i.e. national long-term development documents). This work is detailed in Part I (Chapter 1), in which we use the analysis conducted to build the database to also link national priorities and the global framework of the SDGs, by discussing its comprehensiveness and indivisibility.

In Part II, we propose a methodology to discuss the extent to which national economic development and climate mitigation targets are aligned (Chapter 4). It is based on the KLEM computable general equilibrium (CGE) model, which we first present in Chapter 2. Indeed, to depict synergies and trade-offs between future mitigation and development policies CGE models are a tool of choice. They provide a comprehensive vision of the economic implications of mitigation. They are particularly relevant in providing insights on the effects of various policies on select development goals (such as growth, poverty, employment). They are thus adapted to study crowding out effects and can be expanded to discuss distributional effects and transformations. It is first, however, essential to qualify the robustness of our evaluation. As the literature in general CGE modelling shows that the economic assessment of policies is strongly dependent on the choice of "macroeconomic closure" associated with the model,³² we conducted an in-depth analysis of the model's sensitivity to closure options, that is detailed in Chapter 3. It informs the use of the KLEM model in the methodology proposed in Chapter 4. The interactions between national climate and development objectives is rather well studied for large emitters (Dubash et al., 2018; Gupta et al., 2020; Su et al., 2022). Most medium to small-size emitters, on the other hand, remain understudied. Existing studies are either detailed but focused on only one country, or cover a large amount of countries but with no room for the translation of national-specific contexts (different timelines, development priorities, available data and quantified targets). We here propose an intermediate methodology - general enough to include as many countries as possible, but allowing for flexibilities in the depiction of national targets.

Finally, this discussion aims at informing countries' policy-making, but also has implications for international cooperation on climate change. Indeed, should inconsistencies between climate and development targets be revealed at the national level, and given that national mitigation policies automatically have an impact on global climate change, the proposed way forward would depend, to a large extent, on equity considerations. What does the existence of inconsistencies say about the targets themselves, and their ambition? In the context of the Paris Agreement, where the downscaling of global mitigation targets is not automatic, concluding on the countries' level of ambition is not self-evident. We thus complement the positive discussion on the alignment of national development and climate targets, with a normative discussion on the fairness of countries' mitigation contributions, which can be summarized as follows:

³²that is, as detailed in Chapter 3, the modelling choice that is made to equate the number of equations and variables of a CGE model, which has an impact on its causal structure.

How can the fairness of countries' mitigation contributions be re-assessed, taking into account the context of the Paris Agreement and the broader range of SDGs? In Part III, we first review the current fairness evaluation tools, which face stumbling blocks linked to the absence of a single, agreed upon vision of what a fair NDC would be (Chapter 5). We intend to improve existing tools by using citizens' opinions to legitimize collective judgements. In Chapter 6, we propose surveys as a way to observe their judgements. We also open, in the conclusion of this dissertation, the discussion on reframing the debate on equity to take into account other development targets and the broader context of SDGs.

Methodologies and outputs

This thesis draws from three main strands of literature, on development planning and SDGs, on computable general equilibrium modelling applied to climate-related questions, as well as literature on fairness principles, empirical social choice and survey studies.

We use a wide range of methodologies, from qualitative analysis of development plans to collect data, to computable general equilibrium modelling. We also conduct a survey to collect judgements from the general population. One major output is the database mapping national development priorities, along with a visualization tool, which, to the extent of our knowledge, is entirely new. We also propose methodological innovations, using KLEM models to discuss the compatibility of climate and development targets in countries with scarce data, and using empirical social choice to build a survey and draw normative insights from citizens' opinions. Finally, we shed light, in an energy-economy-environment modelling context, on a debate around the notion of macroeconomic closure that originates from the development CGE community.

0.5 Structure of the thesis

PART I – *On collecting national priorities, and using the SDG framework to classify them*

Chapter 1 - Mapping national development priorities under the Sustainable Development Goals framework – a systematic analysis (Auriane Meilland, Franck Lecocq)

Our initial work involves systematically collecting data on the national long-term development priorities of 121 countries, and linking them with the framework of the Sustainable Development Goals (SDGs). This framework, deemed "universal" and "indivisible," serves as a dominant structure for addressing development issues globally. This chapter then aims at bringing information on whether or not the SDGs provide a good mapping of development priorities as expressed by countries. We thus categorize each national priority, extracted from national development documents, under its related SDG(s), and create a typology of the documents along with a visualization tool which displays how SDGs are prioritized across countries. We show that only a few priorities do not fit in—notably some related to defence and population growth. Moreover, some SDGs are largely more prioritized, and there are many documents in which not all SDGs appear. The tool and database might inform many development-related questions—here enabling us to discuss the relevance and targeted universality of the 2030 Agenda in light of its connections with national development priorities.

PART II – *Modelling synergies and trade-offs between development priorities and climate targets*

Chapter 2 – Using CGE modelling to study development and climate targets – presentation of the KLEM modelling framework (Auriane Meilland)

In this chapter, we introduce Computable General Equilibrium modelling, and its policy relevance in the context of this thesis work. We present the KLEM (Capital-Labour-Energy-Materials) modelling framework, which is the basis of the two models that will be used in Chapters 3 and 4. We provide an analytical description of the models, highlighting the differences between the modelling framework in comparative statics used in Chapter 3 and the dynamic modelling framework used in Chapter 4. We also introduce the model variants related to different ways of "closing" the model, the consequences of which will be studied in more detail in Chapter 3. We finally present the generic calibration procedures of the models.

Chapter 3 - Closing models, opening debates: theoretical uncertainty and the low-carbon transition (Frédéric Gherzi, Louis Daumas, Auriane Meilland, Soline Ralite, Julien Lefèvre, Gaëlle Le Treut)

This chapter builds upon the observation that the Energy-Economy-Environment (E3) literature has largely left aside the question of model ‘closure’ options and the underlying economic theories in the building of macroeconomic models or modules. The fact is all the more surprising as the Computable General Equilibrium (CGE) communities of other branches of economics have long been concerned with such issues. From Amartya Sen’s seminal article in 1963, the question of the effects of model “closures”, i.e., ways to write the causal structure of a given CGE, has indeed elicited intense discussions. The aim of the following work is to put these two literatures together in order to sketch the effect of “closures” on the behaviour of E3 models. To this end, we implement the stylized Capital-Labour-Energy-Material (KLEM) computable general equilibrium model and test a spectrum of energy consumption reduction targets, using different causality structures. Our results show that model outcomes depend highly on how KLEM is closed. This leads to our conclusions that relying quasi-exclusively on one set of assumptions may present an artificially unified picture of transition possibilities, and that alternative model closures should be further explored across E3 studies.

Chapter 4 - Are Long-term National Goals on Climate Change Mitigation and Economic Development Compatible? Evidence and Modelling on Malawi, Colombia and Iraq (Auriane Meilland, Franck Lecocq)

Climate change mitigation and development are closely linked. In practice however, at the national scale, climate and development goals are usually produced in separate documents, sometimes issued by separate institutions or ministries, within separate timelines. Moreover, even when frameworks are integrated, their compatibility is still the subject of debates. Are countries’ long-term development targets consistent with their short and medium term climate commitments? In this chapter, we propose a step-by-step method based on the compact two-sector computable general equilibrium model KLEM, to help discuss the compatibility between climate and select economic development targets, in various countries. We design it to provide first insights on the issue, especially for countries for which there is no detailed national modelling framework, and little data available. We use the fully exogenous energy sector and other exogenous drivers of the KLEM model to translate climate mitigation targets and macroeconomic targets as described in the country’s climate and development documents, then adjust

select other parameters to reproduce the country's GDP growth target. The extent to which the pathway can be reproduced with realistic values for these parameters provides a basis for discussion on the compatibility. We apply the methodology to case studies on Malawi, Iraq, and Colombia – countries that represent a diversity of development priorities and display quantified long-term development targets. For the first two countries, it shows a large compatibility between both frameworks, and some possible inconsistencies within the development targets for Iraq. We finally discuss avenues for improvement to the methodology, bearing in mind that each complexification of the model would be associated with an increased need for data.

PART III – *On re-assessing the fairness of countries' contributions in the present context*

Chapter 5 – Who does enough? A review of equity rules and fairness evaluation tools for national climate contributions (Auriane Meilland, Yann Kervinio, Aurélie Méjean)

From the signature of the UNFCCC on, many effort-sharing approaches have been built to operationalize the “Common but differentiated responsibilities – respective capabilities” principle, which links development and equity in the context of climate change mitigation. Most of them rely on allocation rules which identify a global carbon budget for a given year then share it equitably among countries. This chapter proposes a framework to present, in a formalized and harmonized manner, existing allocation rules that operationalize the distribution of a given climate budget. However, in the bottom-up approach of the Paris Agreement, no single “effort-sharing” and allocation framework has been agreed upon by the Parties. Any assessment of a country's effort implies having a vision of what would be an ambitious contribution from this country, with no single “effort-sharing” rule now legitimized at the international scale. We then propose a new framework to list and evaluate the existing tools that assess the fairness of Nationally Determined Contributions. We sort them in three categories and compare their practical relevance within the current context. We show that they all come to a compromise between multiplying the viewpoints on equity (as there is no theoretical reason to prefer one rule) and providing a firm assessment. We discuss their limits in relation with the inclusion of other development targets of countries.

Chapter 6 - International climate justice: what the people think. (Auriane Meilland, Yann Kervinio, Aurélie Méjean)

One of the thesis' endeavours is to reframe equity considerations within international climate cooperation, to adapt them to the recent contexts of the Paris Agreement and Sustainable Development Goals. First, the Paris Agreement's shift to voluntary commitments hasn't eradicated equity discussions. To what extent do countries make equitable climate contributions within the Paris Agreement? The answer to this central question can rely on the existence of explicit and shared views about fairness. Yet, studies on existing fairness views are rare and often have a limited practical scope. In this article, we discuss how using citizens' judgements can be justified to discriminate among the large set of reasonable views that can define international climate justice. We design and administer a survey to elicit relevant judgements among French and US citizens. We find that in both countries, most respondents think that principles of climate justice should be settled internationally even if they go against some countries' interests, and express a preference for common (rather than differentiated) responsibilities - all the more when they are concerned about climate change. We observe support for two effort sharing rules: convergence towards equal per capita emissions, and an operationalized version of grandfathering. Our survey also shows inconsistencies in fairness judgements, and that citizens have difficulties coordinating on simple judgements regarding existing nationally determined contributions. This calls for the development of standardised surveys on these questions.

Finally, the conclusion of this thesis summarizes its main findings and the research avenues it opens, particularly on equity and endeavours to rethink, in the light of our discussions, the climate equity framework as a framework integrating other development targets.

Published Articles

Chapter 1: Meilland, A., & Lecocq, F. Mapping national development priorities under the Sustainable Development Goals framework: a systematic analysis. *Sustain Sci* (2023). <https://doi-org.inshs.bib.cnrs.fr/10.1007/s11625-023-01377-2>

Working Papers

Chapter 3: Gherzi, F., Daumas, L., Meilland, A., Ralite, S., Lefèvre, J., Le Treut, G. - Closing models, opening debates: theoretical uncertainty and the low-carbon transition

Chapter 4: Meilland, A., & Lecocq, F. Are Long-term National Goals on Climate Change Mitigation and Economic Development Compatible? Evidence and Modelling on Several Case Studies

Chapter 6: Meilland, A., & Kervinio, Y., & Méjean, A. - International Climate Justice: What the People Think. Available at SSRN: <https://ssrn.com/abstract=4569583> or <http://dx.doi.org/10.2139/ssrn.4569583> (Manuscript submitted)

Own presentations in conferences and invited seminars

Chapter 1: Meilland, A. and Lecocq, F. - Mapping national development priorities under the Sustainable Development Goals framework – a systematic analysis

- International Energy Workshop (IEW), 2022, Freiburg, Germany
- Annual conference of the French Association of Environmental and Resource Economics (FAERE), 2022, Rouen, France
- Annual PhD Conference of the "Agriculture, Alimentation, Biologie, Environnement et Santé" Doctoral School at Université Paris-Saclay, 2022, Paris, France
- Invited Methodological Seminar "AutoMat", UMR Développement & Sociétés, Université Paris 1 Panthéon Sorbonne, 2022, Paris, France
- CIRED Seminar, Centre International de Recherche sur l'Environnement et le Développement (CIRED), 2022, Paris, France
- Poster: CIRED +50 Conference, 2023, Paris, France

Chapter 3: Gherzi, F., Daumas, L., Meilland, A., Ralite, S., Lefèvre, J., Le Treut, G. - The macroeconomic costs of energy policies at the test of theoretical uncertainty

- PhD. Seminar, Centre International de Recherche sur l'Environnement et le Développement (CIRED), 2021, Paris, France
- International Modelling Platform Annual Workshop, 2021, Paris, France
- Annual conference of the European Association of Environmental and Resource Economics (EAERE), 2023, Limassol, Cyprus
- International Conference on Development Economics - Annual conference of the French Association of Development Economics (AFEDDEV), 2023, Paris, France

Chapter 4: Meilland, A. and Lecocq, F. - Are Long-term National Goals on Climate Change Mitigation and Economic Development Compatible? Evidence and Modelling on Several Case Studies

- Annual Conference of the Global Trade Analysis Project (GTAP), 2023, Bordeaux, France
- Annual conference of the French Association of Environmental and Resource Economics (EAERE), 2023, Montpellier, France

Chapter 6: Meilland, A., Kervinio, Y. and Méjean, A. - International Climate Justice: What the People think.

- "COP 21: 5 years later" international symposium for PhD Students of the Sorbonne Sustainable Development Association, 2021, Paris, France
- Invited Methodological Seminar "AutoMat", UMR Développement & Sociétés, Université Paris 1 Panthéon Sorbonne, 2022, Paris, France

I. On collecting national priorities, and using the SDG framework to classify them

Mapping national development priorities under the Sustainable Development Goals framework – a systematic analysis

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Abstract

Since their adoption in 2015, the Sustainable Development Goals (SDGs), with their ambition to be universal and indivisible, have become a dominant framework to discuss development matters, especially on the international stage. This work aims at bringing information on whether or not the SDGs provide a good mapping of development priorities as expressed by countries. We develop a new analysis of the SDG framework (within the 2030 Agenda) by systematically mapping the national development priorities displayed by 121 countries in their long-term development documents. We thus categorize each priority under its related SDG(s) and create a typology of documents, along with a visualization tool—which displays how SDGs are prioritized across countries. We show that only a few priorities do not fit in—notably some related to defence and population growth. Moreover, some SDGs are largely more prioritized, and there are many documents in which not all SDGs appear. The tool and database might inform many development-related questions—here enabling us to discuss the relevance and targeted universality of the 2030 Agenda in light of its connections with national development priorities.

Contributions:

Auriane Meilland: Conceptualization, Methodology, Investigation, Data collection, Programming, Analysis, Writing (original draft), Visualization

Franck Lecocq: Conceptualization, Methodology, Analysis, Writing

1.1 Introduction

As exposed in the general introduction of this thesis, the 2030 Agenda adopted by the United Nations General Assembly in 2015 - the same year as the Paris Agreement on climate change (UNFCCC, 2015) and the Addis Ababa Action Agenda for financing development (UN General Assembly, 2015a) - aims at completely mainstreaming the concept of sustainable development into development issues (Griggs et al., 2013; Sachs, 2012). To this respect, its 17 Sustainable Development Goals (SDGs) and 169 targets for the year 2030 were designed to create a universal framework for achieving sustainable development (UN General Assembly, 2015b; Ki-Moon, 2019).¹ They differ from their predecessors, the Millennium Development Goals (MDGs), in their bottom-up formulation process as well as in their scope. The SDGs indeed result from a consultative process, apply to all countries, and are presented as “integrated and indivisible” (UN General Assembly, 2015b), altogether covering sustainable development in most aspects of society.

Since 2015, this framework has become widely used in international discussions, where it has progressively been more highlighted than other related frameworks such as the “three pillars of development (economic, social and environmental)”. This popularity at the international level is reflected in the academic and grey literature on sustainable development, which has expanded.² Documents from the United Nations and its subsidiary agencies (UNDP, 2020), international bodies such as the IPCC (P.R. Shukla et al., 2022) or IPBES (Watson et al., 2019), international research organizations such as Future Earth (Smith et al., 2018), or international development banks (World Bank, 2022b) now routinely use the SDGs as a framework to think about development priorities.³

¹As detailed in the introduction, and cited in the UN resolution “Transforming our world: the 2030 Agenda for Sustainable Development”: *“The Sustainable Development Goals and targets are integrated and indivisible, global in nature and universally applicable, taking into account different national realities, capacities and levels of development and respecting national policies and priorities. Targets are defined as aspirational and global, with each Government setting its own national targets guided by the global level of ambition but taking into account national circumstances. Each Government will also decide how these aspirational and global targets should be incorporated into national planning processes, policies and strategies. It is important to recognize the link between sustainable development and other relevant ongoing processes in the economic, social and environmental field “*

²During the year 2011, before the principle of the SDGs was proposed, 14 653 articles including “sustainable development” in their title, abstract or keywords were listed on the platform ScoPus. During the year 2020, that number had more than doubled - 39 295.

³In the latest example to this date, the IPCC’s third working group states that *“The Sustainable Development Goals (SDGs) adopted under the UN 2030 Agenda for Sustainable Development can be used as a basis for evaluating climate action in the context of sustainable development. (high confidence)”*

Throughout this manuscript, we aim at discussing how countries articulate their national climate and development targets. The SDGs are a *collectively* agreed set of goals for the year 2030: that they would provide a good mapping of the diversity of *national* development aspirations across countries and regions is not self-evident. Using the SDGs as a guide to describe national development priorities may be tricky if the alignment between these international and national frameworks is limited for some countries, as some national priorities could be mistranslated or simply lost at the international level. The primary objective of this chapter is thus, while collecting long-term national development priorities, to carefully test the hypothesis, implicitly made when using the SDGs to think about all development issues, that the SDGs provide a comprehensive mapping of development priorities everywhere.

To do so, we have to discuss which development priorities we intend to observe. Indeed, there are many understandings of this concept and how to observe it, each with conceptual and practical difficulties. Stated priorities found in various communication documents and discourses of governments or stakeholders may not reflect adopted policies due to discursive gaps (Czaika and De Haas, 2013).⁴ Priorities observed in the laws and regulations that are effectively adopted might neither reflect enforced policies due to implementation gaps (Hudson et al., 2019) nor fully capture societal preferences. Some priorities emerge from citizens' preferences (Miller, 1992) expressed in votes (Carter, 2013), referendums, or in surveys such as the World Value Survey (Haerpfer et al., 2022), but may only provide information on limited sets of decisions. And in all cases, the priorities of a country may differ depending on time horizons.

Here, we collect and analyse official long-term national development documents and visions, from which we extract stated national development priorities. This enables us to get a harmonized way to observe national priorities across countries: although different in format, content and legal status, these documents are sufficiently similar from one country to the next to allow for relevant comparisons. Their long-term horizon allows one to somewhat abstract from priorities "du jour". And their economy-wide breadth provides a sense of comprehensiveness, and increases the chances that the outcome be internally consistent. The limit of this approach, of course, is that it rests on stated priorities, which may make it subject to gaps between official targets influenced by the international context, and effective policies.

⁴Discursive gaps are defined in Czaika and De Haas (2013) as "*gaps between discourses and actual policies in the form of laws, regulations and measures on paper*"

The advantage, however, is that development documents and visions are available in a large number of countries. Economy-wide development planning at the national scale can be traced back to the early 20th century, mainly in colonial territories such as the then-called Gold Coast (Guggisberg, 1922). Widely used in the 1940s-1960s, this approach later declined following the collapse of centrally planned economies, and is now resurfacing as national development plans are becoming a widespread tool to frame short and long term development goals and strategies (Munro, 2020; UN DESA, 2015). The number of national development documents has been increasing sharply: a global inventory of national plans conducted in 2007 (World Bank, 2007) identified 62 documents, a number that had more than doubled when the exercise was reiterated in 2018 (Chimhowu et al., 2019). Resurgence of national planning is coming from developing countries, and could stem from five distinct causes (Munro, 2020): (i) an inheritance from the Heavily Indebted Poor Countries Initiative and the associated Poverty Reduction Strategy Papers (IMF, 2016), (ii) a tool to manage the risks of globalization, (iii) the promotion of transformative national agendas, (iv) a convergence with the international framework to integrate sustainable development issues (which would imply a natural convergence between the SDGs and the stated priorities featured in the plan) or, on the opposite, (v) a counter-narrative to it.

This last reason was formulated for plans that were contemporary to MDGs, which were more specific. Although SDGs were designed to ensure global inclusion, counter-narratives could still exist nowadays as some challenges have been raised on their declination: the number and lack of precision of targets which leaves much room for interpretation (Gupta and Vegelin, 2016; Stewart, 2015; Biermann et al., 2017), the “silo approach” used to present the goals that hides the strong interlinkages between them (Nilsson et al., 2016; McGowan et al., 2018; Bogers et al., 2022), and the detailed data needed to monitor the progress (ICSU and ISSC, 2015; Lu et al., 2015).

In this study, we examine the extent to which the SDG framework provides an accurate and exhaustive mapping of development priorities and aspirations.

To discuss the alignment between SDGs and national targets, we test a first hypothesis that derives from the aimed “universality” of the SDGs: it is assumed that *most national development goals, such as those detailed in long-term national development documents and visions, enter the scope of one or several SDGs (H1)*. We check this hypothesis both for “sustainable development plans” that directly refer to the SDGs and for other national development documents that do not strictly stick to this framework –recent or not (Munro, 2020).

The other way around, to discuss the alignment of national documents with the international framework, we test a second hypothesis: *that all SDGs are pursued, at least to some extent, in each development document (H2)*. Indeed, although the governance of SDGs implies an adaptation to national contexts, cherry-picking between SDGs would go against the aimed “indivisibility” of the framework.

The literature on national development planning and the SDGs has started to provide tools for analysing development frameworks in light of the SDGs (UNDP, 2017; Institute, 2021), but only focuses on specific countries (Morita et al., 2020; Jönsson and Bexell, 2021; Horn and Grugel, 2018) or regions (CEPAL, nd). Priorities have been extracted from documents provided to the UN (Forestier and Kim, 2020; Janetschek et al., 2020; Iacobuță et al., 2022), or emanating from public development banks (Jacouton, J et al., 2022) for a limited number of countries, but it has not yet systematically been checked whether or not national long-term planning documents only contain goals that fit into the SDG framework.

Here, we create a systematic mapping of the national targets displayed in planning documents by fitting each one of them under the SDG(s) tackling the issue, and isolating goals that are not consistent with this global framework. This typology also provides insights on the national prioritization of the global Sustainable Development Goals, thus enabling us to test both hypotheses while collecting national development priorities that will be used in Chapter 4 of this thesis.

The chapter is structured as follows. Section 1.2 presents the methodology developed to build the database of existing national development documents and mapping of priorities. Section 1.3 provides a first description and analysis of it. We first discuss the countries represented in the analysis, then isolate the national priorities that deviate from the global framework, and finally comment on the global representation of each SDG in long-term planning documents. Section 1.4 highlights and discusses the main findings: **H1** can be confirmed with exceptions such as targets on population growth and defence that do not fit into the SDG framework, and **H2** is rejected, in that SDGs are differently prioritized across countries and some of them, such as SDG 5 on Gender, are not systematically mentioned in all the documents.

1.2 Materials and Methods

To conduct this analysis, we first collect national development documents based on a set of criteria that is detailed in Section 1.2.1. We then create a database by systematically mapping the national development targets displayed, using the SDGs as a basis, such as detailed in section 1.2.2.

1.2.1 Collecting national development documents and visions

National development planning documents and visions are not harmonized at the global level. A national development document outlines a country’s planning vision, targets and policies for a given time period. It is specific to each country situation and governance system, and can take various forms, such as long-term broad national visions, while others are short-term action plans or sectoral plans.

The documents featured in the database were thus selected based on a set of detailed criteria, as the results might depend on the type of documents that were chosen. We collected the documents as inspired by previous studies (Chimhowu et al., 2019; World Bank, 2007) with criteria adapted to the targeted analysis as detailed in this section and summarized in Table 1.1.

Table 1.1: Summary of the criteria used to collect national long-term development documents to build the database.

CATEGORY	CRITERION
FORMAT	Single file
LANGUAGE	All languages (English, French, German, Spanish prioritized)
TIME COVERAGE	Covering at least 9 years, still running in 2020
SCALE	National, economy-wide
NATURE	Diverse, but Voluntary National Reviews are excluded
ORIGIN	State ministry or institution, ideally related to economy or planning
DUPLICATES	Included

The documents featured in the final database are listed in Appendix A with their source and language

Based on these criteria, we conducted an exhaustive web search for long-term documents and visions for each country listed as a United Nations Member State. Documents were collected until December 2022, with the help of the FAOlex database of the Food and Agriculture Organisation (FAO, nd), the World Bank website (World Bank, nd), the Planipolis database of the United Nations Education, Science and Culture

Organization (UNESCO, nd), plan repositories from the UN Economic Commissions for Latin America (CEPAL, nd) and for Western Asia (UNESCWA, nd) or more often directly on governmental websites. The documents collected are listed with their source in Appendix A.

Format

There is no unique format to a national development document. Although most of them are structured documents, some countries produce so-called plans that are displayed on websites (as is the case for Kuwait), or mentioned in speeches (as is the case for Algeria). For the purpose of this analysis, we only keep plans and visions that are detailed in a document so that all the priorities and targets are set in a unique file – and can be read through without missing some elements.

Language

Some countries only issue their development document in their official administrative language, whereas others also propose translations. To limit the need for an automatic translator, the documents were collected in French, English, Spanish or German when available in these languages, otherwise in the original language. The languages in which all documents were collected are listed in Appendix A.

Time coverage

Our main target is to observe the extent to which SDGs form a good mapping of development aspirations across countries. In order to avoid collecting one-time priorities that could be unstable in time, long-term development plans, documents and visions were selected, as most short-term development plans contain targets that might rapidly change or be prioritized over others. Indeed, not all targets can be pursued or achieved in the short term. In that, there is a higher chance that all development aspirations of a country are encapsulated in longer-term documents than for 5-year development plans. Observing long-term development goals is then a way to roughly align with the temporal framework of the SDGs, adding to the relevance of the mapping. We arbitrarily set the limit at 9 year-long documents, and exclude shorter-term development plans, except when they explicitly include a longer-term vision that wasn't detailed in a specific document. For example, we include the 5-year plans of China or Fiji as the documents included a longer-term vision that was unreleased elsewhere, whereas for

Cambodia, we keep the long-term vision document setting global priorities but not the short-term action plans directly applying the vision. We finally collected documents for which the expiration date was 2020 or later.

Scale

In order to correctly check for **H2**, the documents and visions selected have to be national and cover most aspects of society. Regional plans, and plans of states within countries with a federal governance (as is the case for the United Arab Emirates where Abu Dhabi has a plan) are not included in the database. Moreover, in a sectoral plan, it is natural that not all SDGs are represented and that **H2** is invalidated – to accurately map the country’s national targets in such a case, we would need to collect and analyse all its sectoral plans. We thus rule out documents that only cover specific sectors, as well as spatial development plans with no other dimension, and keep documents that are national and at least economy-wide.

Nature

To cover the diversity of governance systems in terms of development and planning, our definition of “national long-term planning document” includes so-called long-term development plans with quantitative, specific targets, as well as broader, less detailed development visions and strategies.

As briefly mentioned in the introduction of this chapter, development documents may have different legal statuses depending on countries, but all display stated priorities. Although the redaction of all development documents produced after 2015 might have been influenced the SDGs, excluding official communication documents to the UN enables us to reduce the risk of having an extended gap between stated priorities produced for international cooperation and enforced policies. Although a few of them mention development aspirations, we thus exclude the “Voluntary National Reviews” (VNRs), that are voluntary documents produced for the High-Level Political Forum of the United Nations in the context of the SDGs’ implementation, as they mostly report on the current state of achievement of the SDGs for a given country.

Institution

We collected development documents or visions issued by a government or state institution, in order to ensure that they reflect the State’s ambition in terms of

development. Depending on the country, such documents are usually produced by the Ministry of economy and finance, the Ministry of planning and development, or a dedicated state institution such as a National Planning Commission. We exclude documents produced by think-tanks, companies, NGOs and other non-state institutions.

As long as they emanate from the States, we do not operate a selection based on how the documents were constructed. We do not discriminate between documents resulting from a “top-down” process (established by experts with prospective economic modelling as a basis), a more “bottom-up” process (based on concertation) or all intermediates (Chimhowu et al., 2019).

Duplicates

Some countries have several development plans and documents that run for a given time period, for example a plan that runs from 2000 to 2020, and a vision that runs from 2005 to 2050. In this case, we do not choose between documents and analyse both.

This results in a repository of 132 documents from 121 countries satisfying all the criteria. The list of documents included is significantly different from those presented in previous articles, which feature many shorter plans as well as plans that ended before 2020. Compared to the latest one (Chimhowu et al., 2019), only 19 documents are common to both databases.

1.2.2 Typology of the documents

The study is conducted on the obtained repository of 132 documents from 121 countries satisfying all the detailed criteria. The mapping is included in a database that was built by collecting in a table, for each document, information on 55 entries listed in Appendix A, and grouped in four categories: general information on the document and country, information on the content and elaboration of the document, mapping of the targets, information on the data.

General information on the document and country

This category concerns broad information on the document and country, collected automatically. The entries are the official name of the document, its year of publication, the language in which it was collected for the analysis, the country to which it refers, a small justification as to why the document fits the criteria detailed in section 1.2.1,

and country characteristics including its 2020 population, belonging to OECD countries, LDCs or countries listed in the Annex I of the UNFCCC, and finally whether the country has produced a Nationally Determined Contribution within the Paris Agreement or not.

Content and affiliation

This category regroups information on the nature of the document, for which we qualify whether it is branded as a detailed strategy (with several quantified targets), a large vision (more broad with only one or two quantified targets) or a so-called “sustainable development plan” (including these words). Entries also include the official horizon year and emanating institution or body, whether the consultation of stakeholders and civil society is mentioned or not (as this gives information on whether the document was more built on collective concertation or on top-down expert-led studies), whether there is any reference to the 2030 Agenda or not, all information collected automatically through a screening of the document.

Mapping

This category of entries is designed and organized to guide the checking for both hypotheses **H1** and **H2**. To check for **H1**, all the main development targets featured in the document are extracted and listed, then connected to the SDG(s) that would include them. In doing so, the priorities that do not fit into the framework are highlighted. In order to check for **H2**, we then qualify the level of priority given to the targets entering the scope of each SDG. The SDG(s) that are not covered in the document then stand out.

For the first step, the national priorities have to be collected manually in the documents, using Google Translate for some languages. Indeed, both the diversity of languages and heterogeneity of formats of the documents – some have explicitly listed priorities, in others priorities are summed up in a paragraph - do not allow us to apply advanced text mining techniques in a relevant way.

Language processing techniques are also ineffective in associating relevant SDGs to each listed target, for translation reasons but also because the lexicons associated to some SDGs often overlap with others. National development targets are rarely formulated in exactly the same way as their corresponding SDG, except for a few countries that fully adopted the framework to detail a development document (for example Indonesia). Ultimately, the association is done manually for all the targets and documents, which

proves helpful in the discussion and analysis as it provides a deeper understanding of the narratives that are developed in the long-term plans and visions. Attention is however given to a few methodological details in order to ensure robustness of the results. First, each national target is associated with related SDG targets based on the formulation but also, when in doubt, on the indicator associated. The mapping of national targets is thus done by Sustainable Development Goal but looking at the SDG target level, as only taking into account the text of the Goal would lead to a more indecisive result. When a single national target refers to different SDG targets or SDGs, it is put under both categories. When national targets are in the spirit of SDG targets but too specific or too broad to be explicitly formulated in the same way, or only partially match it, they are still associated with that SDG. Indeed, as the aim of this mapping is to check for **H1**, these methods enable us to robustly isolate national targets that do not fit under the SDG framework.

For the second step, a priority level accorded to each SDG in the document is attributed manually out of four levels:

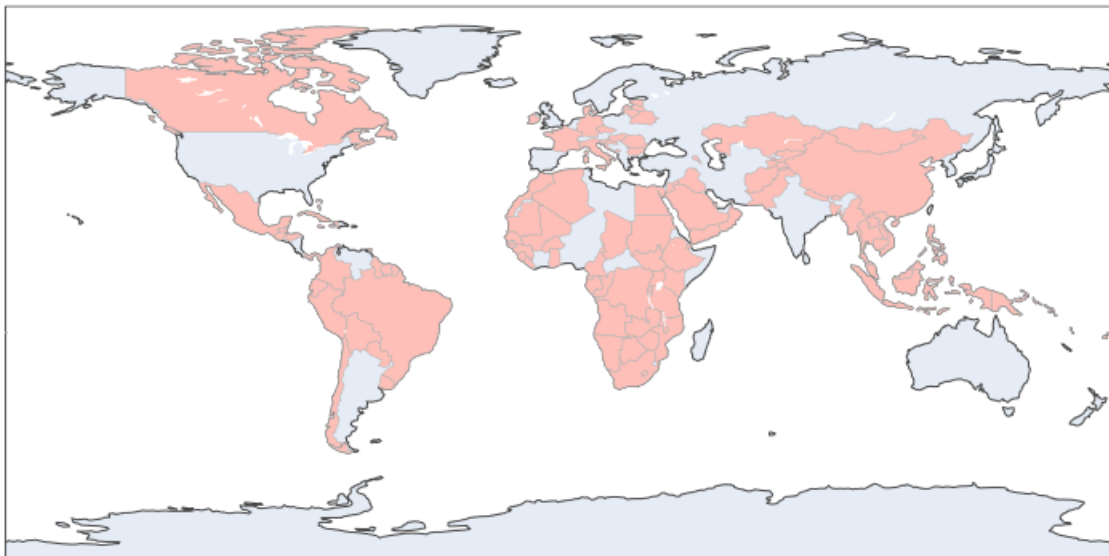
- “**Priority**” refers to SDGs covered in one of the few key and highlighted targets or indicators of the document – this means that in documents where no target stands out, there is no SDG with the “Priority” level.
- “**Mentioned**” refers to SDGs that are covered by at least a target of the document.
- “**Barely mentioned**” refers to SDGs that are only covered by one or a few sub-targets of the document.
- “**Absent**” refers to SDGs that are not covered in any target or sub-target of the document, even when briefly mentioned.

To sum up, in the final database, there are two entries for each of the 17 SDGs:

- First, a column listing all the key targets and goals of the development document that do fit under said SDG.
- Second, a column categorizing the level of priority given to said SDG in the document, with 4 different categories: Priority, Mentioned, Barely mentioned, or Absent.

In an additional 35th entry, targets that do not fit under any SDG are isolated, providing elements to discuss **H1**.

Figure 1.1: Map of the countries that are featured in the database.



In pink, countries with documents that are represented in the database. Some countries are noticeably absent, including countries that are known for their planning tradition, for example Russia and India. These cases are often explained by the fact that development plans exist, but were not long-term enough to be featured in the database – in the case of India however, no more formal plans are made for the economy.

Nature of the data

This category aims at qualifying the targets and data proposed in the document. For each document, we determine whether it is based on mentioned quantitative data or not, and we qualify the data (describing whether it comes from institutional sources or not, based on modelling or not, etc). We then note whether the targets are quantified or not.

After a brief description of the collected documents and information, we provide, in Section 1.3 a first description of the database to discuss the main hypotheses.

1.3 Results

1.3.1 Description of the documents collected

The resulting database regroups a total of 132 documents, in 12 languages, covering 121 countries displayed in a map in Figure 1.1.

Although there is a large number and diversity of countries covered, it is noticeable that *most non-OECD countries have a long-term development plan, document or vision.*

Moreover, the national documents are branded “sustainable development plans” in 25% of the cases (and visions in 52% of the cases), but this proportion is much higher (more than 70%) when considering OECD countries. *This observation on long-term development documents would be in line with the presence of a link between the increase in the use of planning for developed countries and the integration of sustainability considerations into the international framework in the form of SDGs* (Munro, 2020; UN General Assembly, 2015b).

1.3.2 Length and horizon of the development documents

Figure 1.2 shows the distributions of national development documents collected, depending on their date of publication, horizon year, and length. Figure 1.2 (a) shows that *most documents (more than half) have 2030 as a horizon*, which would be consistent with the time framework of the SDGs and in line with an increase in the number of development plans as a response to the international context – 12 documents (10% of the total documents) use the SDGs as a base for their structure and 45 more (36%) mention the framework in their text. However, we also observe in Figure 1.2 (b) that more than 40% of the documents existed before the year the 2030 Agenda was published.

In Figure 1.2 (c), the distribution of the durations of documents is shown, and broken down by horizon year. From this figure, *three main types of documents can be distinguished*:

- First, 20% of the documents were published around 2015 with a 2030 horizon (as is the case for Egypt or Germany). Although these documents are in line with the international context (more than 85% of them mention the SDGs), we cannot directly conclude on whether they all are a direct consequence of the adoption of the 2030 Agenda – some documents could simply replace a previously existing document that expired in 2015.
- Second, there are longer-term documents (covering a period longer than 25 years). Most of them are “visions”, sometimes complemented by shorter-term documents that were not included in our database (as is the case for example for Cambodia).
- Finally, around 20% of the documents cover a period of around 20 years and were published before 2010 (as is the case for example for Tanzania). None of these

documents refer to the 2030 Agenda and their analysis will be particularly helpful in informing **H1** – checking whether previously established development goals all fit into the framework or not. Indeed, because of the time framework, we can rule out a natural alignment of the stated priorities with the SDGs as a displayed effort to fit to the framework.

1.3.3 Typology of the development documents

Our analysis with regards to **H1** and **H2** leads us to two main observations, detailed hereafter.

Main observation 1: Most national targets in development documents fit into the SDG Framework

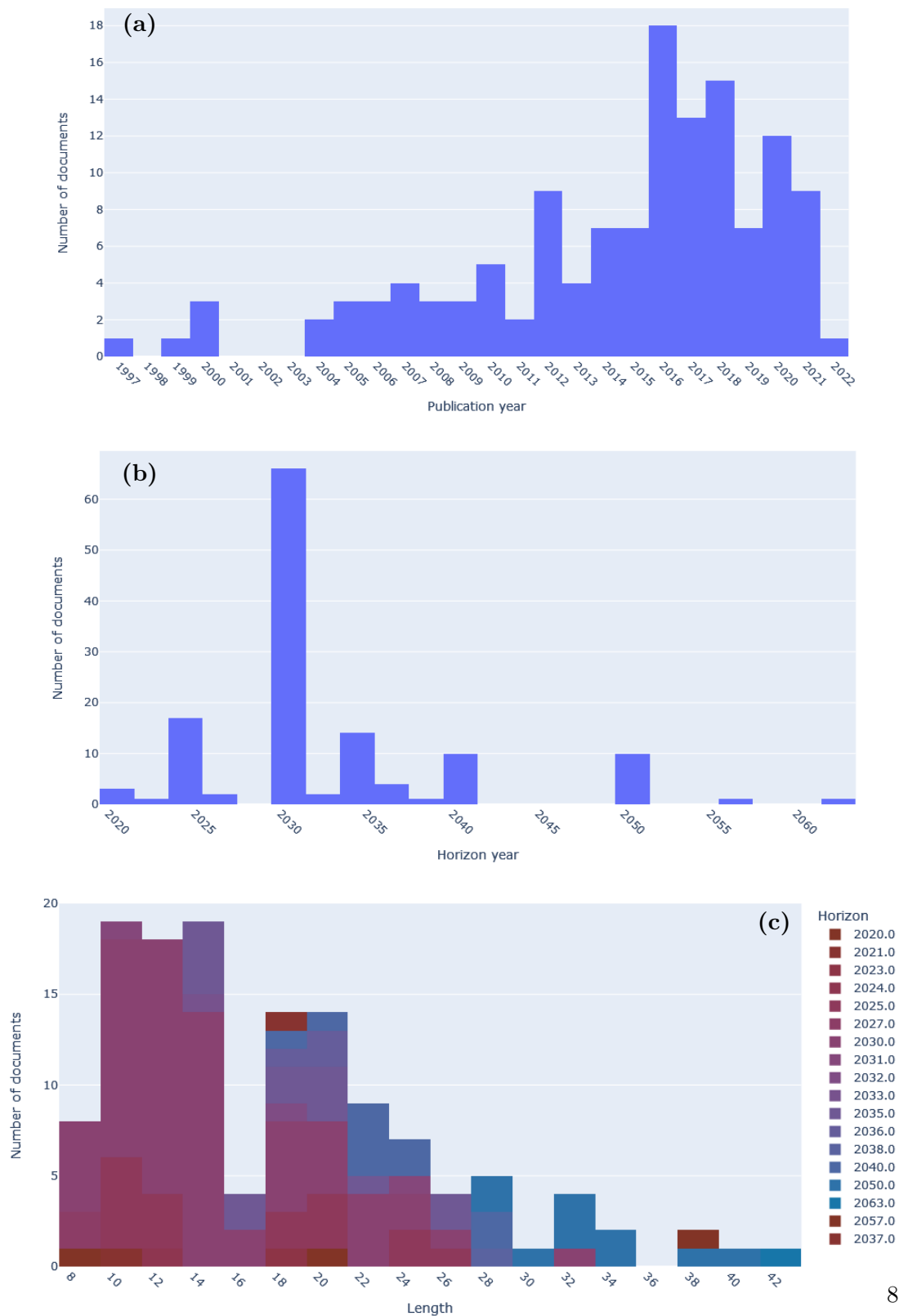
Overall, the development goals displayed in the national documents tend to fit into the SDG framework and can usually be linked to one or several SDGs, which would tend to confirm hypothesis **H1** (“All the development goals that can be found in countries’ national long-term development documents fit under one or several SDG(s)”).

Targets in development documents sometimes simultaneously fit into several SDG categories. Indeed, because SDGs were designed as “integrated and indivisible” (UN General Assembly, 2015b), two different SDGs can feature targets that are close or identical. It is then relatively easy for a development goal to not be specific enough that it enters under one SDG but not another. Two theoretical illustrations of this observation are detailed hereafter:

- A development goal entitled “ensure reliable access to internet and telecommunication services” can be linked with at least two indicators of the SDG Framework – the fixed internet broadband for 100 inhabitants, and the proportion of population covered by a mobile network by technology. However, these two indicators are associated with two different SDGs. The former is associated with SDG 17 (“Strengthen the means of implementation and revitalize the global partnership for sustainable development”) under its target 6.⁵ The latter is associated with SDG 9 (“Build resilient infrastructure, promote inclusive and sustainable industrialization

⁵SDG 17.6: “Enhance North–South, South–South and triangular regional and international cooperation on and access to science, technology and innovation and enhance knowledge sharing on mutually agreed terms, including through improved coordination among existing mechanisms, in particular at the United Nations level, and through a global technology facilitation mechanism”.

Figure 1.2: Distributions of national development documents collected depending on their date of publication (a), horizon year (b) and length (c)



In Figure (c), the distribution of horizon years is also displayed for each length.

and foster innovation”) under its target c.⁶ Discriminating between the two categories would call for a level of detail and specification that is often not present in a country’s development document, leading to this goal fitting under both SDGs.

- A development goal entitled “achieve sustainable land management” can similarly be linked with at least three indicators – the proportion of land that is degraded over total land area (SDG 15)⁷, the ratio of land consumption rate to population growth rate (SDG 11)⁸ and the proportion of agricultural area under productive and sustainable agriculture (SDG 2).⁹

Similar examples can be found for development targets revolving around transportation, or decentralization, and national development documents are not usually specific enough for each target to fit under a single SDG category. Even if so, when it comes to indicators, some of them are common to two SDGs – for example the material footprint per GDP which belongs to both SDGs 12 and 8, or the number of death attributed to disasters which belongs to both SDGs 1 and 11. Still, the main result is that the vast majority of national targets are englobed by at least one SDG.

Three types of development goals, however, do not fit under any SDG and were reported in a separate column of the typology. An analysis of these development goals shows that they can be classified into three broad categories.

First, 23 development documents mention individual values, behaviours and religion – as is for example the case for the Philippines, targeting work-life balance and time with friends, South Sudan, targeting strong religious values for their citizens, or Tuvalu with targets on sharing and reciprocity. These can be considered as out of the range of SDGs 11 on cultural heritage or 4 on education, and tend to not fit under any SDG category – although it can be noted that they are not among priorities in the mentioned development documents.

The second category revolves around national security and defence budgets in 26 documents, such as the ones of Kyrgyzstan or Mali. Such targets are not covered by

⁶SDG 9.c: “Significantly increase access to information and communications technology and strive to provide universal and affordable access to the Internet in least developed countries by 2020”.

⁷SDG 15 under the target “By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world”.

⁸SDG 11 under the target “By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries”.

⁹SDG 12 under the target “By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality”.

SDG 16 (“Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels”) and are thus left out of the framework.

The third type of targets that do not fit into the framework are those explicitly mentioning the limiting of population growth in 15 development documents, such as the ones of Niger or Bangladesh. Indeed, even though the means of implementation of these targets are a part of the framework (e.g. family planning in SDG 3: “Ensure healthy lives and promote well-being for all at all ages”), the very finality of limiting population growth is not mentioned.

Apart from these exceptions that are never priorities but feature in 45 documents, all the development targets encountered can fit under at least one SDG. This tends to validate our first hypothesis **H1**, and the SDGs as a framework that englobes most development priorities formulated both before and after its adoption.

The documents which are explicitly based on the 2030 Agenda and follow the structure of SDGs do not mention any target that would not fit into the framework, which could either mean a natural alignment between both, or an omission of stated priorities that would not fit into the SDG framework. In this light, it is still important to note that most development documents that were published after 2015 and explicitly refer to the SDGs, as is the case for Afghanistan or France, do not follow the structure of the 17 SDGs – they are mentioned and referred to, but the targets are usually structured in a different way. This could be related to hypothesis **H2** and how development goals are prioritized by countries.

Main observation 2: Some SDGs receive greater emphasis than others in the development documents.

By mapping the development goals of countries on the basis of SDGs, insights were also given on the level of prioritization of each SDG in a given document, and then globally. In order to discuss hypothesis **H2** (each country pursues in its national long-term development document, to some extent but simultaneously, every SDG), we observe the distributions of priority levels associated with each SDG globally, then for specific groups of countries.

Figure 1.3 represents how SDGs are prioritized at the global scale, over all the planning documents featured in the database. Here, it is quite obvious that *not all SDGs are pursued with the same priority level in the development documents.*

Figure 1.3: Global distributions of the levels of priority given to each SDG.



For each SDG, the horizontal bar represents the proportion of documents where the priority level is Absent, Barely mentioned, Mentioned or a Priority.

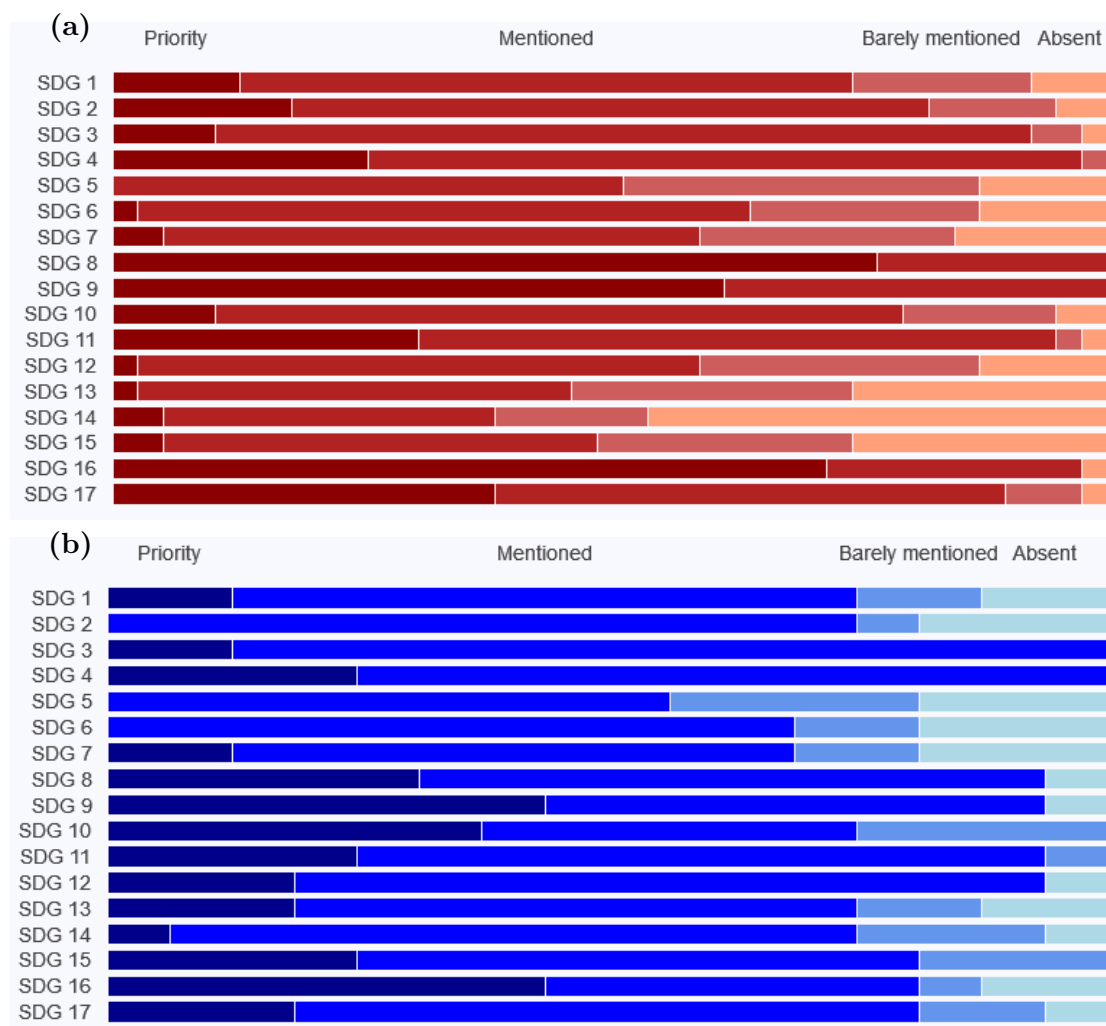
The most prioritized SDGs are SDG 8 (Work and economy), SDG 9 (Industry, Infrastructure, Innovation) and SDG 16 (Peace and institutions) with respectively around 70%, 60% and 64% of the development documents mentioning them as a priority. These are not only prioritised, but also very rarely omitted – they are all absent in less than 5% of the documents. SDG 11 (Sustainable cities and communities) and SDG 17 (Partnerships for global development) are also often a priority – in respectively 37% and 38% of the documents – and equally, rarely omitted.

SDG 1 (Poverty reduction), SDG 2 (Food and agriculture), SDG 3 (Health), SDG 4 (Education), SDG 10 (Inequalities) and SDG 12 (Responsible production and consumption) tend not to be as much prioritized, in less than 25% of the documents, but they are also absent in less than 13% of the documents – they are almost always mentioned, but with a varying degree in their priority level.

SDG 5 (Gender), SDG 6 (Water and sanitation), SDG 7 (Energy), SDG 13 (Climate change), SDG 14 (Life below water) and SDG 15 (Life on land) are all prioritized in less than 10% of the development documents. Moreover, SDG 5, 13, 14 and 15 are all omitted in more than 15% of the documents. This invalidates **H2**, in that not all SDGs are simultaneously pursued by countries at least to some extent, even in the more recent development documents – in total, only 33 documents of the database feature all 17 SDGs.

This result calls for a closer look at which countries prioritize which SDGs. Figure 1.4 breaks down how SDGs are prioritized for Least Developed Countries and for OECD countries in the database. The results displayed show that *depending on their development level, countries do not tend to prioritize the same SDGs*.

Figure 1.4: Distributions of the levels of priority given to each SDG, for least developed countries (a) and OECD countries (b).



For each SDG, the horizontal bar represents the proportion of documents where the priority level is Absent, Barely mentioned, Mentioned or a Priority. In red, the proportions for LDCs (based on the UNCTAD list). In blue, the proportions for OECD countries.

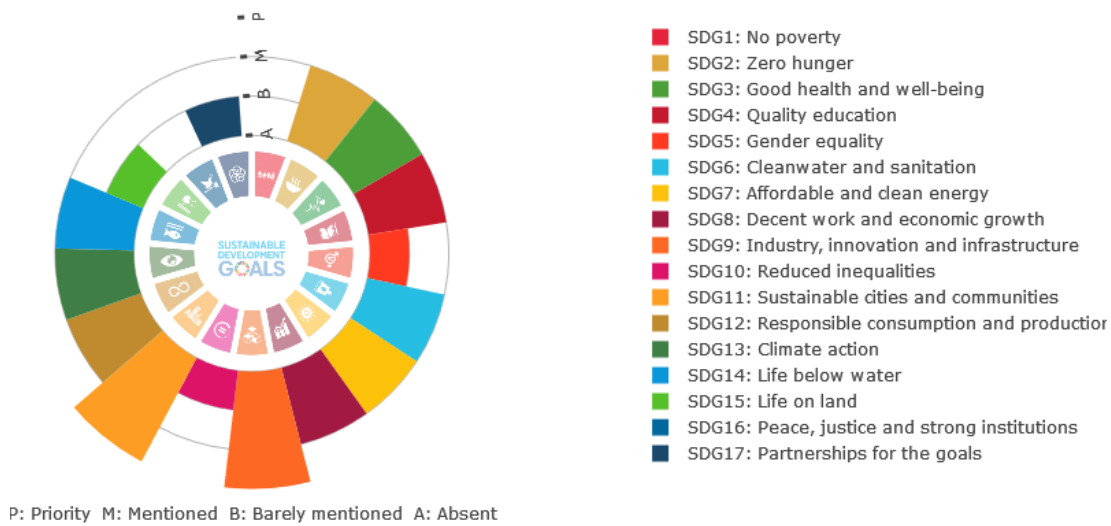
Indeed, SDG 5, 13, 14 and 15, which were omitted in more than 15% of the total documents, are prioritized in less than 10% of the least developed countries' documents or visions. SDG 5 is often mentioned or at least barely mentioned (in more than 87% of the LDCs' documents), which shows that gender is taken into account but not displayed as a priority. However, SDGs 13, 14, and 15 are not as mentioned: in more than 50% of the LDCs' documents, they are barely mentioned or absent, which shows that environmental considerations are rarely prioritized and often not included in national development documents from Least Developed Countries.

Symmetrically, OECD countries never prioritize SDGs 2, 5 and 6, but more than 10% omit SDGs 8, 9 or 16, that are the most mentioned globally. In comparison to the global proportions, they tend to mention the environmental SDGs more.

To get a better sense of how specific countries prioritize SDGs in their development document, and navigate through the database, we created a visualisation tool¹⁰ displaying, for a chosen country, the level of priority given to all the SDGs, the development goals associated with each one of them, and targets that did not fit into the framework. Figures 1.5 and 1.6 show how the prioritization of SDGs is displayed, on the examples of the Kiribati and Ireland. Here, Ireland puts the emphasis on SDGs 11 and 9, and SDGs 1 and 16 are absent in its plan. The Kiribati's national development document prioritizes SDGs 8,9, 16 and 17 and SDGs 12 and 15 are absent.

¹⁰The tool can be accessed to using the following link: <https://sdg-explorer.onrender.com/>.

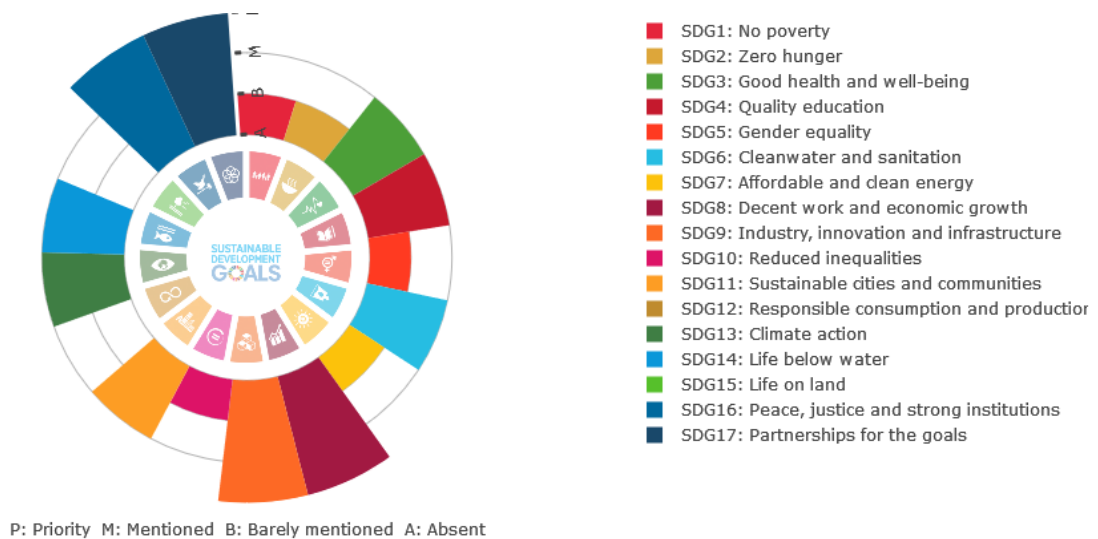
Figure 1.5: Level of priority given to each SDG in Ireland’s national long-term development document (National development plan 2018-2027)



SDGs are represented in the position they occupy in the SDG logo and the size of the bar indicates the level of priority accorded to a given SDG in the document according to our analysis – Absent (no bar), Barely mentioned (small bar), Mentioned (medium bar) and Priority (large bar).

1. MAPPING NATIONAL DEVELOPMENT PRIORITIES UNDER THE SUSTAINABLE DEVELOPMENT GOALS FRAMEWORK – A SYSTEMATIC ANALYSIS

Figure 1.6: Level of priority given to each SDG in Kiribati’s national long-term development document (20-year vision 2016-2036)



SDGs are represented in the position they occupy in the SDG logo and the size of the bar indicates the level of priority accorded to a given SDG in the document according to our analysis – Absent (no bar), Barely mentioned (small bar), Mentioned (medium bar) and Priority (large bar)

1.4 Conclusion - Discussion

In this chapter, we created an innovative typology by mapping national development documents (and their stated targets) using the SDGs as a basis, along with a visualisation tool. This enabled us to comment on the alignment between the international development context - SDGs – and national development goals, and complement a still emerging literature on the subject. In doing so, we tested two hypotheses:

- *All the development goals that can be found in countries' national long-term development documents fit under one or several SDG(s) (**H1**)*
- *Each country pursues in its national long-term development document, to some extent but simultaneously, every SDG (**H2**)*

Our results show that **H1** can be confirmed with a few exceptions, and **H2** is not confirmed, in that SDGs are differently prioritized across countries and some are not mentioned in all development documents.

Most national targets in development documents do fit into the SDG framework, under one or several SDGs, with marginal exceptions. The first exception concerns goals that could fit into the framework but focus on individual values, which tend to deviate from the global spirit of the SDG framework. The second exception concerns measures revolving around the increase in defence and military budgets. As is confirmed in the summary of discussions of expert meetings on the subject (OECD Expert meeting, 2019), these goals were not a part of the elaboration of the SDG framework. Among the reasons explaining this absence, a risk of distrust provoked by a securitized global development framework if such goals were to figure alongside cooperation and partnership goals. The third exception concerns documents targeting a limit to population growth (Pongiglione, 2015). The absence of such targets in the SDG framework could be explained by the difficulty of elaborating a target on what a “sustainable population growth” should be, given that some countries target an increase in order to maintain a sustainable population pyramid, and others target a decrease in that matter. Overall, these exceptions are present in documents originated both before and after the adoption of the 2030 Agenda.

This main result tends to validate **H1** and strengthen the idea of a universal SDG framework that provides an almost exhaustive mapping of the stated development priorities across the globe.

Some SDGs are largely more covered than others in the development documents, and there are many documents in which not all SDGs tend to appear, which invalidates hypothesis *H2*. Less developed countries tend to prioritize goals targeting the economy or governance more, whereas the most developed countries tend to prioritize and mention environmental goals more. This might be explained by the fact that most of the development documents for developed countries were produced after 2015 and the adoption of the 2030 Agenda. Before that, sustainable development was not integrated as deeply into the framework, which did not aim at being universal in terms of sectors covered or countries concerned – unlike the SDG framework. As for gender issues, older documents might not mention environmental issues as much, as these may have been treated separately in sectoral plans at the time because they had yet to be mainstreamed across various development issues. It is also relatively surprising to see that the Goals 6 or 7 (water, sanitation, and energy) are not widely prioritized and covered, which might also be explained by the existence of separate comprehensive sectoral plans as these issues have been widely identified and isolated as crucial for development (Smajgl et al., 2016) and for a long time. Further analyses including the publication year of the document and looking at sectoral plans could be completed in order to check for these hypotheses.

Still, hypothesis *H2* is rejected even for documents that were produced after 2015, mention the 2030 Agenda or are explicitly based on it. This result shows that countries might tend to cherry-pick between goals by excluding some of them, which goes against the aimed indivisibility of the framework. We interpret this as a result to the silo approach used to present SDGs that omits interlinkages between goals, but goes against the spirit of their “indivisible” nature.

Limits of our study were highlighted in the introduction and methods.

First, because of the importance of long-term development documents for international cooperation on development issues, development priorities presented in the national development documents of countries might show a natural alignment with the international context. This limit is mitigated by the facts that many documents featured in the database pre-date the adoption of the SDGs, and that SDGs were proposed in a bottom-up process. The fact that 25 documents produced after 2015 feature exceptions to the framework shows that the more recent documents do not necessarily align with the new framework. It could be further investigated by additional analyses on the elaboration processes of the documents of a few countries.

A few methods were presented to isolate development priorities of countries, each of them with limits, but using other sources than development documents might show very different results. Interesting next steps to enhance the robustness of these results might include comparing the mapping done for a few national development documents with priorities isolated in other contexts (laws, votes, sectoral plans, budget) in order to limit the possible effect of policy implementation gaps.

Finally, in order to build a database that could be as exhaustive as possible and include documents in other languages than english and with different structures, the mapping was done manually. The results are then sensitive to the criteria kept to attribute each national target to one or several SDG(s), and to determine the priority level associated with each SDG. To ensure their robustness, the criteria used were carefully reviewed and for a few documents the mappings done by different sources were compared and showed consistent results. Further strengthening these methods would imply a detailed analysis on each country, while the purpose of this particular study is to provide broad results on an extended set of countries.

Our conclusions provide interesting insights on the use of SDGs as a framework to think about all development issues, thus proving of particular policy relevance as our literature review shows it is used in a growing number of contexts.

Indeed, this study shows that in using the SDGs, most existing development targets would effectively be included in the framework. National targets in terms of defence and population, however, should be kept in mind as they might go unnoticed at the international level: as they do not fit into the framework, they might not appear in documents following its structure, which does not mean that these targets don't exist. This phenomenon could be identified by comparing the development priorities featured in national documents with exceptions to the ones displayed in the VNR communicated to the UN. It would indeed enable us to check whether these existing goals appear or not in a document with SDGs as an imposed framework. This result can also be kept in mind when setting the post-2030 agenda: although the current agenda provides a relevant mapping of development targets, better including these exceptions along with others that might appear until 2030 (e.g. targets on animal well-being), could be a future refinement.

Moreover, documents produced within the framework are relatively harmonized, with a set of indicators which may prove convenient in comparative work at the international level. However, in relation to the silo approach used to present SDGs, using it as a strict framework has an impact on how national targets appear to be prioritized.

Indeed, when based on the SDGs structure (listing targets SDG by SDG), the national documents tended to mention all the SDGs without reflecting any effective priority. However, most development documents that were published after 2015 and mention the 2030 Agenda do not explicitly follow the structure of the 17 SDGs. The targets are usually structured in a different way, with a narrative which leads to a prioritization of some goals compared to others. We do not argue for an exclusive use of SDGs as a way to structure such documents, as the current documents provide a clearer view on the national downscaling of the framework. It is however interesting to highlight that these narratives might result in the absence of given SDGs in the document. Yet, as an example, targets that involve the development of industrial or energy sectors without any mention to environmental sustainability technically fit into the industry-related SDGs, as the environmental indicators are in separate SDGs. This needs to be kept in mind as cherry-picking between goals has an impact on the overarching goal of the SDG framework. To easily identify and avoid this problem, a simple solution could be to encourage countries – as some already do - to add, in their development documents, a paragraph detailing how their development goals and narratives translate in terms of SDGs.

In addition to enabling us to discuss the relevance and universality of the SDG framework in light of its connections with national priorities, this work provides a database that may prove useful to inform further academic work in economic modelling, institutional economics, political science or environmental studies, both on international cooperation and on development planning. A visualization tool was additionally designed and linked to the study to facilitate the exploration of national priorities mapped within the SDG framework, for a high number of countries. We use them in Part II of this thesis work as a way to examine countries and their targets: we model the consistency between climate and economic development targets in Chapter 4, with the help of a Computable General Equilibrium model presented in Chapter 2 and used to study theoretical uncertainties in Chapter 3.

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II. Modelling synergies and trade-offs between development priorities and climate targets

Using CGE modelling to study development and climate targets – presentation of the KLEM modelling framework

Abstract

In this chapter, we introduce Computable General Equilibrium modelling, and its policy relevance in the context of this thesis work. We present the KLEM (Capital-Labour-Energy-Materials) modelling framework, which is the basis of the two models that will be used in Chapters 3 and 4. We provide an analytical description of the models, highlighting the differences between the static modelling framework used in Chapter 3 and the dynamic modelling framework used in Chapter 4. We also introduce the model variants related to different ways of "closing" the model, the consequences of which will be studied in more detail in Chapter 3. We finally present the generic calibration procedures of the models.

2.1 Introduction - climate, development, and CGE modelling

As mentioned in the introduction, while the alignment and tensions between climate and development policies have been studied from different perspectives at the international (Metz and Kok, 2015) or national (Alam et al., 2011; Hasan et al., 2020) scale, we focus on targets produced in these documents and their consistency at the national level, from a modelling perspective. By collecting development priorities and targets as expressed in national development documents in Chapter 1, we showed that the inclusion of climate-related subjects is not systematic: in more than 15% of the analyzed documents, targets that could be included in the Sustainable Development Goal on climate change were absent. As climate and development documents are usually produced by different institutions, there is little proof that the targets produced within both contexts are aligned. This question has been studied in detail for some large emitters (Dubash et al., 2018; Feng, X, 2019; Su et al., 2022) but remains open in other smaller countries where the data and targets available to build scenarios might be lacking: the second part of this thesis aims to propose a generic methodology that would provide first estimations to answer this question for a large panel of countries. In the present chapter, we introduce the modelling framework that is used in subsequent chapters to discuss the tensions and synergies between mitigation and development objectives. This framework is based on the KLEM computable general equilibrium (CGE) model.

To study the alignment and tensions between development targets and national climate mitigation targets, CGE models are a tool of choice. They are indeed particularly relevant in providing insights on the effects of various policies on select macroeconomic variables. Since their emergence in the 1960s (the first multi-sector CGE was produced by Leif Johansen (1960), applied on Norway), they have served as a workhorse for policy analysis, particularly in the fields of international trade, public finance, development economics and environmental economics (Ballard and Johnson, 2017).

CGE models stem from Léon Walras' general equilibrium theory, which proposes that a market economy reaches an equilibrium between supply and demand, through the adjustment of prices. They differ from the Input-Output models that preceded them (Leontief, 1936) in that the behavior of actors (households, industries) is explicated through optimizing assumptions (e.g. firms maximize their profits), and in that sectors are linked through economy-wide constraints (such as market clearing conditions). They are "applied" or "computable" in that their coefficients and parameters are based on real

data for a specific country/region, in order to simulate the behavior of that specific economy (Dixon et al., 1994). Data permitting, they can represent a single country, several countries or regions or be global, and cover a single or several periods (being static, or in recursive dynamics). They were popularized in the 1970s, as in opposition to macro-econometric models which are based on existing time-series data, they are rooted more deeply in economic theory. This makes it possible for them to give insights on consequences of shocks and policies that had not been experienced in the past - such as oil-related shocks (Nakata, 2004).

CGE models are useful to represent the impacts of changes in terms of, *inter alia*, trade, taxation, public expenditure, resources, infrastructures, on growth, industries, employment (Dixon and Jorgenson, 2013). They are thus particularly relevant to model development policies, but also environmental policies when they are likely to have general equilibrium effects. This is the case for climate change mitigation policies (Bergman, 2005), that can be translated for example with models that put the emphasis on an energy-sector (Burniaux and Truong, 2002; Medvedev and Van Der Mensbrugge, 2011). Other environmental policies can also be represented, notably for economies that are dependent on natural resources (Banerjee et al., 2016b), for example with models having a focus on fisheries (Akbari et al., 2023; Seung and Waters, 2010), forestry (Banerjee et al., 2016a) or water scarcity (Wittwer, 2012).

For this thesis, we use a KLEM (Capital-Labour-Energy-Materials) structure that was adapted from Hoffman and Jorgenson (1977), with two sectors (energy and non-energy). The KLEM dynamic model of an open economy computes macroeconomic trajectories with the specificity of exogenous energy flows and prices which makes it possible to translate climate targets and policies in terms of the evolution of energy-related parameters, thus having applications to economy-energy-environment studies (see for instance Soummane et al. (2019); Su et al. (2022)). In this thesis, we use two versions of the framework : one static version that we develop to analyze the sensitivity of the model results to macroeconomic closure options (Chapter 3), in which the energy sector is endogenous (constrained only by an energy consumption target), and an existing dynamic version¹ for the main purpose of the thesis (with a fully exogenous energy sector), namely analyzing the tensions and synergies between mitigation and development targets (Chapter 4). The two versions are presented in turn, starting with the static one in Section 2.2, then the dynamic one in Section 2.3.

¹Used to be coupled with the model POLES in Sarre (2021) (Masters' thesis available on request)

2.2 Presentation of the ‘KLEM’ static framework, and its model variants related to closure options

The KLEM framework that we use, in Chapter 3, for a discussion on closure options and their impact on a CGE model’s outputs, is static. It represents the changes brought by a change in an exogenous constraint on the domestic energy supply, which weighs on the rest of the economy (the rest of the energy sector of the static framework is thus endogenous). The issue of model closures was introduced by Amartya Sen (1963). He showed that general equilibrium models have more equations than variables if one wants to introduce a rule on investment, and that there are several ways to drop an equation or set one variable to ensure the model can be solved (which were later defined as "closure options" Taylor and Lysy (1979)). As will be explained further in Chapter 3, the motivation for this work on closures is that the choice of closure was shown, in trade and development economics, to have an impact on the results of CGE models (such as KLEM). The economic evaluation of the impact of mitigation policies might then be sensitive to assumptions about model closures. In Chapter 3, we thus describe and implement 8 closure options on the KLEM framework, to provide insights on the impacts of closures on an energy-economy CGE model. In this thesis, "KLEM variant" thus refers to each model resulting from a different choice of closure. Considering our purpose for this chapter, the choice of comparative statics and of such a level of compactness, compared to the extensiveness of multisectoral CGE models that usually produce national transition pathways in the literature, is meant as a way to provide first results on a simplified case, with little data needed and a simple calibration procedure (detailed in this section).

In Section 2.2.1, we present an analytical description of the static KLEM structure, summarize in Section 2.2.2 all 8 model variants associated with different closure options that we implement, along with all model notations, and finally present the model calibration and resolution in Section 2.2.3.

2.2.1 Analytical description and model variants

This section provides the set of equations of the KLEM variants used in Chapter 3. Notations follow common practice (and are detailed in Table 2.2 in Section 2.2.2). The paragraphs successively detail the production of the aggregate non-energy and energy resources, final consumption and investment, international trade, market clearings, price

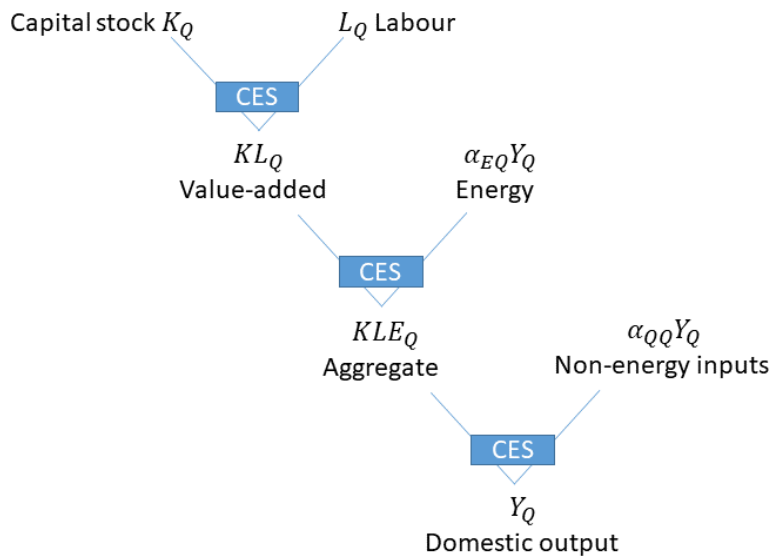
formation of the static models. Whenever required, good-specific variables are indexed by $i \in \{E, Q\}$, with E the energy good and Q the non-energy good.

To present the 8 model closures, we introduce a and b variants for equations (6), (10), (14), (20) and (21). Each of the 8 closure options is a different combination of a and b variants of these equations, which we summarize in Section 2.2.2.

Production structure

KLEM takes its name from its production structure, which is composed of nested Constant Elasticity of Substitution (CES) functions of capital (K), labor (L), energy (E) and materials (M, denoted as Q for composite), represented in Figure 2.1. For the production of sector i (i can be the energy sector or the non-energy sector), Capital K_i and Labour L_i are first aggregated into a value-added bundle KL_i , which is then aggregated with the energy inputs E_i (equivalent to the intermediate energy consumption $\alpha_{Ei}Y_i$ of sector i). The KLE_i bundle, once aggregated with non-energy intermediate consumptions $\alpha_{Qi}Y_i$, yields the domestic output Y_i .

Figure 2.1: Production structure of the non-energy good of the KLEM models



Let x and y be two inputs in this context. The generic CES aggregate z is written:

$$z = \left(\alpha_z x^{\frac{(\sigma_z-1)}{\sigma_z}} + \beta_z y^{\frac{(\sigma_z-1)}{\sigma_z}} \right)^{\frac{\sigma_z}{(\sigma_z-1)}}$$

Standard cost minimisation for the producers yields:

$$x = \left(\frac{\alpha_z}{p_x} \right)^{\sigma_z} \left(\alpha_z^{\sigma_z} p_x^{(1-\sigma_z)} + \beta_z^{\sigma_z} p_y^{(1-\sigma_z)} \right)^{\frac{\sigma_z}{(1-\sigma_z)}} z$$

$$y = \left(\frac{\beta_z}{p_y} \right)^{\sigma_z} \left(\alpha_z^{\sigma_z} p_x^{(1-\sigma_z)} + \beta_z^{\sigma_z} p_y^{(1-\sigma_z)} \right)^{\frac{\sigma_z}{(1-\sigma_z)}} z$$

where σ_z is a central elasticity parameter drawn from the literature; α_z and β_z are coefficients calibrated at reference year ($\alpha_z + \beta_z = 1$); and p_x and p_y the purchaser prices of goods x and y .

Final production: On top of the production structure, the previous formula applies to the production of the domestic output Y_i , which is a CES aggregate between the KLE_i bundle and non-energy input $\alpha_{Qi} Y_i$.

$$KLE_i = \left(\frac{\alpha_{Y,i}}{p_{KLE,i}} \right)^{\sigma_{Y,i}} \left(\alpha_{Y,i}^{\sigma_{Y,i}} p_{KLE,i}^{(1-\sigma_{Y,i})} + \beta_{Y,i}^{\sigma_{Y,i}} p_{Qi}^{(1-\sigma_{Y,i})} \right)^{\frac{\sigma_{Y,i}}{(1-\sigma_{Y,i})}} Y_i \quad (1)$$

$$\alpha_{Qi} Y_i = \left(\frac{\beta_{Y,i}}{p_{Qi}} \right)^{\sigma_{Y,i}} \left(\alpha_{Y,i}^{\sigma_{Y,i}} p_{KLE,i}^{(1-\sigma_{Y,i})} + \beta_{Y,i}^{\sigma_{Y,i}} p_{Qi}^{(1-\sigma_{Y,i})} \right)^{\frac{\sigma_{Y,i}}{(1-\sigma_{Y,i})}} Y_i \quad (2)$$

where $\sigma_{Y,i}$ is an elasticity parameter drawn from the literature; $\alpha_{Y,i}$ and $\beta_{Y,i}$ are coefficients calibrated at reference year ($\alpha_{Y,i} + \beta_{Y,i} = 1$); and $p_{KLE,i}$ and p_{Qi} the purchaser prices of KLE_i and Y_i .

Bundled demand for energy and value-added: KLE_i is a CES aggregate between value-added KL_i and energy $\alpha_{Ei} Y_i$:

$$KL_i = \left(\frac{\alpha_{KLE,i}}{p_{KL,i}} \right)^{\sigma_{KLE,i}} \left(\alpha_{KLE,i}^{\sigma_{KLE,i}} p_{KL,i}^{(1-\sigma_{KLE,i})} + \beta_{KLE,i}^{\sigma_{KLE,i}} p_{Ei}^{(1-\sigma_{KLE,i})} \right)^{\frac{\sigma_{KLE,i}}{(1-\sigma_{KLE,i})}} KLE_i \quad (3)$$

$$\alpha_{Ei} Y_i = \left(\frac{\beta_{KLE,i}}{p_{Ei}} \right)^{\sigma_{KLE,i}} \left(\alpha_{KLE,i}^{\sigma_{KLE,i}} p_{KL,i}^{(1-\sigma_{KLE,i})} + \beta_{KLE,i}^{\sigma_{KLE,i}} p_{Ei}^{(1-\sigma_{KLE,i})} \right)^{\frac{\sigma_{KLE,i}}{(1-\sigma_{KLE,i})}} KLE_i \quad (4)$$

where $\sigma_{KLE,i}$ is an elasticity parameter drawn from the literature; $\alpha_{KLE,i}$ and $\beta_{KLE,i}$ are coefficients calibrated at reference year ($\alpha_{KLE,i} + \beta_{KLE,i} = 1$); and $p_{KL,i}$ and p_{Ei} the purchaser prices of KL_i and Y_i .

Labour and capital demands: Capital K_i and labour L_i combine into value-added KL_i through a CES function, with $\sigma_{KL,i}$ the elasticity of substitution between the two. To allow for a possible disconnection between factor payments and productivities in some closure options, the CES relationship is modelled as follows:

$$KL_i = \left(\alpha_{KL,i} K_i^{\frac{(\sigma_{KL,i}-1)}{\sigma_{KL,i}}} + \beta_{KL,i} L_i^{\frac{(\sigma_{KL,i}-1)}{\sigma_{KL,i}}} \right)^{\frac{\sigma_{KL,i}}{(\sigma_{KL,i}-1)}} \quad (5)$$

where $\alpha_{KL,i}$ and $\beta_{KL,i}$ are coefficients calibrated at reference year ($\alpha_{KL,i} + \beta_{KL,i} = 1$); r is the rental cost of capital K_i and $p_{L,i}$ the cost of labour L_i .

Depending on the closure option, cost-minimisation is either warranted by setting L_i at the appropriate level:

$$L_i = \left(\frac{\beta_{KL,i}}{p_{L,i}} \right)^{\sigma_{KL,i}} \left(\alpha_{KL,i}^{\sigma_{KL,i}} r^{(1-\sigma_{KL,i})} + \beta_{KL,i}^{\sigma_{KL,i}} p_{L,i}^{(1-\sigma_{KL,i})} \right)^{\frac{\sigma_{KL,i}}{(1-\sigma_{KL,i})}} KL_i \quad (6a)$$

or is not enforced, in which case labour and capital inputs are allowed to adjust freely with the only constraint that the labour intensities of both productions evolve in parallel (as justified in Chapter 3):

$$\frac{L_Q}{KL_Q} = A_{KL} \frac{L_E}{KL_E} \quad (6b)$$

with A_{KL} the ratio of the two intensities at their calibration values.

Energy Supply

In the KLEM static framework, the main assumption is a control on domestic energy supply S_E , constrained as:

$$S_E = A_E \quad (7)$$

with A_E the targeted exogenous level of consumption. The sales tax on energy $\tau_{ST,E}$ (presented in the section on prices) then endogenously adjusts to meet this target.²

²In Chapter 3, we run the model for a large range of shocks of S_E , and look at the impact of the closure choice on the model outputs depending on the size of the shocks (i.e., the value of A_E).

Final demand

Public spending G_i is a constant share $\omega_{G,i}$ of GDP (nil by national accounting convention for energy goods *i.e.* $\omega_{G,E} = 0$):

$$p_{G,i} G_i = \omega_{G,i} GDP \quad (8)$$

where $p_{G,i}$ is the purchaser price of good i for public administrations.

Investment of the energy good is nil by convention:

$$I_E = 0 \quad (9)$$

Depending on model closures, investment of the non-energy good (total investment considering Equation 9) results either from savings (Equation 10a), or from exogenous investment effort at constant rate to GDP ω_I (Equation 10b):

$$p_{I,Q} I_Q = s_L \sum_{i \in \{Q,E\}} p_{L,i} L_i + s_K \sum_{i \in \{Q,E\}} r K_i + s_G \left(T - \sum_{i \in \{Q,E\}} p_{G,i} G_i \right) - B \quad (10a)$$

$$p_{I,Q} I_Q = \omega_I GDP \quad (10b)$$

where $p_{I,Q}$ is the purchaser price of good i for investment; s_L , s_K and s_G the saving rates on labour income, capital income and budget surplus; T the total taxes on output and consumption and B the trade balance.

Household consumptions of the non-energy and energy goods, C_Q and C_E , aggregate in a CES function to form household utility:

$$U = \left(\alpha_U C_Q^{\frac{(\sigma_U-1)}{\sigma_U}} + \beta_U C_E^{\frac{(\sigma_U-1)}{\sigma_U}} \right)^{\frac{\sigma_U}{(\sigma_U-1)}} \quad (11)$$

where α_U and β_U are coefficients calibrated at base year ($\alpha_U + \beta_U = 1$); and σ_U is an elasticity parameter adapted from the literature.

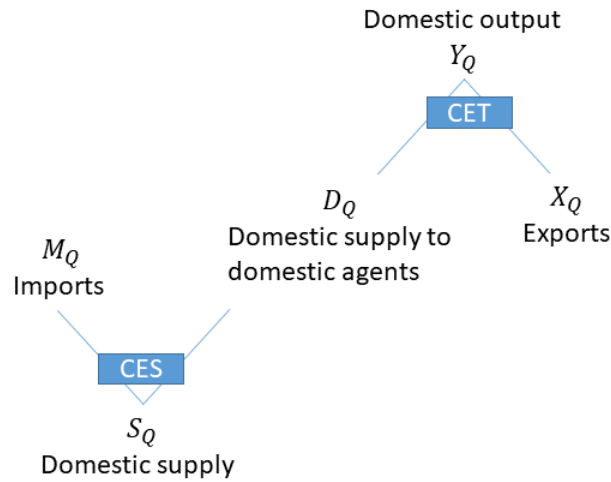
Facing prices $p_{C,i}$ and under constraint of consumption budget R , utility maximisation implies:

$$C_i = \left(\frac{\alpha_U}{p_{C,i}} \right)^{\sigma_U} \left(\alpha_U^{\sigma_U} p_{C,Q}^{(1-\sigma_U)} + \beta_U^{\sigma_U} p_{C,E}^{(1-\sigma_U)} \right)^{\frac{\sigma_U}{(1-\sigma_U)}} R \quad (12)$$

Trade

International trade is accounted for in the form of imports M_i and exports X_i , which link domestic output Y_i and domestic supply S_i . It follows Armington’s specification (Armington, 1969). Domestic output Y_i is distributed among exports X_i and domestic supply to domestic agents D_i following a constant elasticity of transformation (CET) function. There is a trade-off between D_i and the imports M_i in the domestic supply S_i , in the form of a CES function, as summarized in Figure 2.2 for the non-energy sector (and identical for the energy sector).

Figure 2.2: Trade-offs between domestic and international varieties of non-energy goods in the static KLEM variants



The trade balance B writes:

$$B = \sum_{i \in \{Q,E\}} p_{W,i} X_i - \sum_{i \in \{Q,E\}} p_{W,i} M_i \quad (13)$$

with X_i and M_i the exports and imports of good i , and where their prices are equal to a unique world price $p_{W,i}$

In most model variants, B mobilises a constant share of GDP ω_B via implicit adjustments of the real effective exchange rate:

$$B = \omega_B \text{ GDP} \quad (14a)$$

In one variant however, the trade balance adjusts to allow the volume of investment I_Q to evolve as the total capital stock K (through implicit adjustments of foreign savings):

$$\frac{I_Q}{K} = A_K \quad (14b)$$

Following Armington's specification of international trade (Armington, 1969), the trade-off between domestic purchases of domestic output D_i and imports M_i in the supply of domestic markets S_i is settled by a CES function (see Figure 2.2). D_i and M_i thus follow the generic form with respect to producing S_i the aggregate domestic demands, with elasticities $\sigma_{S,i}$, considering their prices $p_{D,i}$ and $p_{W,i}$ (and with coefficients $\alpha_{S,i}$ and $\beta_{S,i}$ calibrated at base year, $\alpha_{S,i} + \beta_{S,i} = 1$).

$$D_i = \left(\frac{\alpha_{S,i}}{p_{D,i}} \right)^{\sigma_{S,i}} \left(\alpha_{S,i}^{\sigma_{S,i}} p_{D,i}^{(1-\sigma_{S,i})} + \beta_{S,i}^{\sigma_{S,i}} p_{W,i}^{(1-\sigma_{S,i})} \right)^{\frac{\sigma_{S,i}}{(1-\sigma_{S,i})}} S_i \quad (15)$$

$$M_i = \left(\frac{\beta_{S,i}}{p_{W,i}} \right)^{\sigma_{S,i}} \left(\alpha_{S,i}^{\sigma_{S,i}} p_{D,i}^{(1-\sigma_{S,i})} + \beta_{S,i}^{\sigma_{S,i}} p_{W,i}^{(1-\sigma_{S,i})} \right)^{\frac{\sigma_{S,i}}{(1-\sigma_{S,i})}} S_i \quad (16)$$

Similarly, the competition between the supply of domestic markets D_i and exports X_i as outlets of domestic output Y_i is settled by constant elasticity of transformation functions (CET) with an elasticity $\sigma_{X,i}$ (and coefficients $\alpha_{X,i}$ and $\beta_{X,i}$ calibrated at base year, $\alpha_{X,i} + \beta_{X,i} = 1$). Usual CES algebra yields:

$$Y_i = \left(\alpha_{X,i} D_i^{\frac{(\sigma_{X,i}-1)}{\sigma_{X,i}}} + \beta_{X,i} X_i^{\frac{(\sigma_{X,i}-1)}{\sigma_{X,i}}} \right)^{\frac{\sigma_{X,i}}{(\sigma_{X,i}-1)}} \quad (17)$$

$$X_i = \left(\frac{\beta_{X,i}}{p_{W,i}} \right)^{\sigma_{X,i}} \left(\alpha_{X,i}^{\sigma_{X,i}} p_{D,i}^{(1-\sigma_{X,i})} + \beta_{X,i}^{\sigma_{X,i}} p_{W,i}^{(1-\sigma_{X,i})} \right)^{\frac{\sigma_{X,i}}{(1-\sigma_{X,i})}} Y_i \quad (18)$$

Market clearings

On the consumption side, S_i is distributed between households consumption C_i , intermediate consumptions, government spending G_i , and investment I_i .

Domestic market balance for each good i equates total supply to domestic markets S_i to the sum of intermediate consumptions $\alpha_{ij}Y_j$, household consumption C_i , consumption of public administrations G_i , consumption for investment I_i :

$$S_i = \sum_{j \in \{Q, E\}} \alpha_{ij}Y_j + C_i + G_i + I_i \quad (19)$$

On the labour market, in some model variants, unconstrained adjustments of wages w warrant balance, *i.e.* that the labour demands of productions L_i sum up to total exogenous labour supply L :

$$\sum_{i \in \{Q, E\}} L_i = L \quad (20a)$$

where labour consumption and output are conventionally related via λ_i , the labour intensity: $L_i = \lambda_i Y_i$.

In other variants, wage adjustments face social or institutional constraints, which results in equilibrium unemployment ($\sum_i L_i \neq L$). The ‘stickiness’ of real wages w is specified through a wage curve correlating real wage and the unemployment rate (as proposed based on labor theories developed in the 1980s, and evidenced by Blanchflower and Oswald (2005)), with an isoelasticity σ_w :

$$\frac{w}{CPI} = A_w B_w^{-\sigma_w} \left(\frac{L - \sum_{i \in \{Q, E\}} L_i}{L} \right)^{\sigma_w} \quad (20b)$$

where B_w is the calibration unemployment, A_w the calibration wage, CPI the consumer price index and $\frac{L - \sum_{i \in \{Q, E\}} L_i}{L}$ is the unemployment rate. The ‘fix price’ case of constant real wages corresponds to $\sigma_w = 0$.

In some model variants finally, the clearing of the labour market is removed and no variant of the equation (20) is used.

On the capital market in most model closures, demands by the two productions i sum up to total capital endowment K :

$$\sum_{i \in \{Q, E\}} K_i = K \quad (21a)$$

where capital consumption and output are conventionally related via κ_i , the capital intensity: $K_i = \kappa_i Y_i$.

Similarly to the above, some model variants rather consider a "sticky price" alternative where the ratio of the rental price of capital r to the price of investment $p_{I,Q}$ evolves in correlation to the idle capacity ratio:

$$\frac{r}{p_{I,Q}} = A_r B_r^{-\sigma_r} \left(\frac{K - \sum_{i \in \{Q,E\}} K_i}{K} \right)^{\sigma_r} \quad (21b)$$

where B_r is the calibration share of total capital stock that is idle, A_r the calibration ratio of r to p_{IQ} . The 'fix real interest rates' case corresponds to $\sigma_r = 0$.

Producer prices

Prices are governed by the CES or CET specifications, plus specific margins and taxes.³

Cost of labour $p_{L,i}$ is net wage w plus labour taxes at constant rates $\tau_{L,i}$:

$$p_{L,i} = (1 + \tau_{L,i}) w \quad (22)$$

To allow factor payments diverging from marginal factor productivity, the input price of aggregate value-added $p_{KL,i}$ does not follow the generic cost minimisation form deriving from the CES formulation, and rather builds on the accounting equation in both sectors:

$$p_{KL,i} KL_i = r K_i + p_{L,i} L_i \quad (23)$$

The price $p_{KLE,i}$ of CES aggregate KLE_i is the function of prices $p_{KL,i}$ and p_{Ei} (the purchaser price of good i input in the production of good j , more generally, being p_{ij}) deriving from cost minimisation:

$$p_{KLE,i} = \left(\alpha_{KLE,i}^{\sigma_{KLE,i}} p_{KL,i}^{(1-\sigma_{KLE,i})} + \beta_{KLE,i}^{\sigma_{KLE,i}} p_{Ei}^{(1-\sigma_{KLE,i})} \right)^{\frac{1}{(1-\sigma_{KLE,i})}} \quad (24)$$

³among them, an endogenous tax on domestic energy consumption that adjusts to reach the exogenous level of domestic energy supply.

The output price $p_{Y,i}$ increases the generic CES form with constant *ad valorem* output tax $\tau_{Y,i}$:

$$p_{Y,i} = \left(\alpha_{Y,i}^{\sigma_{Y,i}} p_{KLE,i}^{(1-\sigma_{Y,i})} + \beta_{Y,i}^{\sigma_{Y,i}} p_{Q,i}^{(1-\sigma_{Y,i})} \right)^{\frac{1}{(1-\sigma_{Y,i})}} (1 + \tau_{Y,i}) \quad (25)$$

All international prices are exogenous: the price of international composite good is the *numéraire* of the model, ($p_{W,Q} = 1$); the price of international energy relative to the price of the international composite good is exogenous ($p_{W,E}$ is calibrated at reference year).

Simultaneously, the price $p_{Y,i}$ proceeds from domestic and international prices, and reflect the CET specification of exports:

$$p_{Y,i} = \left(\alpha_{CET,i}^{\sigma_{CET,i}} p_{D,i}^{(1-\sigma_{CET,i})} + \beta_{CET,i}^{\sigma_{CET,i}} p_{W,i}^{(1-\sigma_{CET,i})} \right)^{\frac{1}{(1-\sigma_{CET,i})}} \quad (26)$$

The price $p_{S,i}$ of CES aggregate S_i is the generic function of prices $p_{D,i}$ and $p_{W,i}$ deriving from cost minimisation:

$$p_{S,i} = \left(\alpha_{S,i}^{\sigma_{S,i}} p_{D,i}^{(1-\sigma_{S,i})} + \beta_{S,i}^{\sigma_{S,i}} p_{W,i}^{(1-\sigma_{S,i})} \right)^{\frac{1}{(1-\sigma_{S,i})}} \quad (27)$$

Purchaser prices

The purchaser price of good i input in the production of good j (p_{ij}) is equal to the resource price $p_{S,i}$ augmented with *ad valorem* taxes and subsidies on products $\tau_{ST,i}$:

$$p_{ij} = p_{S,i} (1 + \tau_{ST,i}) \quad (28)$$

The consumer prices for households ($p_{C,i}$), public administrations ($p_{G,i}$) and investment ($p_{I,i}$) are equal to the resource price $p_{S,i}$ augmented with *ad valorem* net taxes and subsidies on products $\tau_{ST,i}$:

$$\forall x \in \{C, G, I\} \quad p_{x,i} = p_{S,i} (1 + \tau_{ST,i}) \quad (29)$$

The consumer price index CPI is computed according to Fisher's formula:

$$CPI = \sqrt{\frac{\sum_{i \in \{Q,E\}} p_{C,i} C_{i,0} \sum_{i \in \{Q,E\}} p_{C,i} C_i}{\sum_{i \in \{Q,E\}} p_{C,i,0} C_{i,0} \sum_{i \in \{Q,E\}} p_{C,i,0} C_i}} \quad (30)$$

where index 0 represents calibration year.

Accounting aggregates

GDP is defined on the expenditure side as:

$$GDP = R + \sum_{i \in \{Q,E\}} p_{G,i} G_i + \sum_{i \in \{Q,E\}} p_{I,i} I_i + B \quad (31)$$

Total tax revenue T is

$$T = \sum_{i \in \{Q,E\}} \tau_{L,i} w L_i + \frac{\tau_{Y,i}}{1 + \tau_{Y,i}} p_{Y,i} Y_i + \tau_i p_{S,i} S_i \quad (32)$$

2.2.2 Summary of the equations, closures and variables

KLEM static equations

$$KLE_i = \left(\frac{\alpha_{Y,i}}{p_{KLE,i}} \right)^{\sigma_{Y,i}} \left(\alpha_{Y,i}^{\sigma_{Y,i}} p_{KLE,i}^{(1-\sigma_{Y,i})} + \beta_{Y,i}^{\sigma_{Y,i}} p_{Q_i}^{(1-\sigma_{Y,i})} \right)^{\frac{\sigma_{Y,i}}{(1-\sigma_{Y,i})}} Y_i \quad (1)$$

$$\alpha_{Q_i} Y_i = \left(\frac{\beta_{Y,i}}{p_{Q_i}} \right)^{\sigma_{Y,i}} \left(\alpha_{Y,i}^{\sigma_{Y,i}} p_{KLE,i}^{(1-\sigma_{Y,i})} + \beta_{Y,i}^{\sigma_{Y,i}} p_{Q_i}^{(1-\sigma_{Y,i})} \right)^{\frac{\sigma_{Y,i}}{(1-\sigma_{Y,i})}} Y_i \quad (2)$$

$$KL_i = \left(\frac{\alpha_{KLE,i}}{p_{KL,i}} \right)^{\sigma_{KLE,i}} \left(\alpha_{KLE,i}^{\sigma_{KLE,i}} p_{KL,i}^{(1-\sigma_{KLE,i})} + \beta_{KLE,i}^{\sigma_{KLE,i}} p_{E_i}^{(1-\sigma_{KLE,i})} \right)^{\frac{\sigma_{KLE,i}}{(1-\sigma_{KLE,i})}} KLE_i \quad (3)$$

$$\alpha_{E_i} Y_i = \left(\frac{\beta_{KLE,i}}{p_{E_i}} \right)^{\sigma_{KLE,i}} \left(\alpha_{KLE,i}^{\sigma_{KLE,i}} p_{KL,i}^{(1-\sigma_{KLE,i})} + \beta_{KLE,i}^{\sigma_{KLE,i}} p_{E_i}^{(1-\sigma_{KLE,i})} \right)^{\frac{\sigma_{KLE,i}}{(1-\sigma_{KLE,i})}} KLE_i \quad (4)$$

$$KL_i = \left(\alpha_{KL,i} K_i^{\frac{(\sigma_{KL,i}-1)}{\sigma_{KL,i}}} + \beta_{KL,i} L_i^{\frac{(\sigma_{KL,i}-1)}{\sigma_{KL,i}}} \right)^{\frac{\sigma_{KL,i}}{(\sigma_{KL,i}-1)}} \quad (5)$$

$$L_i = \left(\frac{\beta_{KL,i}}{p_{L,i}} \right)^{\sigma_{KL,i}} \left(\alpha_{KL,i}^{\sigma_{KL,i}} r^{(1-\sigma_{KL,i})} + \beta_{KL,i}^{\sigma_{KL,i}} p_{L,i}^{(1-\sigma_{KL,i})} \right)^{\frac{\sigma_{KL,i}}{(1-\sigma_{KL,i})}} KL_i \quad (6a)$$

$$\frac{L_Q}{KL_Q} = A_{KL} \frac{L_E}{KLE_E} \quad (6b)$$

$$S_E = A_E \quad (7)$$

$$p_{G,i} G_i = \omega_{G_i} GDP \quad (8)$$

$$I_E = 0 \quad (9)$$

$$p_{I,Q} I_Q = s_L \sum_{i \in \{Q,E\}} p_{L,i} L_i + s_K \sum_{i \in \{Q,E\}} r K_i + s_G \left(T - \sum_{i \in \{Q,E\}} p_{G,i} G_i \right) - B \quad (10a)$$

$$p_{I,Q} I_Q = \omega_I GDP \quad (10b)$$

$$U = \left(\alpha_U C_Q^{\frac{(\sigma_U-1)}{\sigma_U}} + \beta_U C_E^{\frac{(\sigma_U-1)}{\sigma_U}} \right)^{\frac{\sigma_U}{(\sigma_U-1)}} \quad (11)$$

$$C_i = \left(\frac{\alpha_U}{p_{C,i}} \right)^{\sigma_U} \left(\alpha_U^{\sigma_U} p_{C,Q}^{(1-\sigma_U)} + \beta_U^{\sigma_U} p_{C,E}^{(1-\sigma_U)} \right)^{\frac{\sigma_U}{(1-\sigma_U)}} R \quad (12)$$

$$B = \sum_{i \in \{Q,E\}} p_{W,i} X_i - \sum_{i \in \{Q,E\}} p_{W,i} M_i \quad (13)$$

$$B = \omega_B \text{ GDP} \quad (14a)$$

$$\frac{I_Q}{K} = A_K \quad (14b)$$

$$D_i = \left(\frac{\alpha_{S,i}}{p_{D,i}} \right)^{\sigma_{S,i}} \left(\alpha_{S,i}^{\sigma_{S,i}} p_{D,i}^{(1-\sigma_{S,i})} + \beta_{S,i}^{\sigma_{S,i}} p_{W,i}^{(1-\sigma_{S,i})} \right)^{\frac{\sigma_{S,i}}{(1-\sigma_{S,i})}} S_i \quad (15)$$

$$M_i = \left(\frac{\beta_{S,i}}{p_{W,i}} \right)^{\sigma_{S,i}} \left(\alpha_{S,i}^{\sigma_{S,i}} p_{D,i}^{(1-\sigma_{S,i})} + \beta_{S,i}^{\sigma_{S,i}} p_{W,i}^{(1-\sigma_{S,i})} \right)^{\frac{\sigma_{S,i}}{(1-\sigma_{S,i})}} S_i \quad (16)$$

$$Y_i = \left(\alpha_{X,i} D_i^{\frac{(\sigma_{X,i}-1)}{\sigma_{X,i}}} + \beta_{X,i} X_i^{\frac{(\sigma_{X,i}-1)}{\sigma_{X,i}}} \right)^{\frac{\sigma_{X,i}}{(\sigma_{X,i}-1)}} \quad (17)$$

$$X_i = \left(\frac{\beta_{X,i}}{p_{W,i}} \right)^{\sigma_{X,i}} \left(\alpha_{X,i}^{\sigma_{X,i}} p_{D,i}^{(1-\sigma_{X,i})} + \beta_{X,i}^{\sigma_{X,i}} p_{W,i}^{(1-\sigma_{X,i})} \right)^{\frac{\sigma_{X,i}}{(1-\sigma_{X,i})}} Y_i \quad (18)$$

$$S_i = \sum_{j \in \{Q,E\}} \alpha_{ij} Y_j + C_i + G_i + I_i \quad (19)$$

$$\sum_{i \in \{Q,E\}} L_i = L \quad (20a)$$

$$\frac{w}{CPI} = A_w B_w^{-\sigma_w} \left(\frac{L - \sum_{i \in \{Q,E\}} L_i}{L} \right)^{\sigma_w} \quad (20b)$$

$$\sum_{i \in \{Q,E\}} K_i = K \quad (21a)$$

$$\frac{r}{p_{I,Q}} = A_r B_r^{-\sigma_r} \left(\frac{K - \sum_{i \in \{Q,E\}} K_i}{K} \right)^{\sigma_r} \quad (21b)$$

$$p_{L,i} = (1 + \tau_{L,i}) w \quad (22)$$

$$p_{KL,i} K L_i = r K_i + p_{L,i} L_i \quad (23)$$

$$p_{KLE,i} = \left(\alpha_{KLE,i}^{\sigma_{KLE,i}} p_{KL,i}^{(1-\sigma_{KLE,i})} + \beta_{KLE,i}^{\sigma_{KLE,i}} p_{E,i}^{(1-\sigma_{KLE,i})} \right)^{\frac{1}{(1-\sigma_{KLE,i})}} \quad (24)$$

$$p_{Y,i} = \left(\alpha_{Y,i}^{\sigma_{Y,i}} p_{KLE,i}^{(1-\sigma_{Y,i})} + \beta_{Y,i}^{\sigma_{Y,i}} p_{Q,i}^{(1-\sigma_{Y,i})} \right)^{\frac{1}{(1-\sigma_{Y,i})}} (1 + \tau_{Y,i}) \quad (25)$$

$$p_{Y,i} = \left(\alpha_{CET,i}^{\sigma_{CET,i}} p_{D,i}^{(1-\sigma_{CET,i})} + \beta_{CET,i}^{\sigma_{CET,i}} p_{W,i}^{(1-\sigma_{CET,i})} \right)^{\frac{1}{(1-\sigma_{CET,i})}} \quad (26)$$

$$p_{S,i} = \left(\alpha_{S,i}^{\sigma_{S,i}} p_{Y,i}^{(1-\sigma_{S,i})} + \beta_{S,i}^{\sigma_{S,i}} p_{W,i}^{(1-\sigma_{S,i})} \right)^{\frac{1}{(1-\sigma_{S,i})}} \quad (27)$$

$$p_{ij} = p_{S,i} (1 + \tau_{ST,i}) \quad (28)$$

$$\forall x \in \{C, G, I\} \quad p_{x,i} = p_{S,i} (1 + \tau_{ST,i}) \quad (29)$$

$$CPI = \sqrt{\frac{\sum_{i \in \{Q,E\}} p_{C,i} C_{i,0} \quad \sum_{i \in \{Q,E\}} p_{C,i} C_i}{\sum_{i \in \{Q,E\}} p_{C,i,0} C_{i,0} \quad \sum_{i \in \{Q,E\}} p_{C,i,0} C_i}} \quad (30)$$

$$GDP = R + \sum_{i \in \{Q,E\}} p_{G,i} G_i + \sum_{i \in \{Q,E\}} p_{I,i} I_i + B \quad (31)$$

$$T = \sum_{i \in \{Q,E\}} \tau_{L,i} w L_i + \frac{\tau_{Y,i}}{1 + \tau_{Y,i}} p_{Y,i} Y_i + \tau_i p_{S,i} S_i \quad (32)$$

Overview of the 8 closure options

Table 2.1: Closure options and market specifications of KLEM model variants

KLEM closure	Domestic savings	Investment	Foreign savings (Trade balance)	Labour market	Capital market	Primary factor payments	Equation variants
Neoclassical	Constant rates $s_L = s_K$, $s_G = 1$	Through closure	Constant GDP share	Flexprice	Flexprice	At marginal productivity	6a, 10a, 14a, 20a, 21a
Kaldorian	Constant rates $s_L = s_G = 1$, s_K calibrated	Constant GDP share	Constant GDP share	Flexprice	Flexprice	Through closure	6b, 10a, 10b, 14a, 20a, 21a
Johansen	Through closure	Constant GDP share	Constant GDP share	Flexprice	Flexprice	At marginal productivity	6a, 10b, 14a, 20a, 21a
Keynes-Marshall	Constant rates $s_L = s_K$, $s_G = 1$	Constant GDP share	Constant GDP share	Through closure	Flexprice	At marginal productivity	6a, 10a, 10b, 14a, 21a (neither 20a nor 20b)
Keynesian	Constant rates $s_L = s_K$, $s_G = 1$	Constant GDP share	Constant GDP share	Fixprice ($\sigma_w = 0$)	Flexprice	Through closure	6b, 10a, 10b, 14a, 20b, 21a
Keynes-Kaldor	Constant rates $s_L = s_G = 1$, s_K calibrated	Constant GDP share	Constant GDP share	Fixprice ($\sigma_w = 0$)	Flexprice	Through closure	6b, 10a, 10b, 14a, 20b, 21a
Neo-K1	Constant rates $s_L = s_K$, $s_G = 1$	Through closure	Constant GDP share	Sticky price ($\sigma_w = 0.1$)	Sticky price ($\sigma_K = 0.1$)	At marginal productivity	6a, 10a, 14a, 20b, 21b
Neo-K2	Constant rates $s_L = s_K$, $s_G = 1$	Constant ratio to K	Through closure	Sticky price ($\sigma_w = 0.1$)	Fixprice ($\sigma_K = 0$)	At marginal productivity	6a, 10a, 14b, 20b, 21b

See Chapter 3 for detailed justification and description of each closure rule

KLEM static framework notations

Table 2.2: Static KLEM notations

Notation	Description	Status in static KLEM
L	Labour endowment	1 parameter
K	Capital endowment	1 parameter
L_i	Volume of labour in good i production	2 variables
K_i	Capital stock in good i production	2 variables
KL_i	Value-added aggregate of K_i and L_i in the production of good i	2 variables
KLE_i	Aggregate of value-added KL_i and energy $\alpha_{E_i}Y_i$ in the production of good i	2 variables
C_i	Consumption of good i by households	2 variables
G_i	Consumption of good i by public administrations	2 variables
I_i	Investment of good i	2 variables
X_i	Exports of good i	2 variables
M_i	Imports of good i	2 variables
Y_i	Output of good i	2 variables
S_i	Total supply of good i to domestic market	2 variables
D_i	Domestic supply of good i to domestic market	2 variables
α_{ij}	Intensity of good j in good i	4 variables
w	Wage	1 variable
r	Rental price of capital	1 variable
$p_{KL,i}$	Price of value-added KL_i in good i production	2 variables
$p_{KLE,i}$	Price of KLE_i aggregate in good i production	2 variables
$p_{L,i}$	Labour cost in good i production	2 variables
$p_{Y,i}$	Producer price of good i	2 variables
$p_{S,i}$	Price of total supply of good i to domestic market	2 variables
$p_{D,i}$	Price of domestic supply of good i to domestic market	2 variables
p_{ij}	Purchaser price of good i used in the production of good j	4 variables

2. USING CGE MODELLING TO STUDY DEVELOPMENT AND CLIMATE TARGETS –
PRESENTATION OF THE KLEM MODEL(S)

Notation	Description	Status in static KLEM
$p_{C,i}$	Purchaser price of good i for households	2 variables
$p_{G,i}$	Purchaser price of good i for public administrations	2 variables
$p_{I,i}$	Purchaser price of good i for investment	2 variables
$p_{W,i}$	World price of good i	2 parameters
B	Trade balance	1 variable
GDP	Gross Domestic Product	1 variable
R	Households' consumption budget	1 variable
T	Total taxes on output and consumption	1 variable
U	Households' utility	1 variable
CPI	Consumer Price Index	1 variable
s_L	Saving rate on labour income	1 parameter
s_K	Saving rate on capital income	1 parameter
s_G	Saving rate on budget surplus	1 parameter
ω_I	Investment effort as GDP share	1 parameter
$\omega_{G,i}$	Public spending in sector i as GDP share	2 parameters ($\omega_{G,E}=0$)
ω_B	Trade balance as GDP share	1 parameter
$\alpha_{KL,i}$	Coefficient of K_i in the KL_i CES function	2 parameters
$\beta_{KL,i}$	Coefficient of L_i in the KL_i CES function	2 parameters
$\sigma_{KL,i}$	Elasticity of substitution of K_i and L_i in producing KL_i	2 parameters
$\alpha_{KLE,i}$	Coefficient of KL_i in the KLE_i CES function	2 parameters
$\beta_{KLE,i}$	Coefficient of $\alpha_{E_i} Y_i$ in the KLE_i CES function	2 parameters
$\sigma_{KLE,i}$	Elasticity of substitution of KL_i and $\alpha_{E_i} Y_i$ in producing KLE_i	2 parameters

2.2. Presentation of the ‘KLEM’ static framework, and its model variants related to closure options

Notation	Description	Status in static KLEM
$\alpha_{Y,i}$	Coefficient of KLE_i in the Y_i CES function	2 parameters
$\beta_{Y,i}$	Coefficient of $\alpha_{Q_i} Y_i$ in the Y_i CES function	2 parameters
$\sigma_{Y,i}$	Elasticity of substitution of KLE_i and $\alpha_{Q_i} Y_i$ in producing Y_i	2 parameters
α_U	Coefficient of C_Q in the CES utility function	2 parameters
β_U	Coefficient of C_E in the CES utility function	2 parameters
σ_U	Elasticity of substitution of C_Q and C_E in delivering U	1 parameter
$\alpha_{S,i}$	Coefficient of D_i in the CES trade function	2 parameters
$\beta_{S,i}$	Coefficient of M_i in the CES trade function	2 parameters
$\sigma_{S,i}$	Elasticity of substitution of domestic and imported varieties of good i	2 parameters
$\alpha_{X,i}$	Coefficient of D_i in the CES trade function	2 parameters
$\beta_{X,i}$	Coefficient of X_i in the CES trade function	2 parameters
$\sigma_{X,i}$	Elasticity to terms-of-trade of good i exports	1 parameter
$\tau_{L,i}$	Labour tax on good i production	2 parameters
$\tau_{Y,i}$	Output tax on good i production	2 parameters
$\tau_{ST,i}$	Sales tax on good i domestic sales	1 parameter $\tau_{ST,Q}$ 1 variable $\tau_{ST,E}$

2.2.3 Calibration and model resolution

Input-output table

All variants of the KLEM static framework are calibrated on an aggregate 2-sector 2-factor input-output (IO) table, the generic form of which is presented in Table 2.3. Calibration builds on the correspondence of economic flows and products of model variables.⁴ The numerical values of the IO table used to calibrate the model in Chapter 3, as well the elasticities of substitution, are presented in the Appendices of Chapter 3.

Table 2.3: Correspondence of national accounting totals and products of model variables for static KLEM variants

	Non-E	E	C	G	I	X
Non-Energy	$p_{QQ} \alpha_{QQ} Y_Q$	$p_{QE} \alpha_{QE} Y_E$	$p_{C,Q} C_Q$	$p_{G,Q} G_Q$	$p_{I,Q} I_Q$	$p_{X,Q} X_Q$
Energy	$p_{EQ} \alpha_{EQ} Y_Q$	$p_{EE} \alpha_{EE} Y_E$	$p_{C,E} C_E$	-	-	$p_{X,E} X_E$
Labour payments	$p_{L,Q} L_Q$	$p_{L,E} L_E$				
L taxes	$\tau_{L,Q} w L_Q$	$\tau_{L,E} w L_E$				
K payments	$r K_Q$	$r K_E$				
Output taxes	$\frac{\tau_{Y,Q}}{1+\tau_{Y,Q}} p_{Y,Q} Y_Q$	$\frac{\tau_{Y,E}}{1+\tau_{Y,E}} p_{Y,E} Y_E$				
Imports	$p_{M,Q} M_Q$	$p_{M,E} M_E$				
Sales taxes	$\tau_Q p_{S,Q} S_Q$	$\tau_E p_{S,E} S_E$				

Model resolution

All static KLEM variants count 59 scalar variables, and 59 constraints: Equations 1, 2, 3, 4, 5, 6 (a variant), 8, 12, 15, 16, 17, 18, 19, 22, 23, 24, 25, 26 and 27 cover both sectors i.e. define 38 constraints; Equations 7, 9, 10 (a and b variants), 11, 13, 14 (a and b variants), 20 (a and b variants), 21 (a and b variants), 30, 31 and 32 define 11 constraints; Equations 28 and 29 apply to 5 user prices of each production i.e. define 10 constraints. Equation 6 stands out because its 6a variant concerns both sectors (2 constraints) while its 6b variant covers them both simultaneously as 1 constraint only.

⁴We calibrate under the assumption of normalised utility U and prices $p_{Y,i}$, $p_{W,i}$, $p_{S,i}$, $p_{D,i}$, w , r , $p_{KL,i}$, $p_{KLE,i}$.

Models that enforce 6b rather than 6a also enforce two variants of one other equation additionally (see Table 3.1).

The model is programmed and solved using Microsoft Excel's Solver add-in, through an iterative resolution process aimed at minimizing errors with a predetermined threshold of 10^{-6} . The fact that the model can be numerically solved guarantees the existence of a solution. The unicity of this solution has not been formally established, but the convergence towards the same solution from very contrasting starting points tends to support this hypothesis.

2.3 Presentation of the KLEM dynamic framework

In Chapter 4, we discuss the compatibility between countries' energy-related climate mitigation targets featured in their Nationally Determined Contributions, and some of their economic development targets as displayed in their national development plans and visions. To this end, we use the KLEM dynamic framework, which simulates economic growth in yearly time steps, and is characterized by a full exogeneity of its energy sector. The constraint is not only on domestic energy supply (as in the static framework), but on several energy volumes and prices (regarding imports, exports, intermediate consumptions and the consumption of households). This difference allows the KLEM dynamic framework to embark energy systems pathways given exogenously. Previous versions of the KLEM model have been soft-linked with national or global energy system models such as POLES (Sarre, 2021), KSA (Soummane et al., 2019) or MAPLE (Su et al., 2022).

Similar to the static framework, the KLEM dynamic framework has two sectors (energy, and non-energy). The production structure of its non-energy sector is composed of nested Constant Elasticity of Substitution (CES) functions, represented in Figure 2.1. A two-sector model allows for a relatively simple calibration procedure and is thus well suited to the exercise, to ease the implementation on many countries (with little targets needed to build scenarios). Building on the analysis developed in Chapter 3, we develop results for two variants of the KLEM dynamic framework to examine the sensitivity of the results to two model closures (neoclassical and Johansen).

In Section 2.3.1, we present the equations of the KLEM dynamic framework. We summarize equations in Section 2.3.2 along with all model notations, and present the model calibration and resolution in Section 2.3.3.

2.3.1 Description of the dynamic KLEM structure and model variants

This section presents the equations, of the KLEM dynamic framework, that differ from the KLEM static framework. Notations are similar to Section 2.2.1 (additional variables and parameters are summarized in Table 2.4) and the numbering of equations corresponds to the one in the static framework. New equations are numbered with asterisks and replace equations with the same number in the static framework. For example, equation (1*) in the dynamic framework replaces equation (1) in the static one. As in the static framework, whenever required, good-specific variables are indexed $i \in \{E, Q\}$, with E the energy good and Q the non-energy good. As the model is dynamic, all equations are valid at each time step and indexed by t , but the time index is omitted except when necessary. As above, some equations have a and b variants, the combination of which constitute different closure options that were detailed in Section 2.2.1.

Non-energy Production

At each given year, the **non-energy production** Q in the dynamic KLEM framework is similar to the production structure of the KLEM static framework: Capital K_Q and Labour L_Q are aggregated into a value-added bundle KL_Q , which is then aggregated with energy inputs E_Q (equivalent to the intermediate energy consumption $\alpha_{EQ}Y_Q$ of the non-energy sector). The KLE_Q bundle, once aggregated with non-energy intermediate consumptions of the non-energy sector $\alpha_{QQ}Y_Q$, yields the domestic output Y_Q .

Final production: As in the static framework, the domestic output Y_Q is a CES aggregate between the KLE_Q bundle and non-energy input $\alpha_{QQ} Y_Q$. In addition to equations of the static framework, the non-energy input is augmented by a productivity factor ϕ_{QQ} (to translate changes in the productivity of materials in the non-energy sector).

This leads to:

$$KLE_Q = \left(\frac{\alpha_{Y,Q}}{p_{KLE,Q}} \right)^{\sigma_{Y,Q}} \left(\alpha_{Y,Q}^{\sigma_{Y,Q}} p_{KLE,Q}^{(1-\sigma_{Y,Q})} + \beta_{Y,Q}^{\sigma_{Y,Q}} \left(\frac{p_{QQ}}{\phi_{QQ}} \right)^{(1-\sigma_{Y,Q})} \right)^{\frac{\sigma_{Y,Q}}{(1-\sigma_{Y,Q})}} Y_Q \quad (1^*)$$

$$\alpha_{QQ} Y_Q = \frac{1}{\phi_{QQ}} \left(\frac{\phi_{QQ} \beta_{Y,Q}}{p_{QQ}} \right)^{\sigma_{Y,Q}} \left(\alpha_{Y,Q}^{\sigma_{Y,Q}} p_{KLE,Q}^{(1-\sigma_{Y,Q})} + \beta_{Y,Q}^{\sigma_{Y,Q}} \left(\frac{p_{QQ}}{\phi_{QQ}} \right)^{(1-\sigma_{Y,Q})} \right)^{\frac{\sigma_{Y,Q}}{(1-\sigma_{Y,Q})}} Y_Q \quad (2^*)$$

where $\sigma_{Y,Q}$ is an elasticity parameter drawn from the literature; $\alpha_{Y,Q}$ and $\beta_{Y,Q}$ are coefficients calibrated at base year ($\alpha_{Y,Q} + \beta_{Y,Q} = 1$); and $p_{KLE,Q}$ and p_{QQ} the purchaser prices of KLE_Q and Y_Q .

Bundled demand for energy and value-added: In the static KLEM framework, KLE_Q is a CES aggregate between value-added KL_Q and energy $\alpha_{EQ} Y_Q$, and follows generic formulation under a cost-minimisation program. In the KLEM dynamic framework, $\alpha_{EQ} Y_Q$ is augmented by a productivity factor ϕ_{EQ} (to translate changes in the productivity of energy in the non-energy sector) and is constrained, which drops the cost-minimisation program and yields:

$$KLE_Q = \left(\alpha_{KLE,Q} KL_Q^{\frac{(\sigma_{KLE,Q}-1)}{\sigma_{KLE,Q}}} + \beta_{KLE,Q} (\phi_{EQ} \alpha_{EQ} Y_Q)^{\frac{(\sigma_{KLE,Q}-1)}{\sigma_{KLE,Q}}} \right)^{\frac{\sigma_{KLE,Q}}{(\sigma_{KLE,Q}-1)}}$$

Thus, equations (3) and (4) of the previous framework are here replaced with:

$$KL_Q = \left(\frac{KLE_Q^{\frac{(\sigma_{KLE,Q}-1)}{\sigma_{KLE,Q}}}}{\alpha_{KLE,Q}} + \frac{\beta_{KLE,Q}}{\alpha_{KLE,Q}} (\phi_{EQ} \alpha_{EQ} Y_Q)^{\frac{(\sigma_{KLE,Q}-1)}{\sigma_{KLE,Q}}} \right)^{\frac{\sigma_{KLE,Q}}{(\sigma_{KLE,Q}-1)}} \quad (3^*)$$

where $\sigma_{KLE,Q}$ is an elasticity parameter drawn from the literature; and $\alpha_{KLE,Q}$ and $\beta_{KLE,Q}$ are coefficients calibrated at base year ($\alpha_{KLE,Q} + \beta_{KLE,Q} = 1$).

Labour and capital demands: As in the KLEM static framework, primary factor inputs capital K_Q and labour L_Q combine into value-added KL_Q through a CES function, with a $\sigma_{KL,Q}$ elasticity of substitution. To allow for a possible disconnection between factor payments and productivities in some closure options, the CES relationship is modelled as such for all variants:

$$KL_Q = \left(\alpha_{KL,Q} (\phi_{K,Q} K_Q)^{\frac{(\sigma_{KL,Q}-1)}{\sigma_{KL,Q}}} + \beta_{KL,Q} (\phi_{L,Q} L_Q)^{\frac{(\sigma_{KL,Q}-1)}{\sigma_{KL,Q}}} \right)^{\frac{\sigma_{KL,Q}}{(\sigma_{KL,Q}-1)}} \quad (5^*)$$

where $\alpha_{KL,Q}$ and $\beta_{KL,Q}$ are coefficients calibrated at base year; r the rental cost of capital K_Q and $p_{L,Q}$ the cost of labour L_Q ; and $\phi_{K,Q}$ and $\phi_{L,Q}$ productivity factors that translate changes in the productivity of labour and capital in the non-energy sector.

Cost minimisation is warranted by the endogenous adjustment of L_Q at the appropriate level:

$$L_Q = \frac{1}{\phi_{L,Q}} \left(\frac{\phi_{L,Q} \beta_{KL,Q}}{p_{L,Q}} \right)^{\sigma_{KL,Q}} \times \left(\alpha_{KL,Q}^{\sigma_{KL,Q}} \left(\frac{r}{\phi_{K,Q}} \right)^{(1-\sigma_{KL,Q})} + \beta_{KL,Q}^{\sigma_{KL,Q}} \left(\frac{p_{L,Q}}{\phi_{L,Q}} \right)^{(1-\sigma_{KL,Q})} \right)^{\frac{\sigma_{KL,Q}}{(1-\sigma_{KL,Q})}} KL_Q \quad (6a^*)$$

There is no (6b*) variant in the KLEM dynamic framework, as we do not implement Kaldorian, Keynesian and Keynes-Kaldor closures in Chapter 4.

Energy Supply

In the **dynamic KLEM framework**, the energy production and consumption is exogenous. The only required equation on the production side sets exogenous primary energy inputs E_E and E_Q in both sectors E and Q :

$$E_i = \alpha_{Ei} Y_i \quad (7^*)$$

Final demand

As in the static framework, public spending G_i is a constant share $\omega_{G,i}$ of GDP (by national accounting convention for energy goods, $\omega_{G,E} = 0$):

$$p_{G,i} G_i = \omega_{G,i} GDP \quad (8^*)$$

where $p_{G,i}$ is the purchaser price of good i for public administrations.

Similarly, investment of the energy good is nil at base year by convention, and remains so at all time steps:

$$I_E = 0 \quad (9^*)$$

Depending on model closures, investment of the non-energy good (which is also total investment given Equation 9*) comes either from savings (Equation 10a*), or from an exogenously determined investment effort at constant rate to GDP ω_I (Equation 10b*):

$$p_{I,Q} I_Q = s_L \sum_{i \in \{Q,E\}} p_{L,i} L_i + s_K \sum_{i \in \{Q,E\}} r K_i + s_G \left(T - \sum_{i \in \{Q,E\}} p_{G,i} G_i \right) - B \quad (10a^*)$$

$$p_{I,Q} I_Q = \omega_I GDP \quad (10b^*)$$

where $p_{I,Q}$ is the purchaser price of good i for investment; s_L , s_K and s_G the saving rates on labour income, capital income and budget surplus; T the total taxes on output and consumption and B the trade balance.

Household consumption of energy C_E is exogenous in the KLEM dynamic framework. The household consumption of non-energy goods C_Q derives from the constraint of consumption budget R which replaces equations (11) and (12):

$$\sum_{i \in \{Q,E\}} p_{C,i} C_i = R \quad (11^*)$$

Trade

As in the KLEM static framework, the trade balance B writes:

$$B = \sum_{i \in \{Q,E\}} p_{X,i} X_i - \sum_{i \in \{Q,E\}} p_{M,i} M_i \quad (13^*)$$

with X_i and M_i the exports and imports of good i , and $p_{X,i}$ and $p_{M,i}$ their prices.

B mobilises a constant share of GDP ω_B via implicit adjustments of the real effective exchange rate:

$$B = \omega_B GDP \quad (14a^*)$$

There is no (14b*) variant in the KLEM dynamic framework, as we do not implement the Neo-K2 closure in Chapter 4.

Imports M_i link domestic output Y_i and domestic supply S_i . Unlike in the static framework, S_i is a simple sum of imports M_i and production Y_i . Equation (15*) thus replaces equations (15) and (16) of the static framework with:

$$S_i = M_i + Y_i \quad (15^*)$$

As noted above, energy imports and exports M_E and X_E are exogenous in the KLEM dynamic framework. For the non-energy good, the share of imports M_Q and of exports X_Q in total supply S_Q are elastic to terms-of-trade, with elasticities $\sigma_{M,p}$ and $\sigma_{X,p}$ (and A_M and A_X constants):⁵

$$\frac{M_Q}{S_Q} = A_M \left(\frac{p_{Y,Q}}{p_{M,Q}} \right)^{\sigma_{M,p}} \quad (17^*)$$

$$\frac{X_Q}{S_Q} = A_X \left(\frac{p_{X,Q}}{p_{M,Q}} \right)^{\sigma_{X,p}} \quad (18^*)$$

⁵This difference with the KLEM static framework comes from the fact that in the dynamic framework, we use a pre-existing KLEM model in which this specification is implemented. For the static framework, as we implemented more model closures than existed before in the model, we also implemented CES/CET specifications following Armington (1969).

Market clearings

Since imports and exports are not handled through CES/CET functions, the market balance for each good i in the dynamic framework stems from the definition of total domestic supply S_i , which is distributed among the households consumption C_i , intermediate consumptions, government spending G_i , investment I_i , and exports X_i :

$$S_i = \sum_{j \in \{Q, E\}} \alpha_{ij} Y_j + C_i + G_i + I_i + X_i \quad (19^*)$$

On the labour market, labor supply and demand are balanced via unconstrained adjustments of wages w , taking into account an exogenous unemployment rate u :

$$\sum_{i \in \{Q, E\}} L_i = L(1 - u) \quad (20a^*)$$

where labour consumption and output are conventionally related via λ_i , the labour intensity: $L_i = \lambda_i Y_i$.

There is no (20b*) variant in the KLEM dynamic framework, as we do not implement Keynesian, Keynes-Kaldor, Neo-K1 and Neo-K2 closures in Chapter 4.

As in the static framework, on the capital market, demands by the two productions i sum up to total capital endowment K :

$$\sum_{i \in \{Q, E\}} K_i = K \quad (21a^*)$$

where capital consumption and output are conventionally related via κ_i , the capital intensity: $K_Q = \kappa_Q Y_Q$ and the production of energy good K_E is constrained by the depreciation rate δ introduced later, $K_{E,t} = \max((1 - \delta)K_{E,t-1}, \kappa_E Y_E)$

There is no (21b*) variant in the KLEM dynamic framework, as we do not implement Neo-K1 and Neo-K2 closures in Chapter 4.

Producer prices

As quantities, prices are governed by the CES or CET specifications, plus specific margins and taxes. The dynamic frameworks, however, includes exogenous prices for the energy sector.

In both sectors, cost of labour $p_{L,i}$ is net wage w plus labour taxes at constant rates $\tau_{L,i}$:

$$p_{L,i} = (1 + \tau_{L,i}) w \quad (22^*)$$

To allow factor payments diverging from marginal factor productivity, the input price of aggregate value-added $p_{KL,i}$ does not follow the generic cost minimisation form deriving from the CES formulation, and rather builds on the accounting equation in the non-energy sector:

$$p_{KL,Q} KL_Q = r K_Q + p_{L,Q} L_Q \quad (23^*)$$

Unlike in the KLEM static framework, $\alpha_{EQ} Y_Q$ is exogenously fixed as E_Q . $p_{KLE,E}$ is not explicited and $p_{KLE,Q}$ is not a CES aggregate but is directly inferred from the following equation (so the price of the KLE bundle is the quantity weighted average of the KL and E aggregates):

$$p_{KLE,Q} KLE_Q = p_{KL,Q} KL_Q + p_{EQ} E_Q \quad (24^*)$$

Output price $p_{Y,i}$ increases the generic form with constant *ad valorem* output tax $\tau_{Y,i}$ as well as a constant rent mark-up $\tau_{R,Q}$.⁶ For the energy good, the producer price is the sum of production costs, which transforms equation (25) of the static framework into two equations:

$$p_{Y,Q}(1 - \tau_{Y,Q} - \tau_{R,Q}) = \left(\alpha_{Y,Q}^{\sigma_{Y,Q}} p_{KLE,Q}^{(1-\sigma_{Y,Q})} + \beta_{Y,Q}^{\sigma_{Y,Q}} \left(\frac{p_{Qi}}{\phi_{Qi}} \right)^{(1-\sigma_{Y,i})} \right)^{\frac{1}{(1-\sigma_{Y,i})}} \quad (25^*)$$

$$p_{Y,E} = p_{QE}\alpha_{QE} + p_{EE}\alpha_{EE} + p_{L,E}\lambda_E + p_K\kappa_E + \tau_{R,E}p_{Y,E} + \tau_{Y,E}p_{Y,E} \quad (25 \text{ bis}^*)$$

⁶A difference between the static and dynamic variants of the model is that in our implementation of the static variants, we consider that the the costs without taxes are the tax base, whereas in the dynamic variants, the price including taxes constitutes the tax base. This does not bear major consequences on the results of the models.

All import prices are exogenous: the price of international composite good is the *numéraire* of the model and is thus constant ($p_{M,Q} = 1$); the price of international energy relative to that of the international composite good $p_{M,E}$ is exogenous. Unlike in the static framework, the price $p_{Y,i}$ does not reflect the CET specification of exports (equation (26) of the static framework does not hold in recursive dynamics). The average supply price of good i , $p_{S,i}$, derives from:

$$p_{S,i}S_i = p_{Y,i}Y_i + p_{M,i}M_i \quad (27^*)$$

Purchaser prices

The purchaser price of good i input in the production of good j (p_{ij}) is equal to the resource price $p_{S,i}$ augmented with *ad valorem* net taxes and subsidies on products $\tau_{ST,i}$, and, conversely to the static framework, to agent-specific margins $\tau_{MS,ij}$:

$$p_{ij} = p_{S,i} (1 + \tau_{ST,i})(1 + \tau_{MS,ij}) \quad (28^*)$$

The consumer prices for households ($p_{C,i}$), public administrations ($p_{G,i}$) and investment ($p_{I,i}$) are equal to the resource price $p_{S,i}$ augmented with *ad valorem* net taxes and subsidies on products $\tau_{ST,i}$, and, conversely to the static framework, specific margins $\tau_{MSx,i}$:

$$\forall x \in \{C, G, I\} \quad p_{x,i} = p_{S,i} (1 + \tau_{ST,i})(1 + \tau_{MSx,i}) \quad (29^*)$$

Unlike in the static framework where all international prices are exogenous, the export prices for the non-energy good are here constructed in a similar way as in equation (29*) without sales taxes, which yields an additional equation:

$$p_{X,Q} = p_{S,i} (1 + \tau_{MSX,Q}) \quad (29 \text{ bis}^*)$$

In the case of the energy good, the price $p_{X,E}$ is exogenous and the specific margin $\tau_{MSX,E}$ adapts to its value.

The consumer price index CPI is computed according to Fisher's formula:

$$CPI_t = CPI_{t-1} \sqrt{\frac{\sum p_{C,i} C_{i,t-1} \sum p_{C,i,t} C_{i,t}}{\sum p_{C,i,t-1} C_{i,t-1} \sum p_{C,i,t-1} C_{i,t}}} \quad (30^*)$$

where $CPI_0 = 1$.

An import price index MPI is also computed according to Fisher's formula, which yields an additional equation:

$$MPI_t = MPI_{t-1} \sqrt{\frac{\sum p_{M,i} M_{i,t-1} \sum p_{M,i,t} M_{i,t}}{\sum p_{M,i,t-1} M_{i,t-1} \sum p_{M,i,t-1} M_{i,t}}} \quad (30 \text{ bis}^*)$$

Accounting aggregates

GDP is defined on the expenditure side as:

$$GDP = R + \sum_{i \in \{Q,E\}} p_{G,i} G_i + \sum_{i \in \{Q,E\}} p_{I,i} I_i + B \quad (31^*)$$

Total tax income T is:

$$T = \sum_i \tau_{L,i} w L_i + \tau_{Y,i} p_{Y,i} Y_i + \frac{\tau_{ST,i}}{1 + \tau_{ST,i}} \left(\sum_{j \in \{Q,E\}} p_{ij} \alpha_{ij} Y_j + p_{C,i} C_i + p_{G,i} G_i + p_{I,i} I_i \right) + \tau_i p_{S_i} S_i \quad (32^*)$$

Capital dynamics in the recursive dynamic model variants

In the dynamic framework, a standard accumulation rule defines the trajectory of the capital stock for each year t as:

$$K_{t+1} = (1 - \delta)K_t + I_{Q,t} \quad (33^*)$$

where δ is the rate of capital depreciation, fixed at 4% by default (following the GTAP model).⁷

⁷This equation is not, per se, a part of the general equilibrium system as it describes capital dynamics from one step to the next in recursive dynamics.

2.3.2 Summary of the equations and variables

Equations of the dynamic KLEM framework

Here, the details of Johansen and Neoclassical closure options are not repeated as they follow closure options presented in Section 2.2.2.

$$KLE_Q = \left(\frac{\alpha_{Y,Q}}{p_{KLE,Q}} \right)^{\sigma_{Y,Q}} \left(\alpha_{Y,Q}^{\sigma_{Y,Q}} p_{KLE,Q}^{(1-\sigma_{Y,Q})} + \beta_{Y,Q}^{\sigma_{Y,Q}} \left(\frac{p_{QQ}}{\phi_{QQ}} \right)^{(1-\sigma_{Y,Q})} \right)^{\frac{\sigma_{Y,Q}}{(1-\sigma_{Y,Q})}} Y_Q \quad (1^*)$$

$$\alpha_{QQ} Y_Q = \frac{1}{\phi_{QQ}} \left(\frac{\phi_{QQ} \beta_{Y,Q}}{p_{QQ}} \right)^{\sigma_{Y,Q}} \left(\alpha_{Y,Q}^{\sigma_{Y,Q}} p_{KLE,Q}^{(1-\sigma_{Y,Q})} + \beta_{Y,Q}^{\sigma_{Y,Q}} \left(\frac{p_{QQ}}{\phi_{QQ}} \right)^{(1-\sigma_{Y,Q})} \right)^{\frac{\sigma_{Y,Q}}{(1-\sigma_{Y,Q})}} Y_Q \quad (2^*)$$

$$KL_Q = \left(\frac{KLE_Q^{\frac{(\sigma_{KLE,Q}-1)}{\sigma_{KLE,Q}}}}{\alpha_{KLE,Q}} + \frac{\beta_{KLE,Q}}{\alpha_{KLE,Q}} (\phi_{EQ} \alpha_{EQ} Y_Q)^{\frac{(\sigma_{KLE,Q}-1)}{\sigma_{KLE,Q}}} \right)^{\frac{\sigma_{KLE,Q}}{(\sigma_{KLE,Q}-1)}} \quad (3^*)$$

$$KL_Q = \left(\alpha_{KL,Q} (\phi_{K,Q} K_Q)^{\frac{(\sigma_{KL,Q}-1)}{\sigma_{KL,Q}}} + \beta_{KL,Q} (\phi_{L,Q} L_Q)^{\frac{(\sigma_{KL,Q}-1)}{\sigma_{KL,Q}}} \right)^{\frac{\sigma_{KL,Q}}{(\sigma_{KL,Q}-1)}} \quad (5^*)$$

$$L_Q = \frac{1}{\phi_{L,Q}} \left(\frac{\phi_{L,Q} \beta_{KL,Q}}{p_{L,Q}} \right)^{\sigma_{KL,Q}} \times \left(\alpha_{KL,Q}^{\sigma_{KL,Q}} \left(\frac{r}{\phi_{K,Q}} \right)^{(1-\sigma_{KL,Q})} + \beta_{KL,Q}^{\sigma_{KL,Q}} \left(\frac{p_{L,Q}}{\phi_{L,Q}} \right)^{(1-\sigma_{KL,Q})} \right)^{\frac{\sigma_{KL,Q}}{(1-\sigma_{KL,Q})}} KL_Q \quad (6a^*)$$

$$E_i = \alpha_{Ei} Y_i \quad (7^*)$$

$$p_{G,i} G_i = \omega_{Gi} GDP \quad (8^*)$$

$$I_E = 0 \quad (9^*)$$

$$p_{I,Q} I_Q = s_L \sum_{i \in \{Q,E\}} p_{L,i} L_i + s_K \sum_{i \in \{Q,E\}} r K_i + s_G \left(T - \sum_{i \in \{Q,E\}} p_{G,i} G_i \right) - B \quad (10a^*)$$

$$p_{I,Q} I_Q = \omega_I GDP \quad (10b^*)$$

$$\sum_{i \in \{Q,E\}} p_{C,i} C_i = R \quad (11^*)$$

$$B = \sum_{i \in \{Q,E\}} p_{X,i} X_i - \sum_{i \in \{Q,E\}} p_{M,i} M_i \quad (13^*)$$

$$B = \omega_B \text{ GDP} \quad (14a^*)$$

$$S_i = M_i + Y_i \quad (15^*)$$

$$\frac{M_Q}{S_Q} = A_M \left(\frac{p_{Y,Q}}{p_{M,Q}} \right)^{\sigma_{M,p}} \quad (17^*)$$

$$\frac{X_Q}{S_Q} = A_X \left(\frac{p_{X,Q}}{p_{M,Q}} \right)^{\sigma_{X,p}} \quad (18^*)$$

$$S_i = \sum_{j \in \{Q,E\}} \alpha_{ij} Y_j + C_i + G_i + I_i + X_i \quad (19^*)$$

$$\sum_{i \in \{Q,E\}} L_i = L(1 - u) \quad (20a^*)$$

$$\sum_{i \in \{Q,E\}} K_i = K \quad (21a^*)$$

$$p_{L,i} = (1 + \tau_{L,i}) w \quad (22^*)$$

$$p_{KL,Q} KL_Q = r K_Q + p_{L,Q} L_Q \quad (23^*)$$

$$p_{KLE,Q} KLE_Q = p_{KL,Q} KL_Q + p_{EQ} E_Q \quad (24^*)$$

$$p_{Y,Q}(1 - \tau_{Y,Q} - \tau_{R,Q}) = \left(\alpha_{Y,Q}^{\sigma_{Y,Q}} p_{KLE,Q}^{(1-\sigma_{Y,Q})} + \beta_{Y,Q}^{\sigma_{Y,Q}} \left(\frac{p_{Q,i}}{\phi_{Q,i}} \right)^{(1-\sigma_{Y,i})} \right)^{\frac{1}{(1-\sigma_{Y,i})}} \quad (25^*)$$

$$p_{Y,E} = p_{QE} \alpha_{QE} + p_{EE} \alpha_{EE} + p_{L,E} \lambda_E + p_{K} \kappa_E + \tau_{R,E} p_{Y,E} + \tau_{Y,E} p_{Y,E} \quad (25 \text{ bis}^*)$$

$$p_{S,i} S_i = p_{Y,i} Y_i + p_{M,i} M_i \quad (27^*)$$

$$p_{ij} = p_{S,i} (1 + \tau_{ST,i})(1 + \tau_{MS,ij}) \quad (28^*)$$

$$\forall x \in \{C, G, I\} \quad p_{x,i} = p_{S,i} (1 + \tau_{ST,i})(1 + \tau_{MSx,i}) \quad (29^*)$$

$$p_{X,Q} = p_{S,i} (1 + \tau_{MSX,Q}) \quad (29 \text{ bis}^*)$$

$$CPI_t = CPI_{t-1} \sqrt{\frac{\sum p_{C,i} C_{i,t-1} \quad \sum p_{C,i,t} C_{i,t}}{\sum p_{C,i,t-1} C_{i,t-1} \quad \sum p_{C,i,t-1} C_{i,t}}} \quad (30^*)$$

$$MPI_t = MPI_{t-1} \sqrt{\frac{\sum p_{M,i} M_{i,t-1} \quad \sum p_{M,i,t} M_{i,t}}{\sum p_{M,i,t-1} M_{i,t-1} \quad \sum p_{M,i,t-1} M_{i,t}}} \quad (30 \text{ bis}^*)$$

$$GDP = R + \sum_{i \in \{Q,E\}} p_{G,i} G_i + \sum_{i \in \{Q,E\}} p_{I,i} I_i + B \quad (31^*)$$

$$T = \sum_i \tau_{L,i} w L_i + \tau_{Y,i} p_{Y,i} Y_i + \frac{\tau_{ST,i}}{1 + \tau_{ST,i}} \left(\sum_{j \in \{Q,E\}} p_{ij} \alpha_{ij} Y_j + p_{C,i} C_i + p_{G,i} G_i + p_{I,i} I_i \right) + \tau_i p_{S,i} S_i \quad (32^*)$$

$$K_{t+1} = (1 - \delta)K_t + I_{Q,t} \quad (33^*)$$

Notations in the dynamic framework

Table 2.4: KLEM notations in recursive dynamics

Notation	Description	Status in recursive dynamics
L	Labour endowment	1 parameter
K	Capital endowment	1 parameter (dynamic evolution)
L_i	Volume of labour in good i production	2 variables
K_i	Capital stock in good i production	2 variables
KL_Q	Value-added aggregate of K_Q and L_Q in the production of good Q	1 variable
KLE_Q	Aggregate of value-added KL_Q and energy $\alpha_{EQ}Y_Q$ in the production of good Q	1 variable
C_i	Consumption of good i by households	1 var. C_Q 1 param. C_E
G_i	Consumption of good i by public administrations	2 variables
I_i	Investment of good i	2 variables
X_i	Exports of good i	1 var. X_Q 1 param. X_E
M_i	Imports of good i	1 var. M_Q 1 param. M_E
Y_i	Output of good i	2 variables
S_i	Total supply of good i to domestic market	2 variables
α_{ij}	Intensity of good j in good i	3 var. α_{QQ} α_{EE} α_{EQ} 1 param. α_{QE}
w	Wage	1 variable
r	Rental price of capital	1 variable
$p_{KL,Q}$	Price of value-added KL_Q in good Q production	1 var. $p_{KL,Q}$
$p_{KLE,Q}$	Price of KLE_Q aggregate in good Q production	1 var. $p_{KLE,Q}$
$p_{L,i}$	Labour cost in good i production	2 variables

Notations/statuses that differ from the static framework are highlighted in grey.

2.3. Presentation of the KLEM dynamic framework

Notation	Description	Status in Recursive dynamics
$p_{Y,i}$	Producer price of good i	2 variables
$p_{S,i}$	Price of total supply of good i to domestic market	2 variables
p_{ij}	Purchaser price of good i used in the production of good j	2 var. p_{Qj} 2 param. p_{Ej}
$p_{C,i}$	Purchaser price of good i for households	1 var. $p_{C,Q}$ 1 param. $p_{C,E}$
$p_{G,i}$	Purchaser price of good i for public administrations	2 variables
$p_{I,i}$	Purchaser price of good i for investment	2 variables
$p_{X,i}$	Export price of good i	1 var. $p_{X,Q}$ 1 param. $p_{X,E}$
$p_{M,i}$	Import price of good i	2 parameters ($p_{M,Q}$ numéraire)
B	Trade balance	1 variable
GDP	Gross Domestic Product	1 variable
R	Households' consumption budget	1 variable
T	Total taxes on output and consumption	1 variable
CPI	Consumer Price Index	1 variable
MPI	Import Price Index	1 variable
s_L	Saving rate on labour income	1 parameter
s_K	Saving rate on capital income	1 parameter
s_G	Saving rate on budget surplus	1 parameter
ω_I	Investment effort as GDP share	1 parameter
$\omega_{G,i}$	Public spending in sector i as GDP share	2 parameters ($\omega_{G,E}=0$)
ω_B	Trade balance as GDP share	1 parameter
ϕ_{QQ}	Productivity of materials in sector Q (index 1 in base year)	1 parameter
ϕ_{EQ}	Productivity of energy in sector Q (index 1 in base year)	1 parameter
ϕ_L	Productivity of labour in both sectors (index 1 in base year)	1 parameter
$\phi_{K,i}$	Productivity of capital in sector Q (index 1 in base year)	1 parameter
$\alpha_{KL,Q}$	Coefficient of K_Q in the KL_Q CES function	1 parameter
$\beta_{KL,Q}$	Coefficient of L_Q in the KL_Q CES function	1 parameter
$\sigma_{KL,Q}$	Elasticity of substitution of K_Q and L_Q in producing KL_Q	1 parameter

Notation	Description	Status in Recursive dynamics
$\alpha_{KLE,Q}$	Coefficient of KL_Q in the KLE_Q CES function	1 parameter
$\beta_{KLE,Q}$	Coefficient of $\alpha_{EQ} Y_Q$ in the KLE_Q CES function	1 parameter
$\sigma_{KLE,Q}$	Elasticity of substitution of KL_Q and $\alpha_{EQ} Y_Q$ in producing KLE_Q	1 parameter
$\alpha_{Y,Q}$	Coefficient of KLE_Q in the Y_Q CES function	1 parameter
$\beta_{Y,Q}$	Coefficient of $\alpha_{QQ} Y_Q$ in the Y_Q CES function	1 parameter
$\sigma_{Y,Q}$	Elasticity of substitution of KLE_Q and $\alpha_{QQ} Y_Q$ in producing Y_Q	1 parameter
δ	Depreciation rate of the capital stock	1 parameter
$\tau_{L,i}$	Labour tax on good i production	2 parameters
$\tau_{Y,i}$	Output tax on good i production	2 parameters
$\tau_{,Ri}$	Constant rent mark-up in good i production	2 parameters
$\tau_{ST,i}$	Sales tax on good i domestic sales	2 parameters
$\tau_{MS,ij}$	Specific margin on good i sales to good j production	4 parameters
$\tau_{MSC,j}$	Specific margin on good i sales to households	2 parameters
$\tau_{MSX,j}$	Specific margin on good i exports	2 parameters

Exogenous assumptions

In addition to exogenous assumptions about the energy sector, the KLEM dynamic framework is based on a set of exogenous assumptions driving economic growth. Namely,

- the evolution of labour endowment L over time (usually derived from labour force projections);
- the evolution of labour productivity ϕ_L over time (usually derived from labour force and GDP projections);
- the evolution of the unemployment rate over time;
- the evolution of the investment rate;
- the evolution of the trade balance to GDP ω_B ;

- and in some modelling exercises, assumptions on the evolutions of capital productivity $\phi_{K,Q}$, energy productivity $\phi_{E,Q}$ and materials productivity $\phi_{Q,Q}$ that can be introduced.⁸

All the names of variables and parameters of the models are listed in Table 2.4, and the specific values, sources and assumptions on these variables for each national variants are listed in Chapter 4.

2.3.3 Calibration and model resolution

Input-output table

All variants of the KLEM structure mobilised in this paper are calibrated on data in the form of aggregate 2-sector 2-factor input-output (IO) tables, the generic form of which is presented in Table 2.3. Calibration builds on the correspondence of economic flows and products of model variables. Notations are those of the KLEM description of Section 2.3.1 with indexes Q and E indicating the non-energy and energy sectors, respectively. The numerical values of the IO tables used to calibrate the model in Chapter 4, as well the elasticities of substitution, are featured in the Appendices of Chapter 4.

Calibration of the capital stock

The standard practice for a calibration procedure is to invert parameters and variables and solve the model equations to get the value of the calibrated parameters. However, at base year in the dynamic variants of KLEM, there is no reference for the capital stocks. We compute it using the following formula:

$$K_0 = I_{Q,0} \frac{1}{\delta + g_1}$$

in which δ is the depreciation rate, equal to 4% by default, and g_1 is the potential growth rate during the first period (and derives from the growths of labour supply and productivity).

Model resolution

All KLEM variants in recursive dynamics count 44 scalar variables, and 44 constraints (the lower number, relative to the static framework, stems from the full exogeneity of

⁸This is of particular relevance in the modelling work presented in Chapter 4.

Table 2.5: Correspondence of national accounting totals and products of model variables for KLEM variants in recursive dynamics

	Non-E	E	C	G	I	X				
Non-Energy	p_{QQ}	$\alpha_{QQ} Y_Q$	$p_{C,Q}$	C_Q	$p_{G,Q}$	G_Q	$p_{I,Q}$	I_Q	$p_{X,Q}$	X_Q
Energy	p_{EQ}	$\alpha_{EQ} Y_Q$	$p_{C,E}$	C_E	-	-	$p_{X,E}$	X_E		
Labour payments	$p_{L,Q}$	L_Q	$p_{L,E}$	L_E						
L taxes	$\tau_{L,Q}$	$w L_Q$	$\tau_{L,E}$	$w L_E$						
K payments	r	K_Q	r	K_E						
Output taxes	$\tau_{Y,Q}$	$p_{Y,Q} Y_Q$	$\tau_{Y,E}$	$p_{Y,E} Y_E$						
Rent	$\tau_{R,Q}$	$p_{Y,Q} Y_Q$	$\tau_{R,E}$	$p_{Y,E} Y_E$						
SM use in Q	-	$\tau_{MSE,Q}$	$p_{S,E}$	$\alpha_{QE} Y_E$						
SM use in E	-	$\tau_{MSE,E}$	$p_{S,E}$	$\alpha_{EE} Y_E$						
SM use in C	-	$\tau_{MSC,E}$	$p_{S,E}$	Y_E						
SM use in G	-	-								
SM use in I	-	-								
SM use in X	-	$\tau_{MSX,E}$	$p_{S,E}$	X_E						
Imports	$p_{M,Q}$	M_Q	$p_{M,E}$	M_E						
Sales taxes	τ_Q	$p_{S,Q} S_Q$	τ_E	$p_{S,E} S_E$						

the energy sector): Equations 7, 8, 15, 19, 22, 25, and 27 cover both sectors i.e. define 14 constraints; Equations 1, 2, 3, 5, 6, 9, 10, 11, 13, 14, 17, 18, 20, 21, 23, 24, 30, 30 bis, 31 and 32 define 20 constraints; Equations 28 and 29 apply to 5 user prices of each production i.e. define 10 constraints.

The model is solved numerically (due to non-linear constraints) using Microsoft Excel's Solver add-in, through an iterative resolution process aimed at minimizing errors with a predetermined threshold of 10^{-6} . The numerical solubility guarantees the existence of a solution. The uniqueness of this solution was not formally established, but the convergence towards the same solution from very contrasting starting points (values of the variables) tends to support this hypothesis.

Closing models, opening debates: theoretical uncertainty and the low-carbon transition

This chapter is adapted from joint work with Frédéric Gherzi, Louis Daumas, Soline Ralite, Julien Lefèvre and Gaëlle le Treut (CIRED)

Abstract

This chapter builds upon the observation that the Energy-Economy-Environment (E3) literature has largely left aside the question of model ‘closure’ options and the underlying economic theories in the building of macroeconomic models or modules. The fact is all the more surprising as the Computable General Equilibrium (CGE) communities of other branches of economics have long been concerned with such issues. From Amartya Sen’s seminal article in 1963, the question of the effects of model “closures”, i.e., ways to write the causal structure of a given CGE, has indeed elicited intense discussions. The aim of the following work is to put these two literatures together in order to sketch the effect of “closures” on the behaviour of E3 models. To this end, we implement the stylized Capital-Labour-Energy-Material (KLEM) computable general equilibrium model and test a spectrum of energy consumption reduction targets, using different causality structures. Our results show that model outcomes depend highly on how KLEM is closed. This leads to our conclusions that relying quasi-exclusively on one set of assumptions may present an artificially unified picture of transition possibilities, and that alternative model closures should be further explored across E3 studies.

Contributions:

Frederic Gherzi: Conceptualization, Methodology, Investigation, Programming, Data collection and curation, Analysis, Writing (original draft), Visualization, Supervision

Louis Daumas, Auriane Meiland, Soline Ralite: Methodology, Investigation, Programming, Analysis, Writing (original draft), Visualization

Julien Lefèvre, Gaëlle le Treut: Conceptualization, Analysis, Writing (review)

3.1 Introduction

Energy-Economy-Environment (E3) modelling, by producing quantitatively detailed low-carbon transition trajectories, is highly relevant to climate change policy-making. E3 models are widely mentioned in the IPCC Working Group III reports (Pörtner et al., 2022). Some of them represent macroeconomic dynamics, and to do so they mostly rely on computable general equilibrium (CGE) methods.

As discussed in Chapter 2, Computable General Equilibrium (CGE) models gained influence in the 1970s as substitutes to Keynesian ‘structural’ models in the wake of Lucas’s critique (Lucas, 1976). They have been used widely in the fields of trade (Löfgren et al., 2001) and development economics (Dervis et al., 1989).¹ However, despite their growing popularity, CGE models have raised criticisms early on, around a specific type of uncertainty. As early as in 1979, Taylor and Lysy showed that the same CGE model could accommodate several causality structures, notably in the relationship between savings and investment (Taylor and Lysy, 1979). Calling “closure” these various causality structures, Taylor and Lysy revived a discussion originally put forward by Amartya Sen.²

In a theoretical article (Sen, 1963), Sen made the observation that general equilibrium models are overdetermined, i.e. have more equations than variables, if one wants to introduce an autonomous or exogenous investment rule (Zalai and Révész, 2016).³ To ensure the model has the same number of equations and variables, one can either drop another equation, or exogenously set one variable. This choice in turn determines the causality structure - e.g. which variables adjust to accommodate for constraints-, or “closure”, of the model. Sen contended that it related to different theories of income distribution as proposed by Kaldor (1955). Importantly, he further argued that none of these theories could be chosen *ex ante* over any other, leaving the final causality structure of the model to the preference of the modeller.

Sen, however, did not try to explore the quantitative consequences of these “closures”. Taylor and Lysy (1979) were the first to do so. Using a compact CGE model applied to Brazil, they showed that the model results and reactions to a nominal

¹More recent, stochastic versions like DSGEs or RBCs are rather employed in central banking (Grandjean and Giraud, 2017).

²And also, to a certain extent, by Stephen Marglin (Marglin, 1976). Note also that previous publications had started to touch upon the issue, without going as far as Taylor and Lysy (Adelman and Robinson, 1989; Lluch, 1979).

³An exogenous investment takes a determined value or trajectory of values. An autonomous investment, here, refers to investment set as a fraction of the GDP, which is an endogenous variable.

wage shock were different depending on the closure. They concluded that the choice of closure was crucial, from an economic standpoint but also politically, if models are used for policy advice.

This research gave rise to many discussions within the CGE literature. Subsequent papers, summarized hereafter, performed similar experiments and expanded the range of possible closures. Rattsø (1982) explores the four closures proposed by Sen within two distinct models. Closures have roughly similar effects on both, suggesting that the study of closures to one given model does have some general validity. Decaluwé et al. (1987) show similar results. Dervis et al. (1989) extend these studies to an intertemporal framework, questioning whether closures should be understood in the short or the long run. Dewatripont and Michel (1987) show that closures can also be understood as ways to give relatively more importance to price or income effects. Robinson (1989) discusses the relevance of the closure issue in light of institutional contexts and the focus of analysis. These debates were reactivated by Taylor and Von Arnim (2007) and Taylor (2004), who noticed that international organisations (the International Monetary Fund, the World Bank) only used closures inspired by neoclassical assumptions and highlighted possible biases in policy recommendations.⁴ More recently, Zalai and Révész (2016) revisited the issue with a large number of closures and discussed their quantitative outcomes, again showing that different closures yield different results.⁵

Apart from a few incursions on the subject (Chisari and Miller, 2015; Gillingham et al., 2018), the E3 modelling literature has remained largely impervious to such discussions - even among work focusing on uncertainties (Rotmans and van Asselt, 2001; Marangoni et al., 2017). Looking at 3762 articles reporting country-level carbon mitigation pathways (Lepault and Lecocq, 2021), out of 585 mentioning the use of a model in their abstract, only 7% explicit the “closure” of the model underlying their analyses. The rest of them apply presumably, “by default”, a neoclassical closure. Indeed, apart from a few exceptions, such as IMACLIM-R (Bibas et al., 2016), which displays strong neo-Keynesian leanings, most IPCC-quoted top-down models (such as WITCH (Bosetti et al., 2007), AIM-CGE (Fujimori et al., 2017), etc.) exhibit clear neoclassical causality structures. It is also the case for models outside the

⁴From then, Ezaki (2006) and Delpiazzo (2010) provide further reappraisals of the closure issue.

⁵The authors dub their closures “macro-closures”, in a bid to separate them from the way to organise the macroeconomic causality structure of an economy from behavioural assumptions at the microeconomic level. Albeit very sound, we leave aside this dichotomy and understand “closures” as “macro(economic) closures” throughout the present thesis.

academic sphere, again with some exceptions (such as Three-ME (Callonnec et al., 2013), GEMMES (Bovari et al., 2018), NEMESIS (SEURECO, 2018)).

As put by Mitra-Kahn (2008), the “closure issue” would have remained an intellectual curiosity, had the quantitative outcomes of the application of different causality structures been of little consequence. The above discussion shows that this is not the case. Because E3 models provide insights to policymakers, relying exclusively on a single causality structure may give a partial picture of transition possibilities and costs, with possibly significant biases in the assessment of adequate policy responses — all the more so as the energy transition is a first-order macroeconomic shock (general increase of energy prices combined with several GDP points investment shock). Our work aims at shedding a new light on the ‘closure’ question in the energy policy context, by providing insights on how the numerical outcomes of a static, compact and stylised E3 model evolve when different closure rules are applied.

The present chapter is organized as follows. Section 3.2 provides a brief presentation of Sen’s initial approach and closures. Section 3.3 shows how the issue translates in the more complex but still stylized KLEM model presented in Chapter 2. Section 3.4 details our methods to numerically implement 8 closures in KLEM, and the performed diagnostic. Section 3.5 describes the outcomes of the model depending on the implemented closures. Section 3.6 concludes with a discussion on closures and uncertainty in the context of E3 modelling, its implications for climate policies, and prospects for future research.

3.2 Sen’s framing of the closure issue

Taylor and Von Arnim (2007) define model ‘closure’ as “CGE jargon for assigning causality in a model. The practice often boils down to deciding which variables should be exogenous or endogenous (or which equations should be included or excluded) to make sure the model is ‘closed’ or has a solution, like a typical problem from high school algebra.” This definition applies well to Sen’s seminal contribution (Sen, 1963), which proposes four such ‘closures’ of a simple macroeconomic model of two factors and one product.

The model initially counts five equations:

- (S1) the production function links the product and the two factors,
- (S2) the wage rate equates the marginal product of the labour factor,
- (S3) profits and wages exhaust total product,
- (S4) total investment equates total savings, and
- (S5) investment follows some exogenous rule.

However, it only counts four variables: output, investment, the wage rate and the profit rate (See Box 1).

Box 1. Sen's seminal introduction to the closure issue (Sen, 1963)

Notations are altered to reflect CGE usage taken up in the formulation of KLEM (see Section 3.3). Equations are numbered with an initial S to avoid confusion with KLEM equations in Chapter 2.

$$(S1) \quad KL = f(K, L)$$

$$(S2) \quad w = \frac{\partial f}{\partial L}$$

$$(S3) \quad KL = wL + rK$$

$$(S4) \quad I = s_L wL + s_K rK$$

$$(S5) \quad I = I^*$$

Sen's model has 5 equations but 4 variables: output (value-added) KL , wage rate w , profit rate r and investment I (labour and capital endowments L and K and the saving rates s_L and s_K are parameters). **Neo-classical** closure solves by dropping equation (S5). **“Neo-Keynesian”** (Kaldorian) closure solves by dropping eq.(S2). **Johansen** closure solves by dropping eq.(S4). **“General theory”** closure solves by turning L into a variable.

Without using the word, Sen identifies four alternative ‘closures’ to lift the consecutive overdeterminacy:

- The **“neoclassical”** way of closing the model is to drop the exogenous investment rule (S5) and to give to the investment-saving equilibrium (S4), originally an accounting identity, the force of causality: available savings determine the level of investment.
- What Sen calls the **“neo-Keynesian”** way of closing the model is to drop the constraint (S2) of labour payments equating the marginal product of labour. Investment retains some independent behaviour (S5), and the balance

of investment and savings (S4) is brought about by the adjustment of income distribution between wages and profits, considering the specific saving rates on each source of income. The corresponding model is Nicholas Kaldor’s interpretation of Keynes, which Sen contests, hence his qualification of ‘neo’ Keynesian.

- The “**Johansen**” way of closing the model is to drop the investment-savings equilibrium (S4). In Sen’s simplified framework, this effectively cuts all connexions between output or factor payments and investment. In Johansen’s own multisectoral model, the connexion remains through the accounting balance of value-added and final consumptions: investment is made at the cost of lower consumption (barring trade balance variations). Implicitly, public policies organise transfers between agents to warrant that differentiated saving rates secure the desired volume of investment.
- What Sen calls a more properly “**Keynesian**” way of closing the model is to drop the assumption of full employment to materialise employed labour as one additional variable.

This broad categorisation has been picked up by consecutive closure analyses throughout the years and we will stick to it in what follows, with some additional categories as well as some intersections and variants.

3.3 Extension to the ‘KLEM’ CGE framework

To investigate the implications of the choice of closure on the cost assessment of energy demand control, we implement a variant of the KLEM (Capital-Labour-Energy-Materials) framework first developed by Hoffman and Jorgenson (1977) and presented in detail in Chapter 2, with several recent peer-reviewed applications to E3 studies (Soummane et al., 2019; Su et al., 2022).

As detailed in Chapter 2, our KLEM framework models, here in their static version, two production factors capital K and labour L and two goods, Energy and ‘Materials’ (in fact, an aggregate of all non-energy goods and services), whose productions are connected through input-output relationships. It tracks final consumptions of the two goods by households C , public administrations G and immobilisations (investment) I , as well as international trade broken down in exports X and imports M .

Considering our purpose, the choice of such level of granularity is meant as a compromise between the compactness of analyses of the sort introduced by Sen and the extensiveness of the multisectoral CGE models that produce the vast majority of transition pathways available from the academic literature (see Section 3.1). Chapter 2 presents the complete set of equations defining KLEM in comparative statics, for all closures introduced below - each closure technically being a different model variant of the KLEM structure.

3.3.1 The closure issue in KLEM

Implementing Sen’s four closure propositions into KLEM hangs on variations of three of the model’s equations, which relate to equations (S2), (S4) and (S5) of Sen’s model (see Box 1). For the sake of clarity, we present these equations under the numbering of our description of KLEM in Chapter 2. For that of concision, we refer the reader to Table 2.2 of Chapter 2 for KLEM notations, which we only partly clarify below.

Equation (6a) of KLEM corresponds to equation (S2) of Sen’s model in the sense that it embodies the producers’ cost minimisation. Rather than expressing the constraint on prices (wages), KLEM specifies it on factors, i.e. defines the optimal labour input L_i into value-added KL_i mobilised in the production of good i , facing (gross-of-tax) labour costs p_L and rental price of capital r , under the assumption that capital and labour trade off with constant elasticity of substitution σ_{KL_i} :

$$L_i = \left(\frac{\beta_{KL_i}}{p_L} \right)^{\sigma_{KL_i}} \left(\alpha_{KL_i}^{\sigma_{KL_i}} r^{1-\sigma_{KL_i}} + \beta_{KL_i}^{\sigma_{KL_i}} p_L^{1-\sigma_{KL_i}} \right)^{\frac{\sigma_{KL_i}}{1-\sigma_{KL_i}}} KL_i \quad (6a)$$

Equation (10a) of KLEM corresponds to equation (S4) of Sen’s model. It equates investment in money-value $p_{IQ} I_Q$ to the sum of national savings at rate s_L on net-of-tax labour payments $\sum_i w L_i$, at rate s_K on capital payments $\sum_i r K_i$ and at rate s_G on the public budget surplus $T - \sum_i p_{Gi} G_i$, net of the trade balance B :

$$p_{IQ} I_Q = s_L \sum_i w L_i + s_K \sum_i r K_i + s_G \left(T - \sum_i p_{Gi} G_i \right) - B \quad (10a)$$

Equation (10b) of KLEM corresponds to Sen’s equation (S5), with the modification that investment is specified as mobilising a constant share of GDP ω_I rather than being fixed at some exogenous level. The reason for this modification is that the relative

formulation allows wider departures from initial conditions (larger energy consumption cuts, see below), which do not solve (induce negative consumption) under Sen's absolute formulation.

$$p_{IQ} I_Q = \omega_I GDP \quad (10b)$$

Two extensions of KLEM compared to Sen's model require specifications that offer additional closure options. Its extension to international trade demands some form of constraint on the trade balance, which, in line with CGE practice, is supposed to mobilise an exogenous ω_B fraction of GDP:

$$B = \omega_B GDP \quad (14a)$$

Besides, KLEM's disaggregation of 2 production sectors demands an explicit specification of the clearing of primary factor markets:

$$\sum_i L_i = L \quad (20a)$$

$$\sum_i K_i = K \quad (21a)$$

The following subsections present variants of the KLEM model based on the replacement of some of these equations by other constraints. They start with the four basic variants laid out by Sen, then add four additional variants reflecting CGE practice beyond the neoclassical paradigm. A summary of the closures presented in the next two sections is provided in Table 3.1.

Table 3.1: Closure options and market specifications of KLEM model variants

KLEM closure	Domestic savings	Investment	Foreign savings (Trade balance)	Labour market	Capital market	Primary factor payments	Equation variants
Neoclassical	Constant rates $s_L = s_K$, $s_G = 1$	Through closure	Constant GDP share	Flexprice	Flexprice	At marginal productivity	6a, 10a, 14a, 20a, 21a
Kaldorian	Constant rates $s_L = s_G = 1$, s_K calibrated	Constant GDP share	Constant GDP share	Flexprice	Flexprice	Through closure	6b, 10a, 10b, 14a, 20a, 21a
Johansen	Through closure	Constant GDP share	Constant GDP share	Flexprice	Flexprice	At marginal productivity	6a, 10b, 14a, 20a, 21a
Keynes-Marshall	Constant rates $s_L = s_K$, $s_G = 1$	Constant GDP share	Constant GDP share	Through closure	Flexprice	At marginal productivity	6a, 10a, 10b, 14a, 21a (neither 20a nor 20b)
Keynesian	Constant rates $s_L = s_K$, $s_G = 1$	Constant GDP share	Constant GDP share	Fixprice ($\sigma_w = 0$)	Flexprice	Through closure	6b, 10a, 10b, 14a, 20b, 21a
Keynes-Kaldor	Constant rates $s_L = s_G = 1$, s_K calibrated	Constant GDP share	Constant GDP share	Fixprice ($\sigma_w = 0$)	Flexprice	Through closure	6b, 10a, 10b, 14a, 20b, 21a
Neo-K1	Constant rates $s_L = s_K$, $s_G = 1$	Through closure	Constant GDP share	Sticky price ($\sigma_w = 0.1$)	Sticky price ($\sigma_K = 0.1$)	At marginal productivity	6a, 10a, 14a, 20b, 21b
Neo-K2	Constant rates $s_L = s_K$, $s_G = 1$	Constant ratio to K	Through closure	Sticky price ($\sigma_w = 0.1$)	Fixprice ($\sigma_K = 0$)	At marginal productivity	6a, 10a, 14b, 20b, 21b

Equation variants refer to Chapter 2 equation numbers

3.3.2 Sen’s four model variants in KLEM

To reflect the dominance of the neoclassical paradigm in CGE modelling, we define all of the above ‘a’ variants of KLEM equations as those belonging to the **Neoclassical model**: input cost minimisation warrants that factor payments reflect factor productivities (6a); investment is constrained by the sum of national and foreign savings (10a), which for the latter are controlled as some exogenous proportion of GDP (14a); and the ‘flexprice’ assumptions of unconstrained adjustments of wages and the capital rental price allow clearing the labour (20a) and capital markets (21a).

The **Kaldorian model** (Sen’s “neo-Keynesian” closure, which we attribute to Kaldor following Sen’s own qualifications) rejects the assumption of factor payments at their marginal productivity (6a) to make room for the exogenous constraint on investment (10b). It thus allows the labour and capital payments of both productions to adjust freely with a view to reconcile savings with this exogenous constraint, through (14a). Importantly, the reconciliation hangs on the assumption of differentiated saving rates on the two factor payments, i.e. $s_L \neq s_K$.⁶

However, Equation (6a) defines two constraints to KLEM (one per sector), whereas Equation (10b) only defines one (one aggregate investment effort). The Kaldorian model thus requires yet another constraint - which must be carefully formulated in consistency with the rest of the model. We settle on an identical evolution of the labour intensities of both values-added:

$$\frac{L_Q}{KL_Q} = A_{KL} \frac{L_E}{KL_E} \quad (6b)$$

with A_{KL} the ratio of the two intensities at their calibration values.

The **Johansen model** maintains all neoclassical assumptions except Equation (10a), to which it substitutes (10b). Dropping (10a) has for consequence that the saving rates s_L , s_K and s_G do not figure in the model anymore. National savings freely adjust to investment demand net of the contribution of foreign savings, i.e. the opposite of the trade surplus defined by (14a).⁷

⁶This is one additional departure from the neoclassical model, which applies one single saving rate to total factor payments. However, that departure regards calibration rather than model specification. We further comment on saving rates calibration in Section 3.4.2 below.

⁷Rattsø (1982) rather materialises the investment constraint by adjusting an explicit income tax, which allows targeting the fiscal surplus required to produce the targeted level of savings.

Lastly, Sen’s “General Theory” model adds total labour L as variable to the neoclassical model to accommodate the extra investment constraint (10b). To maintain the count of equations and variables of the corresponding model identical to that of other variants (see Chapter 2), we rather substitute (10b) to the clearing of the labour market (20a). This is effectively pushing L out of KLEM altogether. The sum of the labour inputs to the two sectors is not constrained anymore and its evolution from calibration value indicates employment creation or destruction. Importantly, this closure maintains the Marshallian payment of factors at marginal productivity and does not constrain wage setting in any way, which goes against many interpretations of Keynes. For this reason, we qualify the corresponding model as the **Keynes-Marshall model** and introduce an extra set of models to further explore fix or sticky wage alternatives.

3.3.3 Four additional model variants

Building on what precedes, we define our **Keynesian model** as departing from the Keynes-Marshall model by abandoning factor payments at marginal productivity (6a) in favour of fix real wages, which we specify through a generic ‘wage curve’ (Blanchflower and Oswald, 2005):

$$\frac{w}{CPI} = A_w B_w^{-\sigma_w} \left(B_w + (1 - B_w) \frac{L - \sum_i L_i}{L} \right)^{\sigma_w} \quad (20b)$$

The wage curve is connecting real wages $\frac{w}{CPI}$ to unemployment $\left(B_w + (1 - B_w) \frac{L - \sum_i L_i}{L} \right)$ with σ_w elasticity, building on calibration values of the real wage A_w and the unemployment rate B_w .⁸ In the case of our Keynesian model, σ_w is nil, which implies that the real wage is fixed at calibration value A_w . Similar to the above Kaldorian model, the model requires one additional constraint to be squared because Equation (20b) only replaces one of the two constraints defined by Equation (6a). To meet this requirement, we retain again Equation (6b) i.e. identical variations of the labour intensities of both values-added.

From this Keynesian model, we derive one additional **Keynes-Kaldor model** variant that considers differentiated saving rates on capital and labour incomes. The canonical Keynesian model (Hicks, 1937) does not make this differentiation — nor did Keynes himself, unlike others at the same time (Lavoie, 2015).

⁸ The definition of unemployment as $B_w + (1 - B_w) \frac{L - \sum_i L_i}{L}$ flows from calibration of KLEM under the perfect market assumption that $\sum_i L_i = L$.

In two additional models, we combine several of the above departures from the neoclassical (a) variants of equations in an attempt to reflect ‘neo-Keynesian’ modelling practice (Gupta et al., 2020; Soummame et al., 2019; Lefèvre et al., 2018).

We thus propose a **Neo-K1 model**, which only departs from the neoclassical model by considering imperfect (‘sticky price’) factor markets: it maintains standard cost minimisation and exogenous domestic and foreign saving behaviours (Equations 6a, 10a and 14a) but enforces the wage curve (20b) with the σ_w elasticity at -0.1 and similarly models capital payments as correlated to idle capital capacities with σ_r elasticity (also at -0.1):

$$\frac{r}{pIQ} = A_r B_r^{-\sigma_r} \left(B_r + (1 - B_r) \frac{K - \sum_i K_i}{K} \right)^{\sigma_r} \quad (20b)$$

Lastly, we consider a **Neo-K2 model** that enforces standard cost minimisation and saving behaviours (Equations 6a and 10a) but,

(1) rather than constraining foreign savings (Equation 14a), links volume investment to the capital demand of sectors:

$$\frac{I_Q}{K} = A_K \quad (14b)$$

with A_K the investment to capital ratio at calibration year.

(2) rather than clearing the labour market through the flexprice assumption (Equation 20a), specifies ‘sticky wages’ through the wage curve of Equation 20b with σ_w at -0.1.

(3) similarly, rather than clearing the capital market through the flexprice assumption (Equation 21a), enforces the ‘fix price’ specification of a constant ratio of the rental price of capital to that of immobilisations: Equation 21b under the special case when $\sigma_r = 0$. This special case brings the Neo-K2 model very close to ‘cost-plus’ pricing (Lavoie, 2015): it specifies capital payments as not exactly a constant mark-up, but as some cost that is directly proportional to the purchaser price of equipment, which is itself the supply price of the non-energy good augmented with ad valorem taxes.

As importantly, the substitution of Equation (14b) to Equation (14a) means that the Neo-K2 model closes the investment and saving balance on foreign savings, which adjust endogenously through ‘flexprice’ fluctuations of the real effective exchange rate (the ratio of domestic to imported prices).

3.4 Numerical implementation of KLEM variants

Although limited to the common, contained number of 59 scalar variables (see Chapter 2), the eight model variants in the preceding section form systems of nonlinear equations that are too complex to solve analytically. We therefore turn to numerical modelling to test their properties.

3.4.1 Numerical experiment

With the intent of framing the aggregate ‘behaviour’ of each model variant, we run, as numerical experiment, one central piece of energy policy: the introduction of a Pigouvian tax on (polluting) energy consumption. Rather than enforcing exogenous tax levels, we implement the dual problem of energy consumption control through the endogenous adjustment of the tax (see Equation 7 of Chapter 2). This is to allow testing of the whole spectrum of energy consumption quotas in the form of percentage reductions below the calibration level, from 5% to 95% in 5-percentage-point steps, then to 99% in 1-percentage-point steps. The endogenous tax applies to all energy consumptions as an ad valorem extension of purchaser prices (see Equations 28 and 29 of Chapter 2).

3.4.2 Calibration data and assumptions

We calibrate all KLEM model variants applied to the above numerical experiment on the same 2-sector input-output table (IOT) of the European Union for the year 2014 (see Appendix B).⁹ The calibration procedure is identical across variants with the exception of one set of specific assumptions regarding the saving rates.

In versions following the neoclassical paradigm of exogenous domestic saving decisions, KLEM implements three saving rates: one on labour income s_L , one on capital income s_K and one on the public surplus s_G (Equation 10a). The IOT does not specify any of these rates but pinpoints the total amount of domestic savings as the sum of investment and the net trade of goods and services. To start with the rate s_G , some macroeconomic models that distinguish public expenditures tend to not transfer to households the public budget surplus (expenditures net of direct taxes’ income), which would lead to $s_G = 1$. When they do, this surplus blends into total household income

⁹ This 2014 year flows from our choice of the GTAP data source rather than of other sources (e.g. Eurostat) because of its handy sectoral granularity (see Appendix B). The level of aggregation of KLEM warrants that building our modelling experiment on more recent data would not significantly (qualitatively) alter our conclusions.

and faces the same aggregate saving rate as labour and capital income, which would lead to $s_G = s_L = s_K$. However, such an assumption reduces the influence of closure by effectively making savings a constant share of aggregate GDP.¹⁰ We thus retain the former assumption ($s_G = 1$) in all our model variants with exogenous savings. We also follow modelling practice of some models that ignore the distinction between capital and labour income and impose one single saving rate on the sum of the two income sources, thus effectively assuming $s_L = s_K$. This common rate turns out at 30.6% in our EU data (see Appendix B). Two Kaldorian variants rather assume that the saving rate on labour income is nil, $s_L = 0$, which leaves s_K as the unique rate calibrated to accommodate the total amount of savings. In that case, s_K rises to 50.3%.

3.4.3 Diagnostic indicators

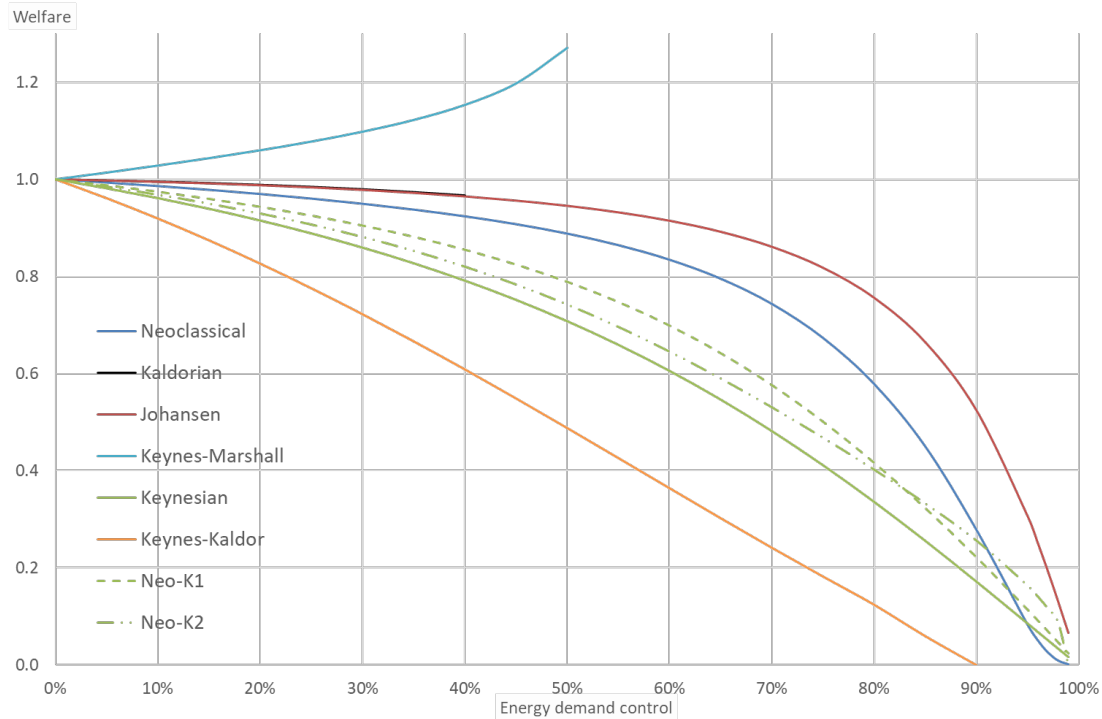
To analyse how the different closures impact the behaviour of the KLEM model, we use a “diagnostic indicators” approach, as pioneered by Kriegler et al. (2015). Although many indicators could be used to run this diagnostic (all informing important policy questions), the central indicator retained is the evolution of Utility per percentage of energy consumption reduction. Following this value indeed informs the question “How does the energy demand control process impact global welfare?”. This question and main results provided for the eight closures are discussed in the following section. Additional diagnostic indicators are reported in Appendix B.

3.5 Numerical results

As previously mentioned, we focus our reporting of modelling results on the utility cost of energy demand control through Pigouvian taxation (Figure 3.1), while presenting a selection of additional variables of interest in Appendix B. Our central indicator confirms that model variants depict the macroeconomics of energy demand control in sharply contrasted manners, both quantitatively and qualitatively (Figure 3.1). Considering its dominance in published analyses, we will use the Neoclassical variant as a benchmark for the comparison with other options. We therefore start our review of modelling results with it.

¹⁰This neutralises any consequence of the choice of closing on savings, the trade balance or the investment effort. The three components sum up to the complementary of households’ consumption in GDP, which is made constant by the exogenous aggregate domestic saving rate.

Figure 3.1: Welfare impacts of energy demand control for 8 KLEM variants reflecting major economic theories



Here, energy demand control represents a reduction of energy demand compared to the initial calibration value. This figure shows the evolution of welfare compared to an initial value with no energy demand control, which represents the utility costs of such a control.

Importantly, interpreting results will require entering the mechanics of each modelling variant to a degree that we do not want to pretend is reflecting active choices of modellers for one variant over all others. We will further discuss this point in conclusion.

Neoclassical closure and perfect market specifications expectedly produce a downward sloping gradient, which reflects the postulated optimality of the producer and the consumer's choices at calibration values. On the production side, the Pigouvian taxation distorts the input choice in favour of value-added (the nested production function of KLEM is described in Chapter 2). Under the constraint of fixed, fully employed labour and capital endowments, this shift inescapably increases the unitary costs of productions. On the consumption side, the energy tax similarly distorts the trade-off between the energy and the non-energy good, thereby reducing the utility that can be gained from one unit of income. Both effects combine to steadily

decrease aggregate welfare as the energy demand control increases. However, the assumed perfection of the labour market warrants full employment of the labour endowment whatever the energy control effort, which limits the impact of unitary cost increases compared to options where the labour market also adjusts through factor underutilisation, i.e. unemployment, because of obstacles to wage adjustments. This explains the stronger curvature of the Neoclassical gradient compared to Keynesian options - notwithstanding the Keynes-Marshall exception (see below): aggregate welfare is more resilient to energy control, with the consequence that the marginal cost of control increases faster than for the Keynesian options, to reach the convergence point of a 100% utility decrease for a 100% energy consumption abatement.

The **Kaldorian model** departs from the Neoclassical reference by renouncing the payment of factors at marginal productivity in favour of a constant investment effort (see Table 3.1). The investment-savings balance consequently results from the adjustment of the labour and capital shares into value-added, which allows controlling domestic savings through the specific (Kaldorian) feature of differentiated saving rates on the two factor payments. Such changes turn out to have mitigating impacts on the welfare costs of energy control: the Kaldorian model produces the least costs of all models barring the Keynes-Marshall exception, at least up to a 40% decrease of energy consumptions, after which it ceases to solve.¹¹ The reason for these lower costs is that the model maintains the consumption budget of households - the direct source of utility - higher than other variants. Indeed, by contrast to the Neoclassical model, the Kaldorian model does not allow the investment effort to increase i.e. the household consumption share of GDP to decrease, considering the constant public consumption and trade balance ratios to GDP. Under a Neoclassical closure, the investment effort increase is linked with the increase of domestic savings through the assumption of a 100% saving rate on the public budget surplus, which benefits from the rising Pigouvian tax income, while the trade balance deficit is constant.

The **Johansen model**'s defining characteristic is to fix the investment effort and let household consumption (and thus savings) adapt to it, rather than the opposite (see Table 3.1). It computes welfare costs quite in line with those of the Kaldorian model, but solves for the complete spectrum of energy control targets: undifferentiated saving rates on labour and capital payments allow splitting value-added between the two factors

¹¹The model solves by concentrating value-added on capital payments to increase savings, all the more so as the energy demand control target rises. At 40%, wages have already been brought down to zero. Only negative wages, which are barred, would allow the model to continue solving.

independently from the savings constraint. Like the Kaldorian model and barring again the Keynes-Marshall exception, the Johansen model produces the lowest welfare costs of all models by simultaneously maintaining the GDP share of households' consumption (as a consequence of maintaining the trade balance, investment effort and public spending shares) and warranting full factor employment.

The **Keynes-Marshall model** strikingly stands out by inducing an upward sloping gradient: welfare and in fact all macroeconomic indicators (see Appendix B for a selection of them) increase along with the decrease of energy consumptions. Compared to the Neoclassical variant, the Keynes-Marshall model substitutes the constraint of a fixed investment effort to that of full employment i.e. of a fixed supply of labour. The consequence is to lift any constraint on the supply of labour, which is allowed to align on sectoral demand following relative price conditions. Under such unconstrained supply of labour, the extra input required to adapt to the Pigouvian distortion of relative prices acts as Keynesian stimulus. More precisely, producers can substitute value-added to energy by playing on the substitution of labour to capital in value-added without any supply constraint on the former input and, most importantly, without any consequence on wages. The substitution effect is so strong that the 'reserve army' of the unemployed, at 10.8% of total labour in 2014 European Union, is close to fully mobilised for a cut of energy consumption of 15% only. Energy cuts beyond 15% mobilise ever more labour, up to 2.5 times the active labour force without energy demand control.

The 'catch' of these appealing Keynes-Marshall mechanics lies in the equilibrium real wage. In the absence of constraint on labour supply, the equilibrium real wage proceeds from the combined constraints of the fixed capital stock, which, in the context of a Keynesian stimulus, induces a higher real rental price; and of the constant trade balance to GDP ratio, which requires some stability of the real effective exchange rate. The consequence is that the price of the other primary factor i.e. the real wage must drop and does so, by as much as 14% for the 15% energy cut that mobilises 10.5% additional employment. This opposed evolution of employment and the real wage is seldom observed in statistics of the short term. It may hold in the longer term, but the point remains that the energy control objective comes at the cost of significantly lower purchasing power of wages, which, combined to the fact that it nonetheless benefits aggregate utility, points at significantly increased inequalities.

The **Keynesian model** exhibits among the highest utility losses, being only surpassed by the Keynes-Kaldor model, and by the Neoclassical model for very high targets. The Keynesian model features indistinct saving propensities across income

types, a fixed real wage and, as a consequence and most importantly, equilibrium unemployment (Table 3.1). With labour unconstrained and a constant real wage, the decrease of energy demand occurs primarily through that of activity. More precisely, raising the energy price increases the consumer price index, which mechanically prompts parallel wage increases. This induces substitution away from labour in the value-added bundle, which translates into less employment as firms are allowed to adjust through quantities. Further, compared to the Neoclassical benchmark, production in the composite sector drops sharply while the polluting energy sector also shrinks, but less so than in the benchmark. This suggests that, with unemployment, and conditional on our set of elasticities, the brunt of decarbonisation is borne by the composite sector through quantity adjustment. This creates a much larger deadweight loss for low targets, losses that the Neoclassical closure would have tempered through intersectoral factor reallocation thanks to wage moderation. The effect on utility is therefore much sharper than in the benchmark since overall consumption diminishes much more for low targets. Finally, the concave shape of utility losses is due to the exhaustion of substitutability possibilities between K and L. Since these two inputs are gross complements, the downward adjustment on the remuneration of capital becomes sharper and sharper as unemployment increases. Hence, the conjunction of higher unemployment and lower capital remuneration entail sharper and sharper utility losses through lower consumption.

The **Keynes-Kaldor model** exhibits utility losses even higher than those of the Keynesian model. The only difference between the two models is that the Keynes-Kaldor version differentiates the saving rates on capital versus labour income. When introducing a control on energy, the quantity of the KL bundle increases relative to the Energy input, which has repercussions on capital and labour higher in the production structure. In the Keynes-Kaldor closure, because there are no savings on the labour income, the savings needed to match investment flow from the capital income only. The capital endowment and the real wage being fixed, the adjustment of the rental price of capital r implies a diminution of employed labour, which leads to higher losses in utility than in the Keynesian closure, itself leading to higher losses than in the Neoclassical one.

Lastly, **the Neo-K1 and Neo-K2 models** exhibit patterns of utility losses similar to that of the Keynesian closure but with slightly lower negative impacts. This is explained by the sticky price nature of the Neo-K1 and Neo-K2 labour markets, which departs from the fully fixprice approach of the Keynesian case. Sticky prices provide an intermediate case between the flexprice and fixprice specifications, with mixed

economic adjustment through both quantities and prices. The degree of price stickiness reflects the capacity of the production system to moderate the increase of production costs by translating part of the energy cost increase into a decrease of labour and/or capital payments. Compared to the Keynesian case, in Neo-K1 and Neo-K2 models the depressive effect of energy and production costs increase on final consumption and labour demand is alleviated by a decrease of factor costs (wages and/or capital rental price), which limits factor unemployment and consumption losses but reduces factor productivity. With an elasticity of -0,1, our sticky price calibration of the labour market is in the lower range of price flexibility, which accounts for the welfare losses being closer to the fixprice Keynesian case than the flexprice Neoclassical one.

The cause of the slightly higher welfare losses of Neo-K2 compared to Neo-K1 lies in the fixprice approach of capital markets in Neo-K2 and the absence of price moderation effects through the reduction of the rental price of capital compared to Neo-K1 (same mechanism as above). The specific investment formulation in Neo-K2 mainly leads to some structural change towards a higher investment share of GDP (and lower share of the trade balance) with limited overall impacts on welfare.

3.6 Conclusion

The endeavour of this work was to explore a theoretical uncertainty in E3 modelling in the form of model closures, which have been left aside in the field. Such an understudy would not have been much of a matter had it been of little consequences on the results of simulations of decarbonation policies. This study has shown across the board that it is not the case. Different closures *do* yield widely different results and insights. Our work also provides some rationales and keys for understanding the behaviour of existing models, for instance the sometimes marginal behaviour of some models departing from strict neoclassical assumptions. Our main conclusion is that theoretical uncertainty may have been underestimated, with possibly significant consequences on the understanding of transition dynamics and subsequent policy recommendations. The main lesson to be drawn is that it is important to broaden the portfolio of possible theoretical insights to explore the variety of outcomes they yield, both from heuristic and policy standpoints.

From a very technical standpoint, as we saw above, a closure in the broadest sense is just a way to choose pairs of variables, one endogenous, one exogenous. As a result, the number of possible closures for a model is equal to the total number of its variables *squared*. Obviously, carrying out an analysis on closures for thousand-equation large

models like those reviewed by the IPCC is a virtually impossible task. Closures must therefore be chosen among a pool of relevant ones, depending on the issue at stake and the research endeavours.

This in turn poses the question of what criteria to summon to justify such theoretical choices around which closure(s) is/are relevant - in order to favour the results associated with one or another depending on the analysis/context. So far, three have been mobilised by the literature, and are detailed in Appendix B:

- A first approach is to gauge closures in light of their empirical relevance for the context and analysis – be it statistical, or derived from historical or institutional studies. This approach was endorsed, in principle, by Rattsø (1982) and most of the literature thereafter (Dervis et al., 1989). There is however, to the extent of our knowledge, no empirical work aiming to discuss the relevance of closures in more general cases. Albeit seemingly very reasonable, relying only on empirics also brings its lots of blind spots and conceptual dead ends, as discussed by Taylor and Von Arnim (2007).
- A second point was raised by Dervis et al. (1989), Dewatripont and Michel (1987) and Robinson (1989), and relates to the time horizon of the analysis. For Dervis et al. (1989), non-neoclassical closures prioritise income effects over relative price effects in driving macroeconomic dynamics - for instance, Kaldor’s “forced savings” mechanism relies entirely on an income effect in the determination of the investment-savings equilibrium. Robinson argues that such effects, which are the theoretical grounds of most non-neoclassical closures, are relevant for short-run considerations, but not in the medium or long-run. This remark is sensible, but quite sketchy on the differences between “long-term” and “short-term” characterisation of equilibrium. As a result, it is unclear whether we should dismiss non-neoclassical assumptions for considerations beyond the short run.
- We saw that closures can be related to clear theoretical standpoints or be used to propose variants along those insights. An important question in that respect is the status of the theories themselves within the broader context of economic analysis. Our view is that economic theories are heuristic propositions that must be taken as such because they all have definite explorative interest, and that *must* be compared in the absence of any *ex ante* consensus on which causality structure pictures an economy best. Goddard et al. (2019), in discussing the building of an ecological economic research programme (to which E3 studies should definitely

belong), argue that no school of thought or “paradigm” should be left aside. As a result, closures *should* be taken as simple mathematical propositions, with low ontological or normative content.

This conclusion is therefore a call for a pluralistic approach to climate economics, in a bid to complement the blind spots of neoclassical views.

Finally, there are some avenues for further improvements to our results. Although we do not discuss in great details the possibility to explore more theoretically sound closures, or consider other diagnosis indicators, it obviously represents an area of research. Simply, this endeavour would not go beyond the points already discussed in the chapter, and would only represent a quantitative prolongation of our endeavour. We here rather emphasise different ways to go beyond some limitations of the present work, both in terms of modelling techniques and theoretical insightfulness:

- An interesting aspect to be explored is the potentiality for a double-dividend if the proceeds of the tax are redistributed. Preliminary results show that Double-Dividend potentials vary strongly across closures. Some exhibit univocal improving effects of tax recycling, while others highlight the possibility for a macroeconomic rebound effect of recycling. Tax recycling is also not neutral from a functional-distribution standpoint, as it usually results in an increase of the remuneration of capital.
- An obvious limitation of our work is the use of comparative statics. Although extremely useful as a heuristic and communication tool, it would be interesting to extend the present work to a dynamic framework, to determine the extent of the influence of closures once the equilibrium-to-equilibrium dynamics are accounted for. On that matter, the work proposed in Chapter 4 using a dynamic KLEM framework is not centered around model closures, but confirms that different model closures (a neoclassical closure and a Johansen closure) yield different GDP trajectories.
- A maybe less obvious limitation of our approach is that of what we could call its “entry point”. Indeed, it is to be kept in mind that the model used to compare the different closures, KLEM, is built on neoclassical foundations (Hoffman and Jorgenson, 1977). Moreover, our general methodology, based on utility losses and Pigouvian taxes, is definitely closer to neoclassical epistemics than to others (Lavoie, 2015). As such, we consider different causality structures only *from the*

standpoint of or as deviations from a neoclassical perspective. Such a methodology has been heavily criticised by dissenting authors, who have repeatedly called for a profound reappraisal of economic modelling (Taylor, 2004), notably away from traditional approaches based on production functions (Shaikh, 1974). As such, a natural prolongation would be to try and implement some of these closures in models based on radically different theoretical underpinnings.

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Are Long-term National Goals on Climate Change Mitigation and Economic Development Compatible? Evidence and Modelling on Malawi, Colombia and Iraq

Abstract

Are countries' long-term development targets consistent with their short and medium term climate commitments? In this chapter, we propose a step-by-step method based on the compact two-sector computable general equilibrium model KLEM, to help discuss the compatibility between climate and select economic development targets, in various countries. We design it to provide first insights on the issue, especially for countries for which there is no detailed national modelling framework, and little data available. We use the fully exogenous energy sector and other exogenous drivers of the KLEM model to translate climate mitigation targets and macroeconomic targets as described in the country's climate and development documents, then adjust select other parameters to reproduce the country's GDP growth target. The extent to which the pathway can be reproduced with realistic values for these parameters provides a basis for discussion on the compatibility. We apply the methodology to case studies on Malawi, Iraq, and Columbia – countries that represent a diversity of development priorities and display quantified long-term development targets. For the first two countries, it shows a large compatibility between both frameworks, and some possible inconsistencies within the development targets for Iraq. We finally discuss avenues for improvement to the methodology.

Contributions:

Auriane Meilland: Conceptualization, Methodology, Investigation, Programming, Analysis, Writing (original draft), Visualization

Franck Lecocq: Conceptualization, Methodology, Analysis, Writing

4.1 Introduction

In the general introduction, we highlighted that the Paris Agreement committed all participating nations to collectively restrict their greenhouse gas (GHG) emissions, the overarching goal being to limit, by 2100, the increase in average global surface temperature well below 2°C (with 1.5°C as an aspirational goal) compared to pre-industrial levels. Unlike the approaches prevailing until the 15th Conference of the Parties (Bodansky, 2010), all nations now put forth voluntary mitigation and adaptation commitments in Nationally Determined Contributions (NDCs), with a horizon typically extending to at least 2030.¹ A quinquennial Global Stocktake evaluates the aggregated NDCs, after which NDCs are expected to be revised with greater ambition. The first Global Stocktake is clear: the aggregation of current NDCs does not, by 2030, align with a global emissions pathway compatible with the +2°C target (UNFCCC Secretariat, 2023b).

As previously discussed, the challenge lies in the fact that scenarios for reducing greenhouse gas emissions in line with 2°C (let alone 1.5°C) (Shukla et al., 2022) imply stabilizing global emissions by 2030, followed by a rapid and unprecedented global decrease. While national trajectories may differ widely across countries, these global pathways cannot but translate into significant limitations in the growth of emissions, and ultimately into reductions, for each individual country.² Global and national mitigation pathways, however, require a fundamental reconsideration of consumption and production patterns, with profound implications for entire economies (Riahi et al., 2017). Consequently, the reduction of GHG emissions and countries' development policies are tightly interlinked.

The interrelations between development and mitigation have long been recognized in the literature:³ development strategies, put forward by countries for example in their national development plans (Chimhowu et al., 2019; Munro, 2020), sectoral plans or communications to the UN (e.g., Voluntary National Reviews in the context of the 2030 Agenda for Sustainable Development), are decisive for GHG emissions and mitigation possibilities. Yet, the alignment between climate and development targets and policies at the national scale is not a given. First, in many policies and stakeholders' discourses,

¹All NDCs are available on an online platform: <https://unfccc.int/NDCREG>

²The wide literature on the downscaling of global scenarios is out of the scope of the present chapter, but we will touch in Part III on the cross-country equity issues that are central to any discussion on effort sharing across countries.

³See general introduction for a detailed review

the climate issue is not integrated with other development priorities. We showed in Chapter 1 that in over 15% of the development documents, targets related to Sustainable Development Goal 13 on climate change were totally absent. In terms of process, climate and development goals are still laid out, for the most part, in separate documents – for example NDCs and development plans and visions –, sometimes issued by separate institutions or ministries, within separate timelines. Some countries display a clear integration of these processes: Nepal, for example, features identical targets in its NDC, in its national long-term development vision (Government of Nepal, 2017) and in its short-term development plan (Government of Nepal, 2020). Other countries do not, and do not even cross-reference their climate and development documents. In these cases, we have no indication that the compatibility between development targets and mitigation targets is checked elsewhere. In fact, even in countries where climate mitigation targets have been built in processes that embark many stakeholders representative of various development priorities (not just climate mitigation), the compatibility between climate mitigation and development priorities remains very much an open question. This is illustrated by recent examples of debates in the UK (UK Climate Change Committee, 2022), Brazil (Rodrigues, 2023) or France (Pisani-Ferry and Mahfouz, 2023).

In this chapter, we aim to provide insights on the alignment and trade-offs between countries' development priorities and climate objectives. Previous research has delved into this issue from a variety of perspectives (Klein et al., 2005), globally (Metz and Kok, 2015) or for individual nations (Alam et al., 2011; Hasan et al., 2020). Here specifically, we examine the compatibility between climate mitigation and development targets as articulated in countries' NDCs and long-term development documents. The choice of NDCs is straightforward. They are produced by all Parties to the Paris Agreement (195 documents to date in the official NDC registry) and usually display quantified targets up to 2030.⁴ As argued in Chapter 1, despite variations in format, content, and legal status, national development documents are numerous (121 countries covered in the database), long-term, economy-wide, and share sufficient similarities from one country to another to allow for meaningful comparisons, even though they do not necessarily feature quantified targets. This choice of documents comes with some limitations: although relatively similar in structure, all NDCs and all development documents do not feature harmonized quantified targets and data.⁵ Moreover, they provide only stated priorities and targets, that can differ from actual policies either because of an implementation gap

⁴Some NDCs being more detailed on the mitigation or adaptation components of the contribution.

⁵In development documents, some countries might provide GDP growth targets and others not, some might provide poverty targets and others not. This is also the case for NDCs: some countries

(Hudson et al., 2019) or because policies effectively put in place differ from the ones that were planned.

Having established where development and climate priorities are collected from, we need to clarify what compatibility means in the context of this thesis, and how we propose to assess it.

As discussed in the general introduction, constraining GHG emissions may impact the achievement of other development objectives through three main effects: a crowding-out effect (mitigation can require additional resources), a distributional effect (as mitigation might affect some groups more than others), a structural effect (as mitigation requires transformations that have an effect on other development goals). These impacts can be negative or positive. As noted in Chapter 1, there are multiple development targets, and the channels through which they are impacted by climate mitigation are complex or sometimes not well understood: for example, among existing Sustainable Development Goals model-based scenarios, most only translate clusters of 2 to 6 SDGs (Orbons et al., 2024). A second challenge is that some development targets (e.g. institutional targets that are related to SDG 16) are often not quantified, making them less amenable to quantitative analysis. Third, our focus is on medium to long-term targets, which means that "compatibility" cannot but be assessed in a context of deep uncertainties. The stakes thus go further than providing a binary answer (concluding that climate and development targets are/are not compatible), and compatibility comes down to discussing the extent to which, or the conditions under which implementing climate targets could impede the achievement of development targets (or conversely). We thus focus on discussing the size of a chosen parameter space for which both national climate and development targets are reached, which qualifies the extent of the compatibility, and could provide information on what would be necessary to reach both types of targets.

Exploring the compatibility space calls for a quantitative analysis, which also narrows down the number of development targets that can be included. Nevertheless, examining the compatibility between mitigation targets and macroeconomic development targets (such as GDP or unemployment trajectories) remains relevant, bearing in mind that they only represent a fraction of development objectives. Among various types of macroeconomic models, as justified in Chapter 2, computable general equilibrium models

provide emission reduction targets compared to a reference scenario, others provide different targets - for example, China has a carbon intensity target and date for emissions peaking (Government of China, 2021).

are a tool of choice, as they are particularly relevant to represent the effects of changes or policies related to development and environment, on select macro-economic variables (Dixon and Jorgenson, 2013).

From the perspective of macroeconomic modelling, however, the effect of climate mitigation policies at the national scale (and their consistency with other policy objectives) have mainly been studied in developed countries and major emitters in the developing world: for example, Altieri et al. (2016) on South Africa, Gupta et al. (2019, 2020) on India, Duan et al. (2018); Bretschger and Zhang (2017); Suo et al. (2021) on China, Soummane et al. (2019) on Saudi Arabia. Global assessment exercises, with models such as IMACLIM-R, WITCH, E3ME, GCAM, MERGE or KLEM-POLES, consider aggregate regions, with little granularity in developing countries outside of major emitters. One of the reasons for this situation is that for global models, these countries do not account for enough emissions and exchanges between regions to justify the efforts associated with their disaggregation, all the more since in small countries, quantified targets can be too scarce build scenarios. In many countries, providing insights on the alignment between national climate and development targets thus remains an open challenge. It is however an important question for all countries: for large emitters, as they currently are the main contributors to climate change, for smaller ones, as their emissions could grow should they meet their development targets on a pathway that is not aligned with their climate commitments. Variants of the KLEM model that we presented in Chapter 2 are relevant to use, as they present an exogenous energy sector that can translate energy-related targets, and exogenous assumptions on unemployment, investment, trade balance, labour endowment and productivity, that can translate development targets. Considering our purpose, the choice of such a level of granularity (two sectors) is meant as a way to be able to display stylized trends and reveal hypotheses on many countries for which the amount of quantified targets can be limited.⁶

In this chapter, we propose a general methodology to give insights on the compatibility between long-term climate and development targets for a large number of countries. It does not aim at replacing detailed modelling exercises, but rather at providing first insights on the issue, especially for countries for which there is no detailed national model available. Developing and calibrating a detailed national model would indeed be ideal, but is a long-term effort and first intuitions are relevant beforehand

⁶To include more development targets when it is relevant and data is available, the KLEM framework can also be extended to include additional sectors, as discussed in the conclusion of this chapter.

(climate mitigation targets are updated regularly through the Paris Agreement's ratcheting up mechanism). The main challenges, as exposed in this introduction section, are that it should allow for the translation of heterogeneous national contexts, and be flexible enough to be adapted to the data and quantified targets available. Indeed, depending on the development orientations and priorities, different synergies and trade-offs might be important to model from one country to the next. As we intend the methodology to be applicable in countries with very limited data available, we focus on a subset of macroeconomic targets, and on climate targets related to the energy sector, which enables us to use variants of the KLEM framework, as presented in Chapter 2, as a tool for our evaluation. We then test our methodology on specific country cases for Malawi, Colombia and Iraq, which have various development orientations and contexts, and discuss possible future extensions of the tool in the light of the first results we have obtained.

The present chapter is organised as follows: Section 4.2 details the methodology, synthesizes the main characteristics of the KLEM variants in the light of this chapter's focus, and finally discusses the choice of case studies based on the countries' development orientations as collected in Chapter 1. Sections 4.3, 4.4 and 4.5 show a relative compatibility between climate and economic development targets in the cases of Malawi and Colombia, and some inconsistencies in the case of Iraq. Section 4.6 discusses the proposed methodology in the light of the case studies, and presents perspectives to broaden the analysis to other development targets, on countries for which it would be relevant.

4.2 Methods

In this study, we propose a step-by-step method to evaluate the compatibility between national economic development targets (as proposed in countries' long-term development documents) and climate targets (as proposed in countries' NDCs), taking into account the specificity of national contexts. We detail the methodology in Section 4.2.1. We then present the specificities of the KLEM variants used in this analysis in Section 4.2.2. This generic method requires *sine qua non* quantified targets that are listed in the section, but can incorporate additional relevant targets, if they are featured in the documents and can be modeled in KLEM. Based on the development plans collected in Chapter 1, we review the countries to which the methodology could be applicable given the minimal amount of targets and data needed, and justify, in Section 4.2.3, the choice of case studies with distinct development orientations to test the methodology in various contexts.

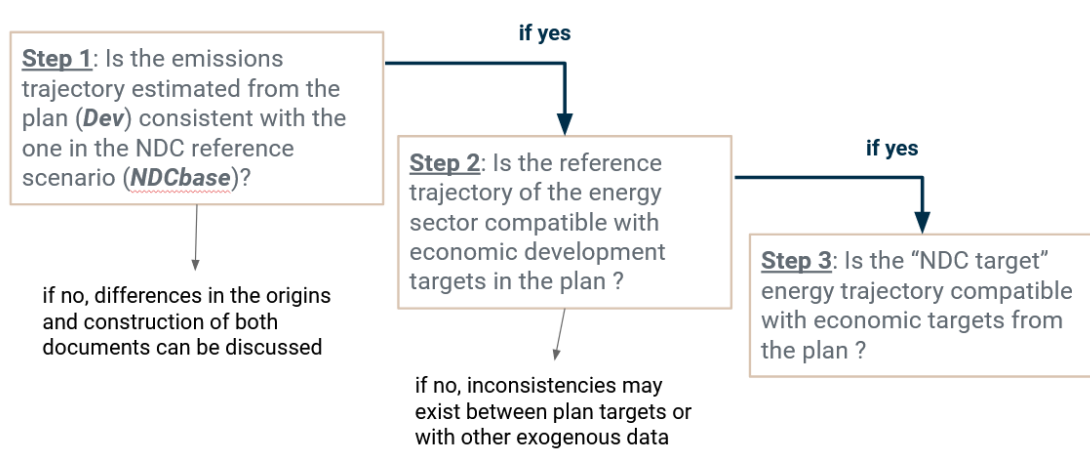
4.2.1 Step-by-step method

The logic behind the proposed methodology is to use the fully exogenous energy sector and other exogenous drivers of the KLEM model to translate climate mitigation targets⁷ and macroeconomic targets (such as unemployment, population growth, etc.) as described in the country's NDC and development plan,⁸ then adjust other exogenous parameters driving growth, to reproduce the country's GDP growth target. The extent to which the GDP target can be met with realistic values of the exogenous parameters mentioned above provides a basis for discussing the compatibility between the development targets and the climate targets. However, other elements of compatibility between both documents should be checked prior to modelling analysis, to avoid resorting to modelling for plans and NDCs for which the incompatibility can be easily spotted. We thus decompose the method in three main steps, that are summarized in Figure 4.1 and detailed hereafter.

⁷We here focus on energy-related targets, but as discussed in the conclusion, a KLEM variant with an agriculture sector is currently being developed, to account for agriculture-related targets.

⁸The development plans considered in this work are the ones collected following the criteria detailed in Chapter 1.

Figure 4.1: Summary of the step-by-step method proposed in this work



Step 1

The first step is to discuss the compatibility between the development targets featured in the national development plan (such as the shares of each sector in the GDP and their associated values), and the reference scenario presented in the NDC. We choose GHG emissions as a point of comparison because they are typically featured in countries' NDCs, and their targeted evolution can be roughly estimated from the development plan. The idea behind this step is that incompatibilities can appear even before the modelling phase.

To do so, we compare two energy-related⁹ GHG emissions trajectories:

- The first one, *Dev*, is estimated using country-specific calculations (an example of which is presented in Section 4.3), that depend on the information available in the development plan. We use targeted growth and other sectoral or population growth targets (if available) to estimate the evolution of GHG emissions using a Kaya-like identity, under plan-specific assumptions on the evolutions of sectoral energy efficiencies and of the energy sector's carbon intensity. If the horizons of both documents do not match (for example, if a plan has a 2025 horizon and a NDC a 2030 horizon) the development targets are linearly extrapolated.
- The second one, *NDCbase*, is directly derived from the targets for the energy¹⁰ sector featured in the NDC.

⁹And, in future extensions of this method, agriculture-related

¹⁰and, in future extensions of this method, agriculture

If this first step shows too much of a difference between the two energy-related emissions pathways, there is no point in proceeding to the modelling exercise. The long-term development document and the NDC are clearly not constructed on the same basic assumptions. Such a difference might occur if the two documents (development plan and NDC) were produced by different institutions without collaboration, if they have too different a time horizon, or if they have been produced very far apart, one of them now being obsolete. If the development plan is more recent and includes the NDC's targets, the *NDCref* trajectory might also not match the *Dev* trajectory. In that case, it is still possible to proceed to Step 2, as will be shown on the example of Colombia in Section 4.4.

Step 2

If Step 1 did not reveal major inconsistencies, we calibrate a KLEM model as will be detailed in Section 4.2.2.

We then use both documents, and available data in the literature (for example from existing modelling exercises of the energy system) to translate the reference scenario of the NDC and the development plan targets into five constraints for the model:

1. pathways of the energy system until the horizon year (with scenarized evolutions of the energy consumption volumes and prices for the energy sector, the non-energy sector, households, as well as imports and exports),
2. the evolution of labour endowment,
3. the evolution of the unemployment rate,
4. the evolution of the investment rate,
5. the evolution of the ratio of trade balance to GDP.

If parameters 2, 3, 4 and 5 are not quantified in the development plan, we use data and projections from the World Bank if available, or from other international organizations such as the International Labour Organization. If there is no quantified target for trade balance in the plan, we follow modelling practice and assume that it converges to 0 at horizon year. The trajectories chosen for all these parameters constitute the Reference scenario used in this step.

We then run this scenario in the KLEM model, which yields a GDP trajectory from base year to horizon year. If the GDP trajectory does not match the targets of the development plan, we introduce evolutions of the productivities of capital, energy and

materials in the composite sector (presented in Chapter 2 and mentioned in the model presentation below), which we explore within realistic ranges to try and reproduce the targeted GDP growth. We justify the relevance and determine realistic ranges for the annual growth rate of these parameters as follows:

- The productivity of energy in the non-energy sector is a key parameter, as it represents the energy intensity of the economy: a large increase in this parameter either means a structural change away from energy-intensive sectors (e.g. the development of the service industry), or large gains in energy efficiency. To determine a plausible range of values for its growth, we use historical evolutions of the economy-wide productivity of energy between 1990 and 2015, as shown in IEA Data reported by the OECD (OECD, 2017). As it has stayed relatively constant for some countries such as Portugal, Costa Rica or South Africa (even decreasing for Brazil), we set the minimum yearly growth of the range at 0%. The chosen maximum growth depends on the development priority of the studied country: for example, for a country that aims at industrializing, we set the maximum evolution at the historical evolution of BRIICS+ ($\times 1,6$ between 1990 and 2015, which corresponds to an annual average growth rate of 3,5%).
- The productivity of capital in the non-energy sector is a key parameter, as it represents the efficiency of the use of capital in the production: a large growth of this parameter can be a sign of technological advancements, rapid industrialization or infrastructure development. Growth values for this parameter thus depend a lot on the development level of the country (and can even be negative, particularly for developed countries), but are hard to estimate. To determine a plausible range of values for its growth for developing countries, we use historical evolutions of the economy-wide incremental capital-output ratios (ICOR, which represents the amount of investment required to generate an additional unit of output) between the 1990-2000 decade and the 2000-2010 decade, as featured in UNCTAD Data (UNCTAD, 2014). As it has stayed relatively constant in some regions (Asia) and countries (Namibia, Chad, Ethiopia), we set the minimum yearly growth of the range at 0%. We set the maximum yearly growth at 7% for least developed countries, which corresponds to the highest regional growth reported by UNCTAD Data on that period, for the African continent. For other developing countries, this growth rate is too high to be a realistic value. Historical rates for developing countries on the American continent are near 2.75%, we arbitrarily choose to test values until 3,5%. For developed countries, we base the realistic evolution (increase or decrease) on country-specific historical trends of capital productivity.

-
- The productivity of materials in the non-energy sector is a key parameter, as it represents the materials intensity of the economy: a large increase in this parameter either means a structural change away from materials-intensive sectors (e.g. the development of the service industry), or technological advancements leading to a decrease in the materials intensity of the economy. To determine a plausible range of values for its growth, we use historical evolutions of the regional material intensities for all sectors between 1970 and 2010, from the UNEP Global Material flows report (Schandl et al., 2016). As it has stayed relatively constant for example in Asia and the Pacific region or in Latin America, we set the minimum yearly growth of the range at 0%. As we have data by continent, we set the maximum yearly growth depending on the continent and development priority of the country. For example, for an African country that aims at industrializing, we set the maximum growth at 1,5% a year (which corresponds to historical trends for the continent, keeping in mind that the productivity of materials mainly increases in countries that develop their services industry).
 - The initial run of the model thus corresponds to the reference values for each parameter range, which assume no evolution of the three productivities.

The question underlying this step of the methodology is the following: are there sets of realistic parameter growths that can reproduce the targeted growth of the development plan, with the business-as-usual energy scenario and the other targets included in the development plan?

- If the answer to this question is no, then either the development document itself is internally inconsistent, or, if we have relied on institutional projections from the ILO or the World Bank to build the reference scenario, that targets of the plan are inconsistent with this data. A closer look at the creation of the plan might then help understand whether, for example, targets within the document came from different institutions with little coordination or whether there is another plausible cause for the inconsistencies.
- If the answer is yes, exploring the previously determined space of yearly growth rates for these three parameters allows to discuss the degree of compatibility between the plan's targets and the NDC's reference scenario.

We thus test combinations of three different values for each of the parameters, as well as other sets arbitrarily chosen to improve the precision of the first results. We finally keep all tested sets of yearly productivity growths that are compatible with the GDP

targets, and proceed to the third step, which aims at evaluating the compatibility of the development document targets, this time not with the NDC's reference scenario, but with the NDC's targets.

Step 3

We adjust the pathway of the energy system used in Step 2, so that it now translates the NDC's targets in terms of energy prices and consumptions, keeping the same assumptions about other exogenous data. Meeting the NDC's targets can for example imply higher energy costs (because of investment needs, or the costs of using clean energy sources), or a lower expected energy consumption - both these features having impacts on the country's GDP. For all sets of growth that, in Step 2, were compatible with the development plan's GDP targets, we compute new GDP trajectories with the updated scenario. The resulting trajectories might be different from the initial trajectory. If they fall below the GDP targets of the plan, depending on the development priority of the country, we then choose one parameter of interest (capital, energy or materials productivity in the non-energy sector). The question guiding this step is then: can we adjust this parameter while staying in a realistic range, to meet the GDP growth targets with the updated "NDC-targets" energy systems scenario? If there is a realistic parameter growth, we can conclude that the development targets of the country, as quantified in the development document, are consistent with the emission targets featured in the NDC (provided the selected parameter is adjusted as needed). If no, tensions underlying the reaching of both climate and development targets of the country can further be discussed, keeping in mind our rough modelling hypotheses.

4.2.2 KLEM variants and calibration

Summary of the framework and scenario inputs

The models considered here are dynamic variants of the KLEM (Capital-Labor-Energy-Material) structure. As presented in Chapter 2 Section 2.3, these KLEM variants are recursive dynamic models representing economic growth on annual time steps, aiming to simulate macroeconomic trajectories under exogenous constraints on unemployment, investment, trade balance, labour endowment and productivity, also with a complete exogeneity of the energy system. As its name conveys, the KLEM framework models two production factors (capital and labour) and two sectors, Energy and 'Materials' (an aggregate of all non-energy goods and services). The production of the non-energy sector

consists of nested Constant Elasticity of Substitution functions. On the consumption side, the model details the final consumptions of the two goods by households, public administrations and investment, as well as international trade.

To compute macroeconomic pathways, a KLEM variant takes, as an input, scenarios on the evolution of the energy sector. In each country case, we derive these scenarios from existing projections of the energy systems, one associated with the NDC reference scenario and another associated with the NDC's targets.

More specifically, the model requires as input the yearly evolution of prices and quantities regarding:

- Energy imports
- Energy exports
- Energy consumption of energy firms
- Energy consumption of non-energy firms
- Energy consumption of households
- The energy output trajectory flows from market balance

The dynamic variants of KLEM compute economic growth based on exogenous assumptions which include:

- the evolution of labour endowment L (usually derived from labour force projections, unless there is a specific target);
- the evolution of labour productivity ϕ_L (usually derived from labour force and GDP projections);
- the evolution of the unemployment rate;
- the evolution of the investment rate (also calibrated at base year);
- the evolution of the trade balance to GDP ω_B ;
- assumptions on the evolutions of capital productivity $\phi_{K,Q}$, energy productivity $\phi_{E,Q}$ and materials productivity $\phi_{Q,Q}$ in the composite sector.

The names of all variables and parameters of the models, as well as detailed equations are summarized and listed in Chapter 2 Section 2.3.2, and the scenario inputs, which are specific to each country case, are detailed in Sections 4.3 and 4.4, with exact values featured in Appendix C.

Model calibration on national data

All variants of the KLEM dynamic model used in this chapter are calibrated on aggregate 2-sector 2-factor input-output tables (IOT), which depict annual economic flows for countries or regions, balancing uses and resources. The calibration procedure builds on the correspondence of economic flows and products of model variables for base-year values (which we determine following the procedure detailed hereunder). Case-specific data sources and procedures are described in Sections 4.3 and 4.4 and in the Appendices.

By default, to obtain the tables, we first aggregate into two sectors corresponding to KLEM the 65-sector IOT of the Global Trade Analysis Project (GTAP 10) database (Center for Global Trade Analysis, Purdue University et al., 2019)¹¹ for its latest available year, 2014. The energy sector aggregates sectors 15 (coal), 16 (oil), 17 (gas), 32 (petroleum products), 46 (electricity) and 47 (gas manufacture). The non-energy sector aggregates the remaining 59 sectors. Capital payments r aggregate all GTAP non-labour value-added components that are not taxes, i.e. include land and natural resource rents. Output taxes aggregate all factor taxes and production taxes.

GTAP presents the advantage of providing globally consistent data, on a large group of countries, since 141 countries or regions are represented in the database. However, we need to reconcile the GTAP Input-Output data with the case-specific energy data on which energy scenarios after 2014 are based. To do so, we adjust the GTAP IOT to the energy quantities and prices calculated from energy-related data sources for 2014.¹² The procedure to create such an hybrid IOT is as follows:

- We substitute the GTAP values for the energy consumptions of households ($p_{C,E}C_E$), of the composite sector ($p_{EQ}\alpha_{EQ}Y_Q$), of the energy sector ($p_{EE}\alpha_{EE}Y_E$), as well as the energy imports ($p_{M,E}M_E$) and exports ($p_{X,E}X_E$) with quantities C_E , M_E , X_E , $\alpha_{EE}Y_E$ and $\alpha_{EQ}Y_Q$ obtained from the UNSD Energy balances for 2014 (United Nations Department of Economic and Social Affairs, 2017) and prices $p_{C,E}$, p_{EQ} , p_{EE} , $p_{M,E}$ and $p_{X,E}$ obtained from country-specific sources.
- We then adjust final uses and imports of the non-energy good ($p_{C,Q}C_Q$, $p_{M,Q}M_Q$, and $p_{X,Q}X_Q$) to ensure that the sum of both sectors for each use remains as in the GTAP initial IOT (e.g., ensuring that $p_{C,E}C_E + p_{C,Q}C_Q$ is identical for the GTAP IOT and the hybrid IOT).

¹¹Database available from www.gtap.agecon.purdue.edu

¹²Country-specific procedures related with the available data are detailed in the case studies and in the Appendices

- We adjust the resources used by the energy sector ($p_{QE}\alpha_{QE}Y_E$, $p_{L,E}\lambda_E Y_E$, $\tau_{L,E}wL_E$, $\tau_{Y,E}p_{Y,E}Y_E$, $\tau_{R,E}p_{Y,E}Y_E$, rK_E), other than its energy consumption and imports, to ensure that the total sum of resources for the energy sector is balanced with the sum of energy uses. We keep the initial GTAP proportion of each resource in the total resources for the energy sector, by multiplying it and its GTAP value by the updated sum of energy uses.
- We finally adjust the intermediate consumption of composite in the non-energy sector ($p_{QQ}\alpha_{QQ}Y_Q$) so that the sum of all intermediate consumptions keeps its initial GTAP value. We adjust the other resources of the non-energy sector ($p_{L,Q}\lambda_Q L_Q$, $\tau_{L,Q}wL_Q$, $\tau_{Y,Q}p_{Y,Q}L_Q$, $\tau_{R,Q}p_{Y,Q}L_Q$, rK_Q) to ensure that the sum of each resource (e.g. $p_{L,Q}\lambda_Q Y_Q + p_{L,E}\lambda_E Y_E$) is equal to the initial GTAP value. This also ensures a balance in the sum of resources and uses in the non-energy sector.

Finally, end-user prices in the energy sector might differ from one user to the other, either because of different taxation levels or because of additional distribution costs. To allow for a gap between pure production costs and end-user prices, agent-specific margins $\tau_{MSE,Q}$, $\tau_{MSE,E}$, $\tau_{MSC,E}$ and $\tau_{MSX,E}$, as detailed in the paragraph on prices in Chapter 2 Section 2.3.1, are introduced for the energy sector. They are calculated by computing the average price of energy supply $p_{S,E}$,¹³ then computing the base-year agent-specific margins from equations (28*) and (29*) in Chapter 2 Section 2.3.2.

The margins $\tau_{MSE,Q}$, $\tau_{MSE,E}$, and $\tau_{MSC,E}$ need to evolve over time, to maintain consistency between the endogenous price system in KLEM and the scenarized energy prices. Indeed, projections of energy prices coming from energy-systems models are calculated assuming that all other relative prices are constant (composite good markets are not represented). As non-energy production factors are represented endogenously in KLEM, their relative prices evolve over time, with links and retroactions for example between energy prices in the composite sector p_{EQ} and investment costs $p_{I,Q}$, that are not represented in the energy price inputs. However, these inputs represent evolutions in the energy mix and in the costs of investment and maintenance of energy technologies. We thus adjust specific margins to reproduce these variations in KLEM while accommodating for the endogenous price system. To do so, we follow a procedure

¹³From the equations detailed in Chapter 2 Section 2.3.2, we get:

$$p_{S,E}S_E = p_{QE}\alpha_{QE}Y_E + p_{EE}\alpha_{EE}Y_E + p_{L,E}\lambda_E Y_E + p_{K,E}k_E Y_E + \tau_{R,E}p_{Y,E}Y_E + p_{M,E}M_E$$

detailed in Sarre (2021)¹⁴ and in (Su et al., 2022)¹⁵. It consists in building "pseudo-price" $p_{C,E}^{BU}$, p_{EE}^{BU} , and p_{EQ}^{BU} trajectories from KLEM equations, that reproduce the logic behind the energy-systems model prices. They are calculated for each year using an energy supply price $p_{S,E}^{BU}$, computed from KLEM price equations assuming that only the energy intensity of the energy sector α_{EE} and its market price p_{EE} (which are directly obtained from the scenarized model inputs) evolve. We then deduce, for each year, which variation of the specific margins is needed to equalize these "pseudo-prices" with their scenarized model input counterpart, which gives us the evolution of the specific margins over time.

Sensitivity to the choice of closure and elasticities of substitution

As shown in Chapter 3, the choice of macroeconomic closure has an impact on the model outputs. By default, we use the neoclassical closure, in which savings determine the level of investment. However, we additionally run the models using a Johansen closure, in which households' savings adapt to secure the required volume of investment, which allows for a better control of growth trajectories.¹⁶

Moreover, the model is based on four Constant Elasticity of Substitution functions, for which an important parameter is the elasticity of substitution. Elasticities differ depending on industries and countries (Van Der Werf, 2008; Okagawa and Ban, 2008; Antoszewski, 2019; Hertel and van der Mensbrugghe, 2016). Unlike in Chapter 3, we only need elasticities of substitution for the non-energy sector as the energy sector is fully exogenous. By default, we average the elasticities of substitution of all non-energy sectors found in Antoszewski (2019) and Hertel and van der Mensbrugghe (2016), unless country-specific estimations are available. The values of the elasticities used are summarized in Appendix C. However, as elasticities have been shown to have a great impact on the model outputs (Okagawa and Ban, 2008), for countries for which we use these default values, a sensitivity analysis is done by testing results for lower ($\times 0,5$) and higher ($\times 1,5$) elasticity values.

¹⁴This Masters' thesis is available on demand

¹⁵See Annex D of this reference

¹⁶Here, we only implement an additional closure to get a first glance at how GDP trajectories evolve with different model closures. Further extensions of this work will make it possible to run the model for the 8 model closures presented in Chapter 3, to get a more comprehensive picture of the impacts of the choice of closure on the model's outputs.

4.2.3 Potential coverage of the methodology and choice of country cases

This methodology is designed to be flexible enough to cover a wide range of country cases, by taking into account the information available in the development plans and NDCs (as long as it can be translated into the scenarios of Steps 2 and 3).

However, long term development documents collected in Chapter 1 and (albeit less frequently) NDCs, do not necessarily feature quantified targets. As little data-intensive as the methodology might be, it still requires quantified targets for a minimal set of indicators. Precisely:

- NDCs need to feature at least business-as-usual as well as target GHG emissions trajectories, (ideally, with a sectoral breakdown of emission targets between the energy sector and the rest of the economy, and a projected energy mix).
- Development documents need to feature at least a GDP growth target (ideally, with a more precise sectoral breakdown, with for example information on the share of the industrial sector to GDP for countries that aim at industrializing).

Out of the 121 countries with development documents in our database, 86 include quantified targets in one plan or vision, of which 53, listed hereafter, have a quantified GDP target and a NDC.

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List of countries with a NDC and a long-term development plan/vision that includes a quantified GDP target.

- Angola
- Armenia
- Bahamas
- Bangladesh
- Barbados
- Belarus
- Botswana
- Brazil
- Bulgaria
- Burundi
- Cambodia
- Cameroon
- Chad
- Colombia
- Djibouti
- Dominica
- Egypt
- Ethiopia
- Fiji
- Ghana
- Grenada
- Guatemala
- Honduras
- Indonesia
- Kenya
- Kiribati
- Latvia
- Lesotho
- Malawi
- Malaysia
- Mauritania
- Micronesia
- Mongolia
- Montenegro
- Mozambique
- Namibia
- Nepal
- Oman
- Pakistan
- Panama
- Papua New Guinea
- Rwanda
- Saint Vincent and the Grenadines
- Samoa
- Senegal
- Solomon Islands
- South Africa
- Sudan
- Suriname
- Tajikistan
- Tonga
- Uganda
- Viet Nam
- Yemen

Interestingly, most of the listed countries are developing countries on which the country-specific literature in energy and economic modelling is still scarce or non-existent. They are also typically not "visible" in global models, where they are aggregated in broad regions. The proposed methodology is thus relevant for at least some countries.

To provide policy-relevant insights, the methodology must also be able to capture (even if in a stylized way), the key features of the development pathway that the country is aiming to follow. As noted in Chapter 1, some countries put forward an overarching

target of peace and reconstruction, others prioritize environmental sustainability, and yet others target a structural change of their economy away from one sector (for example oil in oil-exporting countries) or towards the development of, inter alia, the agro-industry sector, the industry, tourism or services. Some countries, finally, do not display a specific development pathway (Table 4.1).

Each development pathway comes with specific tensions with climate targets. For example, countries that seek to industrialize may see tensions appear around the energy intensity of their economy. Countries that aim at diversifying away from oil might be constrained by the evolution of international fuel prices in a global climate mitigation scenario. Some of these tensions can be captured in the current KLEM model. Others would require further developments. For example, countries that prioritize recovery from an environmental disaster might see an important growth of their construction sector, which is not currently modelled through the presented KLEM framework. A summary of the main development orientations as well as the associated prioritized SDGs, and possible trade-offs with climate targets to represent in a model, is displayed in Table 4.1.

In this chapter, we test our methodology on three countries that illustrate three different priorities, for which the methodology might be relevant: Malawi, which aims at developing its industry (National Planning Commission, 2020), Colombia, which puts forward environmental aspects of its development (Departamento Nacional de Planeación, 2022), and Iraq,¹⁷ which aims at diversifying its economy away from oil (Ministry of Planning, 2020).¹⁸ Sections 4.3, 4.4 and 4.5 present first results obtained on these country cases.

¹⁷Although not featured in the previous list, Iraq is included here to discuss the applicability of the methodology in a context where the needed targets are not available

¹⁸Ongoing extensions of the KLEM framework will enable the addition of an agricultural sector, thus adding relevance in modelling countries that specifically target agriculture, such as Bolivia or Burundi.

Table 4.1: Main development orientations of documents featured in the database created in Chapter 1, and possible trade-offs with climate targets

Name	Main orientation	Prioritized SDGs	Possible tensions	Example
Reconstruction	Recovering from war or an environmental disaster	16 (institutions), or 9, 11 (cities, infra.)	Construction sector + investment	Nepal, South Sudan
Green development	Environmental sustainability	13,14,15 or all with focus on the environment	Financial/technical constraints	Bhutan, Montenegro
Structural change - Diversification	Usually, diversification away from oil sector	8 (economy), 9 (innovation)	International climate targets Stranded assets	Iraq, Algeria,
Structural change - Agriculture, fisheries	Food security and/or agr. exports	2 (food)	Agriculture-related emissions + land use	Bolivia,
Structural change - Industry	Industrialization	8 (economy), 9 (industry)	Energy intensity and emission intensity of energy	Malawi,
Structural change - Tourism, services	Tertiary sector	8 (economy)	Infra., tourist flows (qualitative discussion)	Botswana,
Others	General development	Not specific	Not specific	Germany, Mexico,

4.3 Application of the methodology to the case of Malawi

4.3.1 Context

Located in Southeastern Africa and identified as one of 45 Least Developed Countries, Malawi had, in 2022, a population of over 20 million inhabitants, a per-capita GDP of 645 current US dollars, and an average yearly economic growth of 3,65% between 2012 and 2022 (source: World Bank Data). Malawi's economy heavily relies on agriculture, with a significant portion of the population engaged in subsistence farming. Specifically, agriculture, forestry and fishing accounted for 23,3% of Malawi's GDP in 2020, and for 80% of Malawi's exports (mostly tobacco).

In 2021, Malawi's National Planning Commission published its "Vision 2063" (National Planning Commission, 2020), which replaces a previous "Vision 2020". Vision 2063 is the result of a large consultative process involving many stakeholders, with the support of international partners (including the United Nations). In this document, Malawi envisions a large change in the structure of its economy centered around industrialization: among other targets, the shares of the manufacturing and mining sectors are envisioned to grow from 11.5% and 0.8% of the GDP in 2020, to 33% and 25% in 2063. Environmental goals, on the other hand, are among the "barely mentioned" ones (Appendix C displays the figure obtained with Chapter 1's visualization tool for Malawi), and while the document features a cap on the "carbon footprint" (i.e., here, CO₂ emissions), its 25 *GtCO₂* value in 2040 is not restrictive (or is a mistake) as the NDC's reference emissions are projected to be around 35 000 *ktCO₂*. Although Vision 2063 was released in 2020, there is neither mention of the Paris Agreement nor mention of domestic mitigation targets featured in the NDC. Vision 2063 provides quantified development targets up until 2063 (with milestones in 2030, 2040, 2042, 2050 and 2060) that we summarize in Table 4.2.

As a Party to the Paris Agreement, Malawi has produced a Nationally Determined Contribution through its Ministry of Forestry and Natural Resources, with a recent updated version (Republic of Malawi, 2021) which mitigation component is summarized in Figure 4.2. The bulk of the NDC revolves around adaptation, since Malawi is particularly vulnerable to climate change and extreme weather events and currently emits limited amounts of greenhouse gases (around 0.5 *tCO₂e* per capita in 2017, source: NDC). However, the NDC also includes quantified mitigation targets up to 2040. Relative to the reference scenario, greenhouse gases emissions are expected to be reduced by 6% in 2040 via domestic efforts, and by an additional 45% conditional on

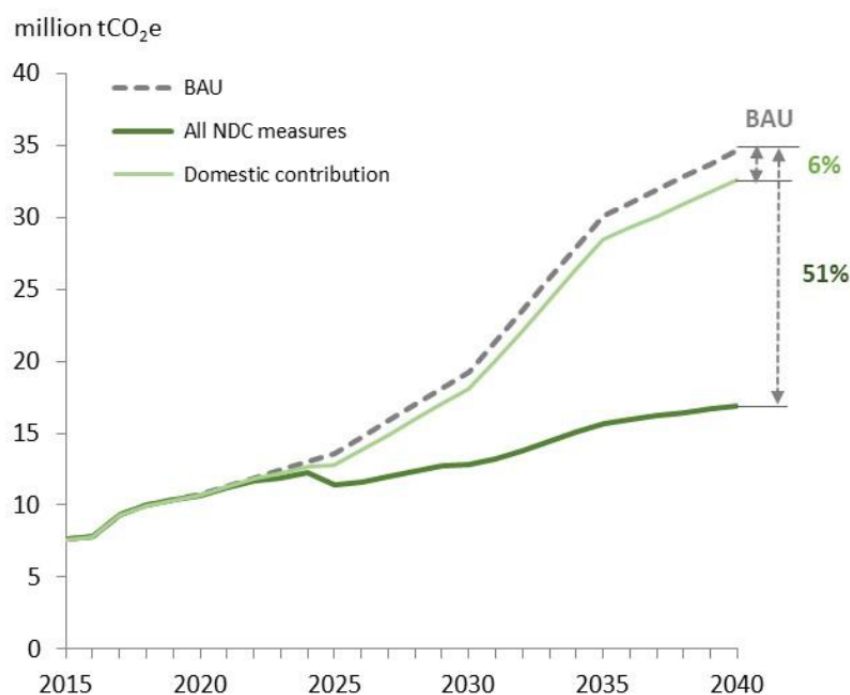
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Table 4.2: Selection of targets displayed in Malawi's Vision 2063

Indicator	Ref value (base year)	2030 target	2040 target
GDP growth	4,6% (2018)	6%	6,2%
Unemployment	21% (2013)	17,2%	13,6%
Share of manufacturing to GDP	11,5% (2020)	12,6%	18,7%
Share of mining to GDP	0,8% (2020)	10%	16,3%
Population growth rate	2,69% (2020)	2,1%	1,8%
Energy generation to energy demand	71,8% (2019)	100%	100%
Access to electricity	12,4% (2020)	50%	75%
CO ₂ emissions (kt)	1 298 (2016)	≤ 10 000 000	≤ 25 000 000

international financing. Most of the mitigation potential is expected to be in the energy sector. The NDC estimates that the country needs around \$46,3 billion between 2020 and 2040 to reach its mitigation and adaptation targets.

Figure 4.2: Climate mitigation targets as featured in Malawi's NDC



Source: Malawi's Updated Nationally Determined Contribution (2021)

4.3.2 Application of the methodology

Step 1

Both climate and development documents for Malawi feature quantified targets up until 2040, which we thus set as the horizon of this case study. In Step 1, we compare the evolution of energy-related emissions that can be projected with development targets in the Vision 2063 (*Dev*), with the evolution that is displayed in the reference scenario of Malawi's NDC (*NDCbase*) - noting that energy-related emissions are the main driver of national emissions.

Energy-related emissions of the reference scenario are directly displayed in the NDC, which means obtaining *NDCbase* is straightforward. To get a first estimation of the evolution of energy-related emissions as envisioned in Vision 2063 (*Dev*), we compute the country's GDP from its 2020 World Bank Data value (in constant 2017 Int\$) to 2040 (assuming a yearly growth equal to the 2030 target until 2030 and to the 2040 target until 2040). We then draw, from Malawi's UNSD energy balance sheets, the 2020 energy consumptions of the mining and manufacturing industries on the one hand, the rest of the economy's energy consumption on the other hand. Assuming a linear growth of the industry's GDP share from its 2020 value to the 2030 and 2040 targets, and a constant energy intensity for each of the two aggregated sectors, we estimate the economy's energy consumption until 2040. We add the energy consumption of the energy transformation sector, for which we assume a similar growth as the industrial sector, plus an additional growth translating the 2063 Vision's target of generating 100% of the energy demand in 2030. This creates a first estimation of the evolution of Malawi's energy supply, and, assuming that the carbon intensity of the energy mix stays constant, of the energy-related emissions associated with Vision 2063's targets.

In a first approximation, the reference path of emissions proposed in the NDC is consistent with the emissions that can be projected from the development vision. Precisely:

- In the national development plan, Malawi's energy-related emissions (*Dev*) are projected to reach 2,7 times their 2020 level in 2030, and 6,5 times their 2020 level in 2040.
- In the NDC, the energy-related emissions of the reference scenario (*NDCbase*) are projected to be multiplied by 2,9 in 2030 and by 7 in 2040.

The difference between the two trajectories is relatively small, and can be explained by our first assumptions (for example, a constant carbon intensity of the energy mix). Following this result, as outlined in Figure 4.1 it is relevant to proceed to Step 2.

Step 2

Model calibration and scenarios We calibrate the KLEM model on Malawi following the generic procedure presented in Section 4.2, and which we detail in Appendix C. We aggregate data from a 2014 GTAP input-output table (IOT) (Center for Global Trade Analysis, Purdue University et al., 2019), and hybridize it based on the 2014 UNSD Energy balance sheet (United Nations Department of Economic and Social Affairs, 2017) for Malawi, building energy user prices from International Renewable Energy Agency data on energy production costs for the Southern African Power Pool (Miketa and Merven, 2013), as well as information on the power mix of Malawi (IRENA, 2021).

We use the above sources and calculations so that the energy prices that we compute to build the scenarios in Steps 2 and 3, detailed below, are calculated using the same sources and calculations as for the year 2014. There has indeed been little attention on energy prices in Sub-Saharan Africa (Luhangala et al., 2022) and for most existing energy-system models and exercises including Malawi, the country is not considered in isolation, but aggregated with other countries. For example, in the POLES bottom-up model (European Commission Joint Research Centre, 2018)¹⁹, Sub-Saharan Africa is one aggregated region, for which Ivory Coast is used as a proxy for data on electricity demand. In another report (European Commission Joint Research Centre, 2019) based on the TEMBA electricity supply model, Malawi is aggregated with the Southern African Power Pool, which includes other countries with very different electricity mixes than Malawi. None of these exercises is representative of Malawi, since the 2014 electricity mix of Malawi very largely consists of hydroelectric power.²⁰

We build a reference scenario (*Ref_IRENA*) for the energy system of Malawi, based on energy demand volumes computed from Malawi Vision 2063 (ventilated across end-uses using hypotheses from the plan, as detailed in Appendix C), and energy prices based on IRENA's country-specific projections of the costs of technologies and distribution (Miketa and Merven, 2013) as well as the electricity mix obtained with the

¹⁹which is one of the models that has already been soft-linked with the KLEM macroeconomic model (Sarre, 2021)

²⁰The TEMBA model, however, exists at the national scale for Malawi, and the use of its country-specific results presented in Pappis (2022) is discussed below.

agency's electricity system model SPLAT (IRENA, 2021). We choose IRENA's report as a source as its reference scenario is consistent with Malawi's Vision 2063 and NDC (in other reports using the TEMBA model, the exogenously set final energy demand and the annual emissions associated with the reference scenario are considerably lower than envisioned in the country's documents). However, as this work only depicts the evolution of Malawi's electricity sector, to compute energy prices, we assume that the shares of other fuels in the final energy demand evolve similarly to the Southern African Power Pool as proposed in European Commission Joint Research Centre (2019) (but keeping a volume of energy demand that is consistent with Malawi Vision 2063 and the NDC reference scenario). Other assumptions to compute energy volumes and prices, as well as the full set of variables in the KLEM model are detailed in Appendix C.

Following the methodology proposed in Section 4.2, we run a KLEM variant with a neoclassical closure option under the *Ref_IRENA* scenario, and compute GDP trajectories for several combinations of assumptions on the growth rates of capital, energy and materials productivities in the non-energy sector. More specifically, we pre-determine values of interest for these yearly growth parameters (as justified in more detail in Section 4.2):

- For the productivity of energy in the non-energy sector, as Malawi aims at developing its industry, we test a 0% growth, a 1,75% growth and a 3,5% growth, based on historical evolutions for BRIICS+ (OECD, 2017).
- For the productivity of capital in the non-energy sector, as Malawi is part of the Least Developed Countries, we test a wide range of growths based on historical regional evolutions (UNCTAD, 2014): a 0% growth, a 3,5% growth, and a 7% growth.
- For the productivity of materials in the non-energy sector, based on historical evolutions for the African continent (Schandl et al., 2016), we test a 0% growth, a 0,75% growth, and a 1,5% growth (although keeping in mind that the productivity of materials increases less in countries that develop their industry, which means the possibility of reaching this last value can be discussed).

To get a more precise view on which sets of values allow the model to reach Vision 2063's GDP growth targets (which are 6% in 2030 and 6,2% in 2040), and based on the results with these 27 sets, we also test 6 other sets with arbitrary values within the determined ranges to get more precision on the boundaries of the parameter space that reproduces the targets.

Figure 4.3 shows the GDP growth evolution computed by the neoclassical KLEM variant under the *Ref_IRENA* reference scenario for Malawi, for the 33 sets of yearly growths in the productivities of energy, capital and materials in the non-energy sector. We show that the plausible range of growths for the three parameters, for which the GDP targets of Malawi Vision 2063 are reproduced, is large. Among the tested sets, only five do not meet Vision 2063's targets: the reference scenario, all the scenarios in which only the productivity of energy in the non-energy sector grows, one scenario for which the productivity of materials grows 0,1875% a year, and one scenario for which the productivity of capital grows 0,4375% a year. Growth is particularly sensitive to changes in capital and materials productivities in the non-energy sector: small increases in these parameters, alone or combined with other productivity growths, yield higher GDP growths that reproduce the Vision targets. However, it is impossible to meet the targets by only modifying the productivity of energy in the non-energy sector within a plausible range. We conclude that for the development plan targets to be met, there needs to be a growth in the productivity of capital in the non-energy sector and/or in the productivity of materials in the non-energy sector. The growth rates that are necessary to meet the GDP targets are, however, rather low given the circumstances of Malawi.²¹

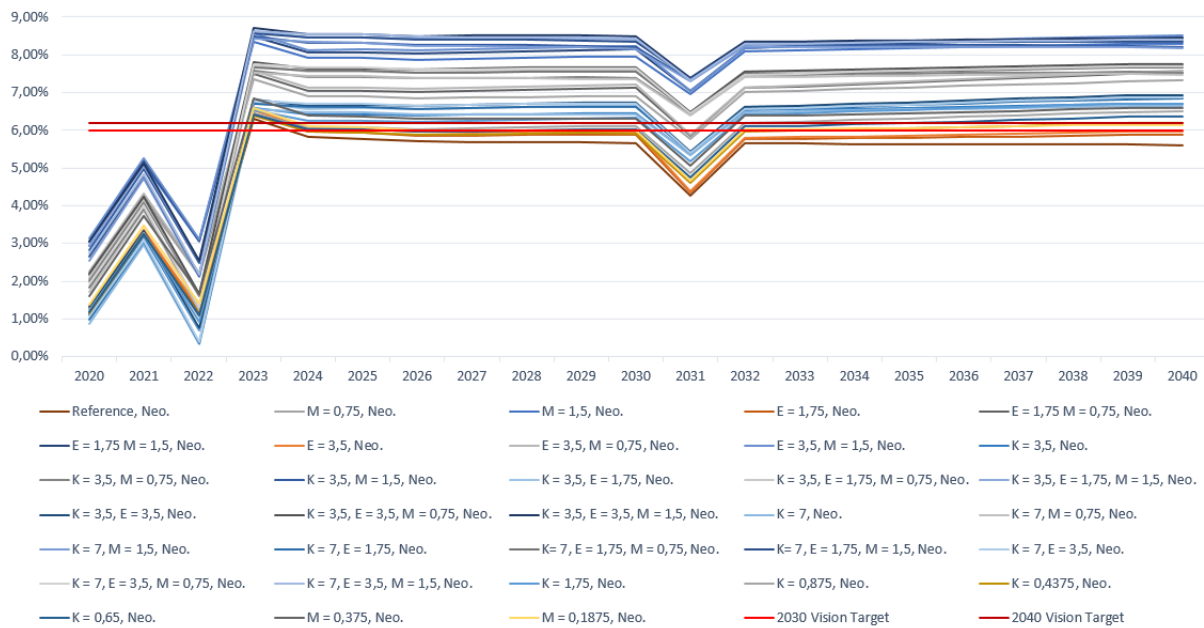
Additional results running a Johansen closure and sensitivity analyses on CES substitution elasticities, presented in Appendix C, also show large ranges of values compatible with Vision 2063's growth targets (for a Johansen closure, the ranges of growths that match the Vision targets are even larger, as the yielded GDP growths are higher for a same set of parameters). This would indicate a numerical robustness of results, but would need to be confirmed on running additional, more different closures.

We thus conclude that the plan targets are largely compatible with one another and with institutional data used to calibrate KLEM, to the extent that a small growth rate in the productivity of capital enables to meet the GDP targets.

²¹Especially for the growth in the productivity of capital, for which larger values can be expected

4.3. Application of the methodology to the case of Malawi

Figure 4.3: Evolution of GDP growths under the Reference scenario of Malawi, depending on evolutions of capital, energy and materials productivities in the non-energy sector



Each line represents a different set of growths of capital, energy and materials productivities in the non-energy sector. The name of the scenario includes the growth considered for each parameter in the scenario (K for capital productivity, E for energy productivity, M for materials productivity). If the parameter does not evolve, it is not mentioned. The series in shades of orange do not meet the GDP targets. Discrepancies before 2022 are due to the fact that the model takes real data for exogenous assumptions up until this year. In 2031, there is a slight discrepancy due to the change of slopes between 2020-2030 and 2030-2040 exogenous targets.

Step 3

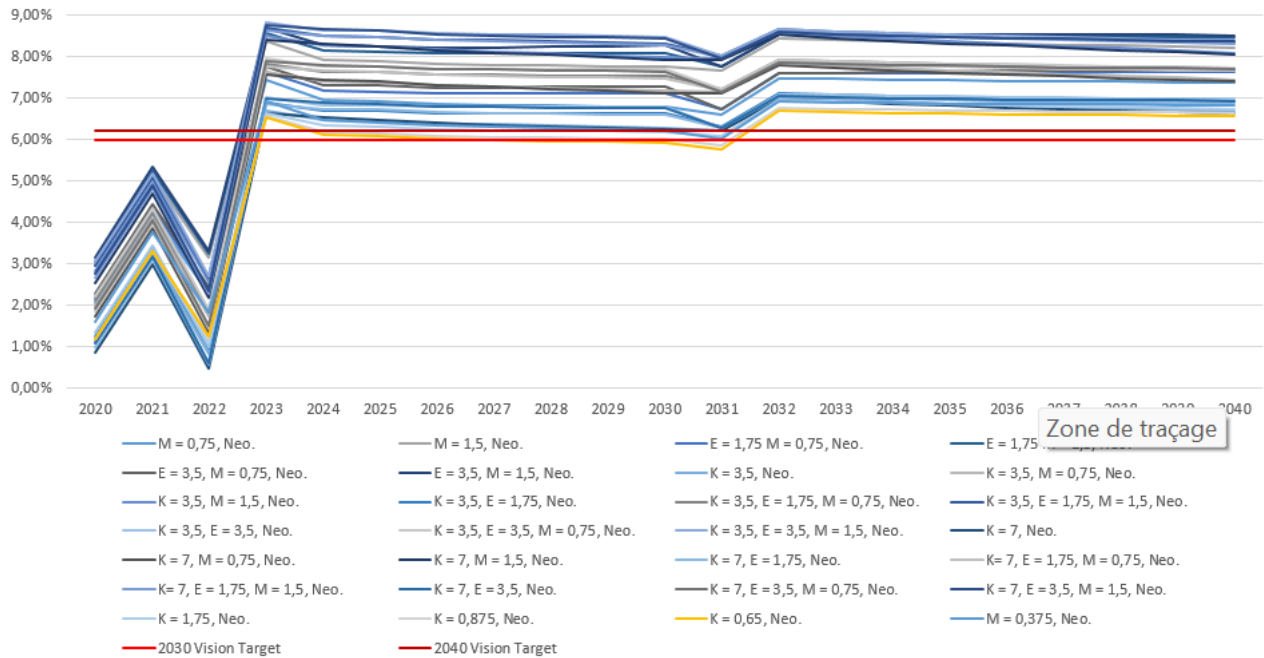
As discussed above, the conditional target of Malawi's NDC is to reduce its energy-related emissions by 15,1 $MtCO_2eq$ in 2040 relative to the reference scenario (19,83 $MtCO_2eq$), a 78% decrease. According to the NDC, around 50% of this reduction should be covered by CCS technology on coal plants, around 30% by changes in the energy mix and around 20% by a decrease in energy demand. This implies a 15,6% reduction of the demand in energy in 2040, that we ventilate on all consumers following a procedure detailed in Appendix C. We then compute energy prices in a similar way as for the reference scenario, using the electricity mix of the "High Renewable Energies" scenario proposed by IRENA (IRENA, 2021), with CCS price for coal generation, and keeping the rest of the fuel proportions in the energy mix consistent with the "2°C scenario" from European Commission Joint Research Centre (2019).

In Step 3, we select the 28 sets of capital, energy and materials productivity growth rates that, in Step 2 (under the reference scenario), were compatible with Malawi's Vision 2063 GDP growth targets. We then run the ***NDC_IRENA*** scenario with these sets. This yields different GDP growth trajectories: the resulting evolutions are presented in Figure 4.4. If the growth now computed by KLEM under the NDC scenario is not consistent with Vision 2063's targets, which is the case for only one series (displayed in orange, for which the GDP growth falls short of the Vision targets by 0.07%), we adjust the growth of productivity of energy in the non-energy sector to determine if there are values within the pre-determined range that can be compatible with the GDP growth targets. In this case, increasing growth in the productivity of energy within the pre-determined range is enough to meet the targets.

For all the other sets for which GDP growth met the Vision targets in Step 2, GDP growth targets are also met in Step 3, without any need to adjust the productivity of energy in the non-energy sector. Growth is even higher for some years. This is probably due to the fact that we use the High Renewables scenario proposed by IRENA. As expected, energy prices are higher in this scenario due to investment needs to decarbonize the energy mix (energy prices reflect the Levelized Costs of Energy, thus including investments), which should have an impact on the GDP growth. However, the large share of renewables implemented in this scenario reduces fuel demand in the power sector, and thus energy imports (as Malawi imports all its oil and gas, and most of its coal after 2024). There are also less electricity imports, which is, in itself, compatible with the Vision 2063's target ratio of energy generation to energy demand. ²²

²²Appendix C reproduces Steps 2 and 3 with reference and NDC scenarios solely based on European

Figure 4.4: Evolution of GDP growths under the NDC scenario of Malawi, depending on evolutions of capital, energy and materials productivities in the non-energy sector



Each line represents a different set of growths of capital, energy and materials productivities in the non-energy sector. The name of the scenario includes the growth considered for each parameter in the scenario (K for capital productivity, E for energy productivity, M for materials productivity). If the parameter does not evolve, it is not mentioned. The series in orange does not meet the newly GDP targets without a modification of the productivity of energy. Discrepancies before 2022 are due to the fact that the model takes real data for exogenous assumptions up until this year. In 2031, there is a slight discrepancy due to the change of slopes between 2020-2030 and 2030-2040 exogenous targets.

In sum, the analysis above leads to the conclusion that Malawi’s climate targets, as proposed in its NDC, and its economic development targets proposed in Vision 2063 are largely consistent with each other, in the sense that the GDP growth targets can be reproduced under the mitigation scenario, within a rather large space of realistic growths in the productivities of capital and materials in the economy. However, the productivity of energy in the non energy sector has little impact on the model’s outputs, which means this parameter alone cannot help reproduce the GDP targets - there still needs to be a growth in the productivities of capital and materials. This might be due

Commission Joint Research Centre (2019) (bearing in mind that this scenario did not exactly match the NDC’s reference nor its targets). We also find a large range of values for which the GDP targets are met.

to the fact that the energy sector still represents a very small share of Malawi's activity, and the current productivity of energy might be too low for a realistic growth to have a significant impact on the GDP.

Finally, this result indicates that some of the targets featured in the NDC and in the development plan are consistent. It does not necessarily mean that they are realistic. As we discussed above, the electricity system pathway proposed in the High Renewables Scenario seems rather ambitious compared to other scenarios proposed for Malawi's energy system (which are not, however, based on the development plan's targets). The results might then be rather dependent on the techno-economic data used to model the energy system (and particularly data used to compute the levelized costs of energy of different technologies). The expansion of CCS technologies, targeted in Malawi's NDC, is also a strong assumption. As Malawi aims at rapidly expanding its industrial sectors, examining potential sources of incompatibilities with other Vision 2063 targets not encompassed within KLEM (e.g. on water or environmental sustainability), remain interesting.

4.4 Application of the methodology to the case of Colombia

4.4.1 Context

Located in the north-west of South America, Colombia is an upper-middle-income country which had, in 2022, a population of over 51 million inhabitants, a per-capita GDP of 6 624 current US dollars, and a GDP growth of 7,3 % following post-Covid recovery (Source: World Bank Data). It joined the Organisation for Economic Cooperation and Development (OECD) in 2020, and is an accession country for the International Energy Agency (IEA) since 2021. The country faces development challenges that revolve around inequalities, institutions and, notably, climate change. Colombia is an important exporter of oil and coal: it exports, for example, around 90% of its coal production (International Energy Agency, 2023), which means that ambitious mitigation targets of its trading partners might come with challenges for the country in the future.

In 2022, Colombia's National Department of Planification published its "Vision 2050" (Departamento Nacional de Planeación, 2022), with an overarching goal of

ensuring the sustainable well-being of its population. This overarching goal rests on four pillars, namely a consolidation of the middle-class, a development model that benefits all territories, an emphasis on technologies, and a transformation of the energy system with the aim of reaching carbon-neutrality by 2050. It integrates and cites other long-term agendas and sectoral plans, such as a national energy plan (Ministerio de Minas y Energía, 2016) and a long-term low greenhouse gas emission development strategy (MinAmbiente, 2021) for 2050. The Paris Agreement and Colombia’s climate targets are thus an integral part of the country’s development document, which also provides various quantified development targets for 2050 that we summarize in Table 4.3.

Table 4.3: Selection of targets displayed in Colombia’s Vision 2050

Indicator	Ref value (base year)	2030 target	2050 target
Net GHG emissions ($MtCO_{2eq}$)	233,58 (2015)	169,44	0
Unemployment	13,7% (2021)	9,8%	5%
GDP growth	10,6% (2021)	4%	5%
TFP growth	0,6% (2021)	0,8%	1,1%
GDP/h worked (\$-ppp 2015)	16,4 (2020)	28,9	54
GDP/capita (\$)	6,197 (2022)	8,685	31,184
Investment growth	8,7% (2022)	6,1%	6,6%
Export growth	5,6% (2022)	6,4%	7,2%
Import growth	7,4% (2022)	6,5%	6,6%
Share of renewables and hydrogen in the energy mix	24,36% (2019)	35%	43%
Energy efficiency (useful energy/total final consumption)	31% (2019)	41,1%	50%

As a Party to the Paris Agreement, Colombia has produced a Nationally Determined Contribution, and updated it in 2020 (Gobierno de Colombia, 2020). The content of the first NDC included an unconditional 20% emission reduction in 2030, and an additional conditional 30% reduction, compared to a reference scenario. In the updated NDC, the reference scenario has been revised and there is an unconditional mitigation target of 51% relative to the new reference: the target is now to limit emissions to 169 $MtCO_{2eq}$ in 2030, with a longer-term aim of reaching carbon neutrality in 2050, that mobilizes key sectors including energy, transportation, and land use.²³

²³In 2023, the President announced a halt in the signing of new hydrocarbon exploration contracts, and at the COP28 in december 2023, that Colombia joined an alliance calling for a fossil-fuel non-proliferation treaty (Greenfield, 2023). To the extent of our knowledge, these engagements are not included in long-term planification documents as of yet, but might feature in the upcoming update of the National Energy Plan.

4.4.2 Application of the methodology

Step 1

Both climate and development documents for Colombia feature quantified targets up until 2050 (2050 in the Vision, 2030 with a mention of carbon neutrality in 2050 in the NDC). In Step 1, we compare the 2030 levels of GHG emissions that can be projected with development targets in the Vision 2050 (*Dev*) with the reference scenario of Colombia's NDC (*NDCbase*).

GHG emissions in the reference scenario are explicitly stated in the NDC. Computing *NDCbase* is thus straightforward. Unlike in the case of Malawi, there are detailed GHG emissions targets in the Vision 2050 as well, which correspond to the NDC emission reduction target: both the Vision and the NDC target a GHG emission level of 169 $MtCO_{2eq}$ in 2030 (and net-zero emissions in 2050). This means that the *Dev* and *NDCbase* emission trajectories are not equivalent (the reference scenario in the NDC reaches 345,8 $MtCO_{2eq}$ in 2030).

The difference with Malawi is that both Colombia's initial and updated NDCs pre-date the Vision 2050 and were included in it. The current NDC targets are formulated relative to a reference scenario (developed with a LEAP model for Colombia (Correa-Laguna et al., 2021)) that does not include mitigation actions, where emissions are mainly driven by projections of the GDP and population growths, as well as projections of the supply of fossil fuels (Pelgrims et al., 2020a). The target for 2030 corresponds to the emission level projected by the LEAP model when implementing a proposed set of mitigation actions (Pelgrims et al., 2020b). The net-zero target for 2050, however, is not based on detailed modelling projections. In fact, the technical report on which the NDC is based states that the proposed mitigation actions are not in line with carbon-neutrality in the long-term.

Although *Dev* and *NDCbase* differ, it is still relevant in this case to proceed to Step 2 of the methodology. However, since the Vision 2050 already integrates the NDC's targets, we directly explore the space of capital, energy and materials productivity growths for which GDP growth targets in the plan can be met in the context of the plan (and NDC) climate targets, (namely 169 $MtCO_2$ in 2030 and net zero in 2050).

Step 2

Model calibration and scenarios We calibrate the KLEM model on Colombia following the generic procedure presented in Section 4.2 (detailed in Appendix C). We aggregate data from a 2014 GTAP input-output table (IOT) (Center for Global Trade Analysis, Purdue University et al., 2019), and hybridize it based on the 2014 UNSD Energy balance sheet (United Nations Department of Economic and Social Affairs, 2017) for Colombia, building energy user prices from data from Cannone et al. (2021) and Ministerio de Minas y Energía (2015).

There is no clear target for the energy sector in the Vision or in the NDC. The literature offers several trajectories for Colombia’s energy system (International Energy Agency, 2023). They include trajectories built using the GCAM (Delgado et al., 2020; Bataille et al., 2020), LEAP (Correa-Laguna et al., 2021), OSeMOSYS (Plazas-Niño et al., 2023b) models, or soft-linkages between bottom-up and top-down models such as M, MEG4C and MARKAL (Winkler et al., 2017). However, only Plazas-Niño et al. (2023b) is up to date with Colombia’s current mitigation target: most other trajectories either translate the targets of the initial NDC,²⁴ or are in line with the current 2030 target, but do not lead to net-zero emissions in 2050. The implications of the Paris Agreement for Colombia’s energy exports are also systematically overlooked.

For our analysis, we use the energy trajectory built by Plazas-Niño et al. (2023b) with the OseMOSYS model. We compute the volumes of energy imports, energy consumption of households and non-energy firms directly from this study, and as crude oil and coal exports are not part of the projections,²⁵ we assume that they remain constant in volume from 2021 onward (which would be in line with the recent pledge of Colombia to halt the signing of new hydrocarbon exploration contracts). We also assume that the intermediate energy consumption of the energy sector remains constant (the electricity sector grows but to include more renewables, and we assume that the extracting and refining remains constant, in line with the constant exports). Energy prices are computed based on production costs, derived from the energy and electricity mix projections of this study, and the technico-economic energy dataset on which it is based (Plazas-Niño et al., 2023a). Detailed calculation of energy volumes and prices, and the full set of KLEM variables are in Appendix C.

²⁴or of the National Energy Plan, which was produced before the NDC was updated with a net-zero target for 2050

²⁵The authors make no assumptions on the evolution of oil and coal exports, as it is highly dependent on the future mitigation pathways of Colombia’s trading partners.

We run a KLEM variant with a neoclassical closure under this *Vision_OSeMOSYS* scenario, and compute GDP trajectories for several combinations of assumptions on the growth rates of capital, energy and materials productivities in the non-energy sector. More specifically, we pre-determine values of interest for these yearly growth parameters as follows:

- For the productivity of energy in the non-energy sector, we test a 0% growth, a 1,25% growth and a 2,5% growth, based on historical evolutions for OECD countries (OECD, 2017).
- For the productivity of capital in the non-energy sector, we test a wide range of growths based on historical regional evolutions (UNCTAD, 2014), as detailed in the Methods: a 0% growth, a 1,75% growth, a 3,5% growth.
- For the productivity of materials in the non-energy sector, based on historical evolutions for South America (Schandl et al., 2016), we test a 0% growth, a 0,6% growth, and a 1,2% growth.

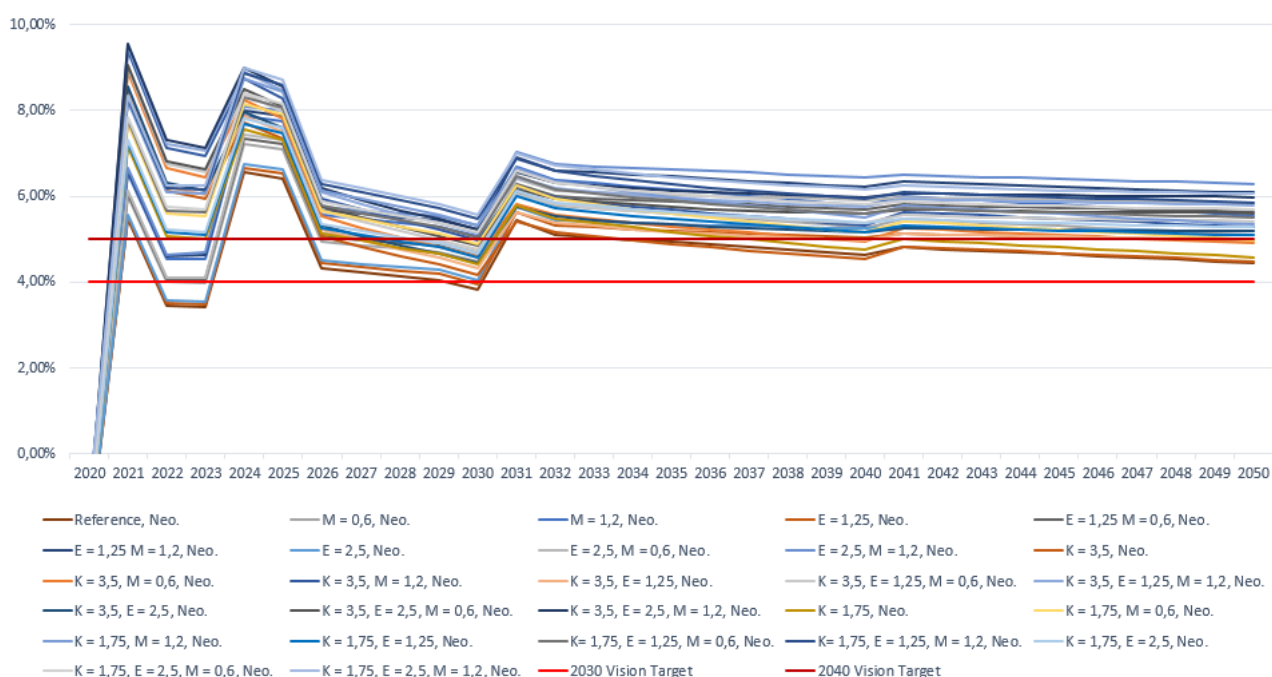
Figure 4.5 shows annual GDP growth rates computed by KLEM under the *Vision_OSeMOSYS* scenario, for the 27 sets of yearly growth rates in the productivities of energy, capital and materials in the non-energy sector. The space of parameters within which the GDP targets of Colombia's Vision 2050 are reproduced is large. Among the 27 tested sets, 7 do not meet Vision 2050's targets. As in the case of Malawi, these include the reference scenario, which means that there has to be a certain growth in the productivities of capital/energy/materials for the GDP targets to be met. Conversely to Malawi, while a growth in the productivity of capital yields a higher GDP growth than the reference scenario, this parameter alone cannot ensure that the GDP targets are met in 2030 and 2050. Indeed, scenarios in which only the productivity of capital grows do not meet Vision 2050's targets. While the productivity of energy has a higher influence on GDP growth for Colombia than Malawi (which might be explained by a considerably larger size of the energy sector), if it is the only parameter that evolves, a 1,25% annual growth does not yield a sufficient GDP growth to meet Vision 2050's targets. The space of realistic parameter growths that meet the GDP targets is thus more limited than for Malawi. This is also due to the fact that the initial realistic ranges tested are smaller, as higher values of sustained productivity growths are less realistic for Colombia than Malawi because the initial values are already high.

Using a Johansen closure also lead to large ranges of values compatible with Vision 2050's growth targets (see Appendix C for details of these simulations). A Johansen

closure results in slightly higher GDP growths than the neoclassical closure. Although the results for the tested sets are similar, we expect the range of values compatible with the Vision 2050 to be slightly broader. The analysis provided from Steps 1 and 2 thus leads to the conclusion that Colombia's energy-related climate targets and some of its economic development targets proposed in Vision 2050 are consistent with each other within the scope of our analysis. Major incompatibilities are thus not revealed in this stylized analysis, but this does not mean that all development and climate targets are compatible. Indeed, Colombia's net-zero ambition does not solely rely on the energy sector. Agriculture and Land Use are also large emitting sectors, and represent a substantial share of the efforts. Tensions might then appear more with the agricultural sector than the energy sector. Another important priority for Colombia is also the decrease in inequalities, which cannot be represented in the present KLEM framework. This result thus calls for an extension of the KLEM framework, in the case of Colombia, to accommodate for an agriculture sector.

4. ARE LONG-TERM NATIONAL GOALS ON CLIMATE CHANGE MITIGATION AND ECONOMIC DEVELOPMENT COMPATIBLE? EVIDENCE AND MODELLING ON MALAWI, COLOMBIA AND IRAQ

Figure 4.5: Evolution of GDP growths under the Vision 2050 scenario of Colombia, depending on evolutions of capital, energy and materials productivities in the non-energy sector



Each line represents a different set of growths of capital, energy and materials productivities in the non-energy sector. The name of the scenario includes the growth considered for each parameter in the scenario (K for capital productivity, E for energy productivity, M for materials productivity). The series in shades of orange do not meet the newly GDP targets without a modification of the productivity of energy. If the parameter does not evolve, it is not mentioned. Discrepancies before 2022 are due to the fact that the model takes real data for exogenous assumptions up until this year. In 2031 and 2041, there are slight discrepancies due to the change of slopes between 2020-2030, 2030-2040 and 2040-2050 exogenous targets.

4.5 Application of the methodology to the case of Iraq

4.5.1 Context

Located in the Middle-East, Iraq is among the most oil-dependent countries in the world: its public revenues depend for more than 90% on oil revenues, and the oil sector accounted for 53% of Iraq's GDP in 2017 (Ministry of Planning, 2020). The country's economy is thus extremely dependent on global oil prices. In 2022, Iraq had a GDP growth of 7%, a population of over 44 million inhabitants, a per-capita GDP of 5 937 current US dollars (Source: World Bank Data). One of the country's main development challenges is to decrease its reliance on its energy sector (World Bank, 2022a).

In 2020, Iraq's Ministry of Planning published its "Vision 2030" (Ministry of Planning, 2020), with five national priorities, among which economic diversification away from the oil sector. The Vision 2030 includes many quantified targets for 2030, a selection of which is presented in Table 4.4. However, although the plan mentions "sustained economic growth", no global GDP growth target is formulated.

Table 4.4: Selection of targets displayed in Iraq's Vision 2030

Indicator	Ref value (base year)	2030 target
Unemployment rate	12% (2018)	4%
Oil revenues as a percentage of the public revenues	92% (2013-2017)	60%
Contribution of the oil sector to the GDP	53,9% (2004-2017)	35%
Oil exports (million barrels per day)	3,5 (2017)	9

As a Party to the Paris Agreement, Iraq released its Nationally Determined Contribution in 2020 (Government of Iraq, 2020). It replaced its Intended Nationally Determined Contribution which included an unconditional 1% emission reduction in 2035, and an additional conditional 13% reduction, compared to a reference scenario. However, the updated NDC makes no mention of a quantitative mitigation target.

4.5.2 Application of the methodology

A recent update of the GTAP database, as well as the availability of a Social Accounting Matrix produced by IFPRI, make it possible to calibrate the KLEM model for Iraq. However, the absence of any GDP growth target makes the modelling steps of our methodology inapplicable in the case of Iraq. This situation turns out to be common amongst fossil fuel-exporting countries: in fact, the development documents of Saudi

Arabia, Jordan and Kazakhstan have other quantified targets (See database built in Chapter 1), but no GDP target (they are not included in Section 4.2.3's list of countries to which this methodology is fully applicable).

Nevertheless, a qualitative discussion of the compatibility between development targets and climate targets remains possible for these countries. The idea is that the major source of incompatibility, for an oil-exporting country, is likely to be between the country's development targets and its trade partners' climate mitigation targets. In the case of Iraq, the development priority is to reduce the share of oil in its GDP from 53,9% to 35% by 2030. At the same time, the plan targets a sustained economic growth (although not quantified), as well as a tripling of oil exports (from 3,5 to 9 million barrels per day). This would imply an average annual growth rate in oil exports of more than 9,3% in volume, and in value (assuming constant international oil price). Assuming that the weight of the oil sector in the GDP follows the growth in oil exports, meeting the above mentioned targets would require that the GDP grows at least by 12,5% on average, every year, from 2017 to 2030. This figure is particularly high and unlikely to be reached (as, according to World Bank data, a double-digit GDP growth sustained over 10 years has almost never occurred anywhere else). This and puts into question the internal consistency of the development targets stated in Iraq's Vision 2030 document.

4.6 Conclusion and discussion

4.6.1 Purpose and applications of the methodology

In this chapter, we propose a methodology to provide first insights on the compatibility between (some) climate and macroeconomic targets, as laid out in countries' NDCs and long-term development documents. We use the stylized KLEM model to reveal the assumptions on exogenous drivers (namely assumptions about the growth rates of the productivities of energy, capital and materials in the non-energy sector) that underly the consistency between energy-related climate targets and macroeconomic targets for the country. This methodology is built to be flexible, so as to be applicable in various national contexts, and for different types of development priorities. This methodology also aims at being as little data-intensive as possible, to be applicable in countries where national quantified targets are scarce and where very little modeling has been done so far.

We test the methodology on three countries, with different development pathways: Malawi, which aims at industrialization, Colombia, which aims at a general improvement

of its economic indicators with additional environmental considerations, and Iraq, which aims at diversifying its economy away from oil. Our results show that the consistency between climate and development goals varies across the three countries. The content of the NDC and development vision appear compatible in Malawi under a broad range of parameters. Colombia has incorporated its climate targets within its development vision, and it turns out that the development Vision appears internally consistent, under a large range of parameters. Iraq is not amenable to the modeling steps of our methodology since its Vision 2030 lacks GDP targets. However, a qualitative discussion reveals inconsistencies between the development targets of the plan, namely the rapid increase in oil exports and the important decrease of the share of the energy sector in the GDP. These cases also enable us to discuss the applicability of the methodology, its flexibility, limitations, and possible future developments.

This first set of case studies suggest that the methodology can be applied (1) when climate and development targets are featured within a single document (Colombia), (2), where national data and projections are scarce (Malawi), (3), where on the contrary, detailed representations of the economy exist (Colombia), the methodology then allowing to get a first insight on a shorter timeline than a more detailed modelling work would (though our methodology does not aim at replacing the latter), and even (4) where there is no quantified target for the GDP, with a qualitative discussion (Iraq). As expected during the construction of this methodology, a modelling analysis is here only possible if the country has a GDP target, which limits the number of countries to which it is applicable. For some countries, like Iraq, it would be possible to compute a GDP trajectory from the other development and mitigation targets, then discuss its plausibility. However, in most cases, computing a GDP trajectory under climate and development targets would not be conclusive and only give insights on the macroeconomic costs of transition.

For Malawi and Colombia, our methodology shows a large alignment between the modelled climate and development targets. Some conditions are needed for the two to be met, as the reference case (with no growth in the productivities of capital, energy and materials) does not meet the GDP targets, in both countries. However, the space of realistic productivities' growth rates, for which development and climate targets can be met, is large. One explanation for these large ranges in both countries might be that current NDCs in many countries do not display a high level of ambition, thereby not creating many trade-offs with economic development. To this regard, inconsistencies would be more likely within the development plan itself (as we find in Iraq). This could be

the case for Malawi, for which the energy sector might not weigh enough on the economy for a moderate NDC-related shock to impede GDP growth. Colombia, however, has an important energy sector and targets net-zero emissions in 2050. In Colombia's case, the large alignment could very-well result from the extensive modelling work deployed to serve as a basis for the targets. To further test the explanation, the methodology would need to be applied in other countries, or in contexts where we artificially increase the level of ambition of NDCs. A second explanation might be that the tensions between the NDC and other development priorities are not fully captured in our current framework. This could be due to the fact that we take in available energy scenarios (whereas for Colombia, different scenarios for the evolution of international energy markets could be tested), and do so without two-way model-linking, which can have an impact on the model results. The tensions might also lie between development targets that are not encompassed within the stylized framework (such as poverty, inequalities or land use).

The work presented in this chapter is still ongoing. The first results obtained outline possible extensions of the methodology and model, in order to overcome some current limitations. Some of them are currently being implemented, while others are future avenues.

4.6.2 Ongoing extensions

Dynamic calibration In this chapter, the KLEM model is calibrated statically, for the year 2014. However, for most countries, there is data from institutional sources on the evolution of exogenous assumptions (like labour productivity, growth, unemployment, trade balance) up until 2022. In future work, KLEM will be dynamically calibrated on these trends for the period 2014-2022, as proposed for example in Soummane et al. (2019). A dynamic calibration aims at ensuring the model better replicates reported trends of macroeconomic variables with reported trends of the energy sector, by adding "crisis-factors" in the model.

Extension to an agriculture sector An obvious limitation of our endeavour comes from the fact that KLEM only features two sectors. This is not a problem for all countries, but major development priorities cannot be represented within this modelling framework. For example, many countries have development targets that relate to the evolution of their agricultural sector (e.g., Bolivia or Burundi).

An extended version of KLEM with an exogenous agricultural sector is thus currently being developed. The agricultural sector would be linked to other sectors

through market closures, and in the intermediate consumptions (non-energy intermediate consumptions in the nested CES structure would be a Leontief function between composite and agriculture). The three-step method would remain the same, with adjustments as to which parameters of productivity could evolve to discuss the consistency between the development and NDC targets (for example, a range of growths in labour productivity could be tested).

Soft-linking As KLEM is calibrated on hybrid IOTs and embarks a fully exogenous energy system, it is tailored to be soft-linked with bottom-up models representing energy systems such as TIAM, POLES or national models such as KSA (Su et al., 2022; Soummane et al., 2019; Sarre, 2021). For countries for which a bottom-up model is calibrated (e.g. Colombia), two-way linking KLEM with the bottom-up model would make it possible to take into account the feedback between both models, with continuous exchanges of variables between the two models until convergence. This would, for example, improve the representation of technological change our modelling exercise. This variant of the methodology is only relevant, of course, for countries where a bottom up model exists and is available.

4.6.3 Possible future extensions

Among the main limits of this study is that we consider national targets outside of their implications for international trade and financial transfers. While currently not translatable into our framework, they could, in the future, be encompassed within further developments of the KLEM structure.

First, meeting targets, on such indicators as on energy exports (for energy-exporting countries), depends on international energy markets, and thus on the mitigation targets of the country's trading partners and of the rest of the world. This could be captured by using a multi-regional version of KLEM. It would also require a multi-regional model on energy systems such as POLES. What currently limits this extension, as discussed earlier, is that most global bottom-up and top-down models that depict trade, KLEM included, are not disaggregated for the countries that have quantified development plans and that we aim at modelling (listed in Section 4.2.3). Another challenge in implementing trade between countries would be the loss of flexibility of the methodology, as there would be a need for harmonization, to a certain extent, between national models. To get first insights on this question, an option would be to test the sensitivity of results to international energy prices (which would work only for countries for which this sensitivity

analysis can be implemented in the bottom-up energy model), assuming that the studied country is a "price taker".

Additionally, most developing countries' targets are conditional on receiving international financing. This, in itself, is not modelled or hardly translatable in the current KLEM framework. A possibility would be to represent a financial market in the model, with a capital account balance representing financial transfers, including foreign direct investments. A better representation of macro-financial flows would be possible to implement on the model, by disaggregating financial flows between economic agents in the spirit of stock-flow consistent modelling. However, this would largely limit the number of countries on which the analysis is possible as this disaggregation is data-intensive.

Finally, the methodology is based on GDP targets. The use of GDP as a central indicator for economic development and as a measure of well-being has long been discussed in the literature (Stiglitz et al., 2018, 2010; Fleurbaey and Blanchet, 2013; Bleys, 2012), and more recently in the context of Sustainable Development Goals (Stewart, 2015), but remains standard practice in macroeconomic modelling. Moreover, some countries do not have quantified GDP target, which makes our methodology difficult to apply beyond Step 1 (see the case study of Iraq for an illustration). Using other indicators such as the human development index, capabilities, or multi-dimensional poverty measures, could also be considered in future modelling endeavours (with all associated limitations coming with data scarcity).

Now, this discussion aims at informing countries' policy-making, but also has implications for international cooperation on climate change. Indeed, should inconsistencies between climate and development targets be revealed at the national level, and given that national mitigation policies automatically have an impact on global climate change, the proposed way forward would depend, to a large extent, on equity considerations. What does the existence of inconsistencies say about the targets themselves, and their ambition? In the context of the Paris Agreement, where the downscaling of global mitigation targets is not automatic, concluding on the countries' level of ambition is not self-evident. We thus complement the positive discussion developed in this Chapter, on the alignment of national development and climate targets, with a normative discussion, in Part III on the fairness of countries' mitigation contributions, which can be summarized as follows: *How can the fairness*

of countries' mitigation contributions be re-assessed, taking into account the context of the Paris Agreement and the broader range of SDGs? We first review the current fairness evaluation tools, which face stumbling blocks linked to the absence of a single, agreed upon vision of what a fair NDC would be (Chapter 5). We intend to improve existing tools by using citizens' opinions to legitimize collective judgements. In Chapter 6, we propose surveys as a way to observe their judgements. We also open, in the conclusion of this dissertation, the discussion on reframing the debate on equity to take into account other development targets and the broader context of SDGs.

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III. On re-assessing the fairness of countries' contributions in the present context

Who does enough? A review of equity rules and fairness evaluation tools for national climate contributions

This chapter is adapted from joint work with Aurélie Méjean and Yann Kervinio

Abstract

From the signature of the UNFCCC on, many effort-sharing approaches have been built to operationalize the “Common but differentiated responsibilities – respective capabilities” principle, which links development and equity in the context of climate change mitigation. Most of them rely on allocation rules which identify a global carbon budget for a given year then share it equitably among countries. This chapter proposes a framework to present, in a formalized and harmonized manner, existing allocation rules that operationalize the distribution of a given climate budget. However, in the bottom-up approach of the Paris Agreement, no single “effort-sharing” and allocation framework has been agreed upon by the Parties. Any assessment of a country’s effort implies having a vision of what would be an ambitious contribution from this country, with no single “effort-sharing” rule now legitimized at the international scale. We then propose a new framework to list and evaluate the existing tools that assess the fairness of Nationally Determined Contributions. We sort them in three categories and compare their practical relevance within the current context. We show that they all come to a compromise between multiplying the viewpoints on equity (as there is no theoretical reason to prefer one rule) and providing a firm assessment. We discuss their limits in relation with the inclusion of other development targets of countries.

Contributions:

Auriane Meiland: Conceptualization, Methodology, Analysis, Writing (original draft)

Yann Kervinio, Aurélie Méjean: Conceptualization, Analysis, Supervision

5.1 Introduction

As presented in the introduction of this thesis, fairness and equity considerations have been discussed since the signature of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 (United Nations, 1992). Article 3 of the Convention states that *"The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof."*

However, there has been little agreement on how to operationalize the Common But Differentiated Responsibilities (CBDR) principle, and the international approach to equity has significantly evolved since the signature of the Convention (Heyward, 2007; Held and Roger, 2018). In the UNFCCC, developed country Parties listed in the Annex I to the Convention have non-binding mitigation targets for 2000. Following the same logic, the Kyoto Protocol, adopted in 1997, sets up binding emissions targets for Annex I Parties, to be met between 2008 and 2012 (Bodansky, 2011).

Before and after the adoption of the Kyoto Protocol, a large number of normative rules were proposed in both the academic and the grey literature to allocate mitigation efforts or, increasingly, a given remaining carbon budget,¹ across all countries. There is a large pool of possible rules to choose from, most of them referring to identified (and competing) equity principles² (see e.g., Höhne et al. (2014) or Fleurbaey et al. (2014) for reviews). These rules were designed to support and operationalize the "top down" approach to mitigation that was dominant at the time, in which countries would decide on a carbon budget and find a way to share it among themselves.

The 2009 Copenhagen conference of parties, however, underlined the limitation of this approach, as Parties could not agree on an equitable sharing of mitigation efforts for the 2013-2018 period. The failure to reach agreement a shift away from the Annex I/non-Annex I divide has consequently been proposed. It led to a shift to a "bottom up" approach, embodied within the Paris Agreement, to ensure broader participation and sidestep distributional considerations (Falkner, 2016).

¹Both approaches being linked (Van Den Berg et al., 2020)

²defined as *"generally acknowledged norms of fairness that have traditionally been seen as valid across a range of issue areas and at different levels"* in Ringius et al. (2002)

In the Paris Agreement, each Party proposes a voluntary "contribution" to the global effort to tackle climate change (Chan, 2016) in terms of mitigation and adaptation. This pledge is summarized in a document called a Nationally Determined Contribution (NDC), that all Parties to the Agreement have to produce. In its NDC, each country also justifies how its contribution to the global target is fair, which has led to heterogeneous explanations (Winkler et al., 2018; Holz et al., 2023; Rajamani et al., 2021). Every 5 years, NDCs are then aggregated during a Global Stocktake (Winkler, 2020; UNFCCC Secretariat, 2023b) and compared to the global target of the Agreement³, after which countries are expected to update their NDCs to increase their ambition.

While the Agreement does not require a pre-agreed vision of what constitutes an equitable sharing of the effort, equity considerations are still central in the new bottom-up approach (Klinsky et al., 2017). Equity is all the more relevant since there is a gap in ambition between aggregated NDCs and the Paris Agreement targets (Den Elzen et al., 2022; Lecocq et al., 2022), implies that some countries have to make additional efforts. In the absence of a globally accepted reference for ambition, evaluating the ambition and fairness of the Parties' contributions proves far from trivial. The stakes around such an evaluation are high: the Intergovernmental Panel on Climate Change's sixth assessment report thus notes that the academic community needs updated tools to evaluate the fair character of individual contributions to global mitigation, with constraints arising to translate collective judgements inside this new bottom-up climate regime (Patt et al., 2022).

In this chapter, we provide an extensive review of the approaches to evaluating individual countries' ambitions in terms of climate change mitigation. In Section 5.2, we focus on *effort-sharing rules* that have been recently used or proposed in the literature to allocate yearly GHG emissions amongst countries, in coherence with a global carbon budget. We complement existing reviews (Höhne et al., 2014; Fleurbaey et al., 2014; Rose et al., 1998) by using a mathematical framework to detail, in a harmonized manner that facilitates comparisons, all the specified formulas on which these rules rely to be implemented. In Section 5.3, we review the evaluation tools and judgement rules that are proposed in the literature to assess the fairness of NDCs. To our knowledge, such review does not exist in the literature. We show that they all result in a trade-off between legitimacy and conclusiveness, as Section 5.4 concludes.

³to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." (UNFCCC, 2015)

5.2 Sharing a carbon budget according to a single rule

Most of the effort-sharing rules belong to one of six categories described by Höhne et al. (2014) and used the IPCC's fifth assessment report (Fleurbay et al., 2014):

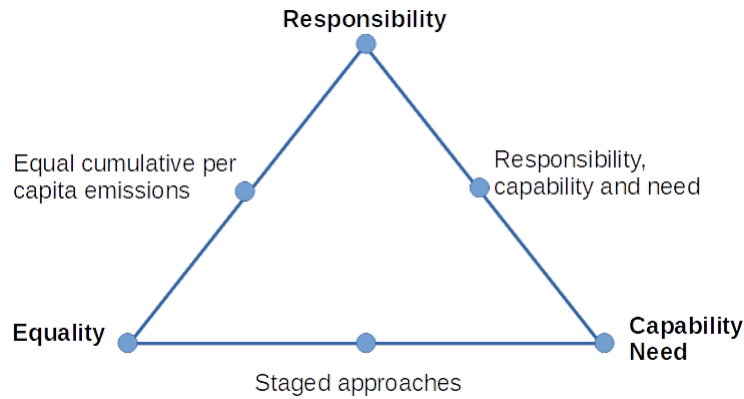
- The *responsibility* approach is related to the polluter-pays principle, as past greenhouse gases emissions are accounted for (for example in den Elzen (1999)).
- The *capability* approach refers to effort-sharing rules in which the more one is able to contribute (e.g. wealthier countries, countries where abatement costs are lower), the more one should (e.g. Jacoby H. D. et al. (2008); Miketa and Schrattenholzer (2006)).
- Although the word "equality" can have many understandings, the *equality* approach refers to approaches where all humans have equal emission rights, which translates into per-capita emissions converging towards an equal level compatible with the global target (e.g. Berk and Den Elzen (2001); Höhne et al. (2006)).
- The *responsibility-capability-need* approach refers to effort-sharing rules that put an emphasis on historical responsibility, capability and the need for countries to sustainably develop (e.g. Kemp-Benedict et al. (2018); BASIC experts (2011)).
- In rules using an *equal cumulative per capita* approach, equal per capita emission budgets, over a cumulative period covering past and future emissions, are allocated to countries then divided into yearly budgets (e.g. Bode (2004)).
- *Staged approaches* include effort-sharing rules in which countries take differentiated commitments in various stages (in accordance with Höhne et al. (2014), rules based on the "grandfathering principle", in which emission "rights" are given in priority to historical emitters, as well as other ad hoc rules are also placed in this category).

These 6 categories are all a combination of three underlying effort-sharing principles: equality, capability, responsibility (see Figure 5.1).

In Höhne et al. (2014), a fourth dimension, 'cost-effectiveness', is added. This corresponds to allocations that would emerge from minimizing the global emission abatement costs. Cost-effectiveness constitutes a useful reference in modeling studies Van Den Berg et al. (2020); Li and Duan (2020). However, it does not correspond to an equity principle in itself. It translates a principle of efficiency, and has to be complemented by a separate discussion on equity about sharing the global cost of mitigation (which typically implies financial transfers across countries, e.g.).

In the remainder of this section, we propose a framework to harmonize the representation of the existing allocation rules to share a given carbon budget. This

Figure 5.1: Six categories for effort-sharing equity approaches, as proposed by Höhne et al. (2014); Fleurbaey et al. (2014)



Adapted from Höhne et al. (2014)

framework aims at capturing all implementation details of each rule in a systematic way. It also aims at making rules easily comparable with one another. We then detail the specified formulas they rely on, sorting them by the above categories and giving examples of their implementation in the literature. We finally discuss the limits of this approach.

5.2.1 Framework

We normalize the starting year of the study to 0. Future years are denoted by $t > 0$, and past years by $t < 0$. r_t is the discount rate.

For a given target L (e.g. "Limiting global warming at 1,5°C in 2100 with 50% chance"), Ω_L describes the associated remaining global carbon budget until the specified horizon year, assumed here to be given without uncertainty (x $GtCO_2e$).

We consider a set N of n countries denoted by i . Each country is characterized by:⁴

- e_{it} , the targeted future (if $t > 0$) or the measured historical (if $t < 0$) emissions of country i at a year t . It does not include LULUCF and international shipping and aviation emissions, unless otherwise specified. We also assume business-as-usual emissions e_{it}^{BAU}

⁴Each individual rule only uses a subset of these parameters.

- T is the year from which past emissions are accounted for (if so), $T < 0$
- Pop_{it} is the projected population at date t if $t > 0$ or the historical population if $t < 0$
- GDP_{it} , the gross (projected or historical) domestic product at date t
- HDI_{it} , the Human Development Index at date t , and its components:
 - LEI_{it} , the Life Expectancy Indicator at date t
 - EDI_{it} , the education indicator at date t
- CI_{it} , the carbon intensity of the economy at date t (by construction, $CI_{it} = \frac{e_{it}}{GDP_{it}}$)
- PCC_{it} , the share of coal consumption to total national primary energy consumption at year t
- G_{it} , the GINI index at date t

A **domain** D consists of a set N of countries and a target L . For example, we can consider the domain $D_{2^\circ C}$ consisting in all countries that signed the Paris Agreement, and its main $2^\circ C$ target (we could also consider the $1,5^\circ C$ target).

An **allocation rule** Φ associates to any country or group of countries $d \in D_{2^\circ C}$, an allocation $\Phi(d) = (e_{i,t})_{i \in N, t > 0}$ such that $\sum_{i \in N, t > 0} e_{it} = \Omega_{2^\circ C}$.

5.2.2 Allocation rules following the responsibility approach

In a responsibility approach, countries are accountable for their past GHG emissions, following the 'polluter - pays' principle. Only a few studies propose quantified effort sharing rules that belong to this category.

Historical Responsibility, HR:

Historical responsibility rule: Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$ in which

$$\begin{cases} e_{it} = e_{it}^{BAU} & \text{if } i \notin P_t \\ e_{it} = e_{it}^{BAU} - \sum_{c \in N} (e_{ct}^{BAU} - e_{ct}) \frac{\sum_{y=T}^0 r_y e_{iy}}{\sum_{c \in P_t} \sum_{y=T}^0 r_y e_{cy}} & \text{if } i \in P_t \end{cases}$$

where $P_t = \{i \in N, \frac{GDP_{it}}{Pop_{it}} > A\}$ is the set of participating countries at year t (participation is defined by a threshold value A of per capita GDP).

Interpretation: There is a participation threshold below which countries can emit as usual. $\sum_{c \in N} (e_{ct}^{BAU} - e_{ct})$ represents, at year t , the global quantity of emissions that needs to be cut compared to the global BAU scenario. This quantity is shared amongst participating countries depending on their share in the global cumulative emissions from the reference year.

Examples of implementation in the literature: In Pan et al. (2017) and Pan et al. (2018). the reference year is 2010 and $T = -160$ (historical emissions count from 1850 on). BAU emissions are calculated under the hypotheses of the IPCC's RCP8.5 and SSP2 (also used for GDP and Population projections) pathways. The chosen annual discount rate is $r_t = 1.5\%$.⁵ The participation threshold of the countries is set at 45% of the Annex I countries' average per capita GDP(ppp) in 1990.

Two global targets are considered, leading to two versions of this rule: "Limiting global warming at 2°C in 2100 with >66% chance" and "Limiting global warming at 1.5°C in 2100 with >50% chance".

The Brazilian proposal, BP:

The Brazilian proposal rule: Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$ in which

$$\begin{cases} e_{it} = e_{it}^{BAU} & \text{if } i \notin P_t \\ e_{it} = e_{it}^{BAU} - \sum_{c \in N} (e_{ct}^{BAU} - e_{ct}) C_{it} & \text{if } i \in P_t \end{cases}$$

where P_t is the set of participating countries at year t and C_{it} is the relative contribution of the country i to the global mean temperature increase before year t (the way C_{it} is calculated is specific to each study and will be detailed in the examples).

Interpretation: There is a participation threshold under which countries can emit as usual. $\sum_{c \in N} (e_{ct}^{BAU} - e_{ct})$ represents, at year t , the global quantity of emissions that needs to be cut compared to the global BAU scenario. This quantity is shared amongst participating countries depending on their relative past contribution to temperature increase.

⁵Its value is not justified.

Examples of implementation in the literature: Although in the first implementation of the original rule (den Elzen, 1999) proposed by Brasil at the 1997 Conference of Parties in Kyoto, only Annex-I countries participate in the effort (P_t is the set of Annex-I countries), this distinction is not relevant after the Paris Agreement: here, we focus on new implementations of this proposal which could include all the countries.

In Berk and Den Elzen (2001), the reference year is 2012 and a reduction scenario is constructed with assumptions on deforestation, major greenhouse gases and the following targets: global mean surface temperature increases less than 2.0°C relative to 1900 in the long term, rate of global temperature increases less than 0.1°C per decade and global mean sea level rises less than 50cm in the long term (2100). The business as usual global scenario is the IMAGE 2.1 A.1 emissions scenario. All countries participate ($P_t = N$) and C_t is calculated following the original proposal: it depends on past historical emissions from 1840 on (with an extrapolation before 1950).

In Den Elzen and Lucas (2005), the reference year is 2012, the baseline scenario is the Common POLES IMAGE baseline scenario, and the reference scenario is calculated with IMAGE for GHG concentration target in 2100 of about 550 ppmv in CO2 equivalent. P_t includes all Annex-I countries and the countries with an income level above 40% of 1995 Annex-I per capita income (ppp). C_{it} is calculated following the original proposal: it depends on past historical emissions from 1840 to $t - 5$.

5.2.3 Allocation rules following the capability approach

This category refers to effort sharing rules that are based on the countries' capacity to contribute to solving the climate problem. The basic idea is that the more one can contribute, the more one should.

Capability, CAP:

Capability rule: Annual emissions allowances of country i depend on whether the remaining global carbon budget is positive or negative (allowing for situations where net carbon dioxide removal is needed). Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$ in which

$$\begin{cases} e_{it} = \sum_{c \in N} e_{ct} \times \frac{\frac{Pop_{it}^2}{GDP_{it}}}{\sum_{c \in N} \frac{Pop_{ct}^2}{GDP_{ct}}} & \text{if } \sum_{c \in N} e_{ct} > 0 \\ e_{it} = \sum_{c \in N} e_{ct} \times \frac{GDP_{it}}{\sum_{c \in N} GDP_{ct}} & \text{if } \sum_{c \in N} e_{ct} < 0 \end{cases}$$

Interpretation: This approach allocates shares of the ‘Target’ pathway’s emissions proportional to the countries’ population and inversely proportional to their per capita GDP.⁶ countries with a higher GDP or a smaller population get the smaller shares. When the ‘Target’ pathway’s net emissions are negative, countries are allocated a share proportional to their GDP.

Examples of implementation in the literature: In Robiou Du Pont et al. (2016) and Robiou Du Pont et al. (2017), the reference year is 2010. A convergence period of 30 years is proposed, and the GDP and population projections are based on SSP2.

In Robiou Du Pont et al. (2017), two targets are considered, leading to two versions of this rule: "Limiting global warming at 2°C in 2100 with >66% chance" and "Limiting global warming at 1.5°C in 2100 with >50% chance". In Robiou Du Pont et al. (2016), the global scenarios chosen are consistent with the G7 Elmau agreement (which sets for target "Limiting global warming at 2°C in 2100 with >66% chance" and "the upper end of the latest IPCC recommendation of 40-70% reductions by 2050 compared to 2010).

Ability to pay, AP:

Ability to pay rule: Emission allowances are allocated following a rule proposed by Jacoby et al. (1999) and $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which

$$\begin{cases} e_{it} = e_{it}^{BAU} & \text{if } i \notin P_t \\ e_{it} = e_{it-1} \times (1 + \gamma - \alpha(\frac{GDP_{it}}{Pop_{it}} - A)^\beta) & \text{if } i \in P_t \end{cases}$$

where $P_t = \{i \in N, \frac{GDP_{it}}{Pop_{it}} > A\}$ is the set of participating countries at year t (participation is defined by a threshold value A of per capita GDP). The parameters α , β and γ are adjusted to best fit the global emission scenario.

Interpretation: There is a participation threshold under which countries can emit as usual. The emission reduction is calculated on the basis of the difference between the per capita GDP trigger level and a country’s per capita GDP.

The parameter γ determines a "grace period" in which the regions should slow down their annual growth of emissions prior to the beginning of absolute reductions. α and β

⁶The combination of population and per capita GDP as criteria explains that the population is squared in the formula.

influence the overall emission reduction (α has a large impact on the emission allowances of regions close to the threshold, whereas β has an impact for the regions that are far from the threshold).

Examples of implementation in the literature: This rule is implemented in Pan et al. (2017) and Pan et al. (2018) (see paragraph on the Historical Responsibility rule for other details on the implementation).

Emission Intensity Targets, EIT:

Emission Intensity Targets rule: Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which

$$\begin{cases} e_{it} = e_{it}^{BAU} & \text{if } i \notin P_t \\ e_{it} = GDP_{it} \times \frac{e_{it-1}}{GDP_{it-1}} \times (1 - \min(a \times \frac{GDP_{it}}{Pop_{it}}, EIR_{max})) & \text{if } i \in P_t \end{cases}$$

where a is a parameter adjusted to match global emissions allowances, $P_t = \{i \in N, \frac{GDP_{it}}{Pop_{it}} > A\}$ is the set of participating countries at year t (participation is defined by a threshold value A of per capita GDP), and EIR_{max} is the maximum decarbonisation rate.

Interpretation: There is a participation threshold below which countries can emit as usual. Countries contribute by improving their emission intensity, on the basis of their per capita GDP.

Examples of implementation in the literature: This rule is implemented in Pan et al. (2017) and Pan et al. (2018) (see paragraph on the Historical Responsibility rule for other details on the implementation). EIR_{max} has a linear increase from 3% in 2010 to 7% in 2050.

5.2.4 Allocation rules following the equality approach

This category refers to effort sharing rules based on immediate or converging equal per capita emissions. A more complex rule proposes to allocate emissions according to the number of citizens that are amongst the highest world emitters.

Linear convergence at national levels, EPC

Linear convergence at national levels rule: Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which

$$e_{it} = \sum_{c \in N} e_{ct} \times \left(\frac{e_{i0}}{\sum_{c \in N} e_{c0}} \times (1 - \tau) + \frac{Pop_{it}}{\sum_{c \in N} Pop_{ct}} \times \tau \right)$$

where τ is the ratio of time elapsed in the transition between the initial international emissions ratios and equal per capita emissions ratios.

Interpretation: In this 'per capita convergence' approach, the allocations converge linearly towards equal per capita emissions with a given transition period. This approach is also known as the "contraction and convergence" approach. In a variant of this approach, 'immediate per capita allocation', there is no convergence period and $\tau = 1$ from the beginning.

Examples of implementation in the literature:

Variant EPC.1: This rule is implemented in:

- Pan et al. (2017) with a convergence in 2050, and in Pan et al. (2018) with a convergence in 2100 (see paragraph on the Historical Responsibility rule for other details on the implementation).
- Robiou Du Pont et al. (2016) and Robiou Du Pont et al. (2017) with a 30-year convergence period (see paragraph on the Capability rule for other details on the implementation).
- Berk and Den Elzen (2001) with population projections derived from the baseline scenario IMAGE 2.1 A1, and two convergence years: 2030 and 2050 (see paragraph on the Brazilian Proposal for other details on the implementation).
- Den Elzen and Lucas (2005), with population projections derived from the Common POLES IMAGE baseline scenario, and two convergence years: 2050 and 2100 (see paragraph on the Brazilian Proposal for other details on the implementation).

In Höhne et al. (2006), it is also implemented with projections derived from the IMAGE 2.2 regional baseline scenarios. Two targets are considered: stabilizing total GHG concentrations at the levels of about 550ppm and 650 ppm CO₂-equivalent (more or less consistent with the 450 and 550ppm targets of CO₂). Two convergence years are used: 2050 and 2100.

Variant EPC.2: In Pan et al. (2017) and Pan et al. (2018), the reference year, data and targets are similar as in Variant EPC.1, but the per capita allocation is immediate. This approach is also featured in older references such as Agarwal and Narain (2019), first published in 1991, which proposes to determine "permissible emissions" on the basis of population.

Linear convergence at individual levels ("One billion high emitters", BHE):

Interpretation: National income distributions are used to create individual CO₂ emission income distributions. A universal cap is imposed on the global distribution of individual emissions, such that eliminating all emissions above that cap achieves the target. The consequences of this cap are country-level emission targets that reflect the number of "high-emitting" individuals in that country and their aggregate emissions.

One billion high-emitters rule: The distribution data of a country is used to obtain⁷ the population income distribution. The population density with respect to income is then transformed into a population density with respect to Co₂ emissions. Individuals below an emission cap (determined by the global emissions allowance) have no constraint, while those above the cap must reduce their emissions to the cap.

Variant 1 BHE.1: The population density with respect to income is transformed into a population density with respect to Co₂ emissions with the help of a lognormal function.

Variant 2 BHE.2: The population density with respect to income is transformed into a population density with respect to Co₂ emissions with the help of gamma probability distribution functions.

⁷with a simple non-linear least square fit of the modeled Lorenz curve

Examples of implementation in the literature: Variant 1 is implemented in Pan et al. (2017) and Pan et al. (2018) (see paragraph on the Historical Responsibility rule for other details on the implementation). Emission-income elasticity is set at 1, and the emission cap is 0 tCO_2eq .

In Chakravarty et al. (2009), variant 2 is used with 2003 as a reference year for emissions and population distribution. The projections are from the EIA and the UN World population prospects. The target year is 2030 and the target emission budgets in 2030 are 35 GtCO₂eq, 30GtCO₂eq, 25 GtCO₂eq and 20 GtCO₂eq (the individual emission caps are calculated accordingly), leading to four different versions of this rule.

5.2.5 Allocation rules following the responsibility - capability - need approach

This category refers to effort sharing rules that put high emphasis on historical responsibility, capability and the need for countries to sustainably develop.

Greenhouse development rights, GDR:

Greenhouse development rights rule: Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which

$$e_{it} = e_{it}^{BAU} - RCI_{it} \times \left(\sum_{c \in N} e_{ct}^{BAU} - \sum_{c \in N} e_{ct} \right)$$

where RCI_{it} is a Responsibility-Capacity Index and depends on a capability index C_{it} and on a responsibility index R_{it} . Three variants exist, depending on how RCI_{it} is calculated.

Variant GDR.1:

$$RCI_{it} = a \frac{R_{it}}{\sum_{c \in N} R_{ct}} + (1 - a) \frac{C_{it}}{\sum_{c \in N} C_{ct}}$$

where a is a weighting factor.

A threshold income is chosen and the cumulated wealth of the members of the population over this threshold is used to determine C_{it} . The income distribution within a country depends on G_{it} and is assumed to be a lognormal function. R_{it} is determined from the cumulated emissions of the population that earns more than the threshold (See Kemp-Benedict et al. (2018)).

Variant GDR.2:

$$RCI_{it} = \frac{C_{it}^{\alpha} \times R_{it}^{\beta}}{\sum_{c \in N} C_{ct}^{\alpha} \times R_{ct}^{\beta}}$$

where α and β are weights for capacity and responsibility.

A threshold income is chosen and the cumulated wealth of the members of the population over this threshold is used to determine C_{it} . The income distribution within a country depends on G_{it} and is assumed to be a lognormal function. R_{it} is determined from the cumulated emissions of the population that earns more than the threshold (see Kemp-Benedict et al. (2018)).

Variant 3 (South African Approach, SAA):

$$RCI_{it} = \frac{C_{it}^{\alpha} \times R_{it}^{\beta}}{\sum_{c \in N} C_{ct}^{\alpha} \times R_{ct}^{\beta}}$$

where α and β are weights for capacity and responsibility.

$R_{it} = \sum_{y=T}^t e_{iy}$ and C_{it} depends on GDP_{it} and an Interim capacity indicator calculated from LEI_{it} and EDI_{it}

Interpretation: Every country is associated to a capability index and a responsibility index, which are combined in a responsibility capability indicator (RCI). This indicator is then used to calculate the allocations of the country with respect to its BAU scenario.

Examples of implementation in the literature: The variant 1 is used with $a = 0.5$ in Robiou Du Pont et al. (2017, 2016), and the emissions are cumulated from $T = -20$ (historical year 1990). The income threshold is \$ 7500 ppp (see paragraph on the Capability rule for other details on the implementation).

The variants 2 and 3 are used Pan et al. (2017) and Pan et al. (2018), with the same threshold, $\alpha = -0.4$ and $\beta = -0.6$ (see paragraph on the Historical Responsibility rule for other details on the implementation).

5.2.6 Allocation rules following the equal cumulative per capita approach

In this category, equal cumulative per capita emission rights are allocated based on a global carbon budget and the population of the country. The resulting national cumulative budget is then assigned to individual years.

Equal cumulative per capita, CPC

Equal cumulative per capita rule: Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which

$$\sum_{y=T}^f r_y e_{iy} = \left(\sum_{y=T}^f r_y \sum_{c \in N} e_{cy} \right) \times \frac{\sum_{y=T}^f Pop_{iy}}{\sum_{y=T}^f \sum_{c \in N} Pop_{cy}}$$

where f is the target year for cumulative emissions.

Variant 1, CPC.1: To decompose the national cumulative emissions, two groups of countries are considered: those who will need to reach negative emissions ($M = \{i \in N, \exists t, e_{it} < 0\}$) and those who are allocated positive emissions only ($P = \{i \in N, \forall t, e_{it} \geq 0\}$). Here,

$$\begin{cases} e_{it} = e_{i0} \left(1 - \frac{t}{T_1}\right) \text{ for } 0 \leq t \leq T_1, i \in M \\ e_{it} = \frac{e_{iT_1}}{T_1 - f} (t - f) \text{ for } T_1 \leq t \leq f, i \in P \\ \sum_{i \in N} e_{it} = \sum_{c \in P} e_{ct} + \sum_{c \in M} e_{ct} \end{cases}$$

where T_1 is chosen so positive and negative countries are allocated equal cumulated per capita budgets.

Variant 2, CPC.2: A quadratic function is applied to decompose cumulative allowances into annual allowances for a given country.

Variant 3, CPC.3: This variant is similar to variant 2, but allocations also simultaneously realize equal per capita emissions across countries.

Interpretation: This approach allocates total cumulative emissions over a given period to a country, relatively to its **cumulative population** over the same period.

Examples of implementation in the literature: The variant 1 is used in Robiou Du Pont et al. (2016), with $T = -20$ (historical year 1990) and $f = 90$ (target year 2100). The annual discount rate to emissions is $r_t = 1$ for $t \geq 0$ and $r_t = (1 - X)^{(0-t)}$ for $t \leq 0$ (see paragraph on the Capability rule for other details on the implementation).

An updated version of this variant, in Robiou Du Pont and Meinshausen (2018), aims at avoiding national positive emissions after a period of negative emissions when

global scenarios have a positive emissions target in 2100 (by deriving national ratios of the global scenarios). Two targets are considered, leading to two versions of this rule: "Limiting global warming at 2°C in 2100 with >66% chance" and "Limiting global warming at 1.5°C in 2100 with >50% chance".

The variant 2 is used in Pan et al. (2017) and Pan et al. (2018) (which also uses variant 3) with the same target year, and the population reference used is the average annual population in the cumulation period (see paragraph on the Capability rule for other details on the implementation).

Equal cumulative per capita:

Equal cumulative per capita rule: Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which

$$\sum_{y=T}^f e_{iy} = \left(\sum_{y=T}^f \sum_{c \in N} e_{cy} \right) \times \frac{Pop_{i0}}{\sum_{c \in N} Pop_{c0}}$$

A quadratic function is applied to decompose cumulative allowances into annual allowances for a given country.

Interpretation: This approach allocates total cumulative emissions over a given period to a country, relatively to its population **at a reference year** (instead of the mean or cumulative population): no population projection is involved.

Examples of implementation in the literature: In Pan et al. (2014), the reference year used is 2000, the convergence year is 2050 ($f = 50$) and the historical years are 1850 ($T_1 = -150$), 1950 ($T_2 = -50$) and 1990 ($T_3 = -10$).

The target considered is the global emission pathway towards the 450 ppm of concentration stabilization levels (S450).

5.2.7 Allocation rules following staged approaches

This category includes approaches where countries take differentiated commitments in various stages.

Grandfathering, CER

Constant emission ratios rule Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which

$$\begin{cases} e_{it} = e_{it}^{BAU} & \text{if } i \notin P_t \\ e_{it} = \left(\sum_{c \in N} e_{ct} - \sum_{c \notin P_t} e_{ct}^{BAU} \right) \frac{e_{i0}}{\sum_{c \in P_t} e_{c0}} & \text{if } i \in P_t \end{cases}$$

where $P_t = \{i \in N, \frac{GDP_{it}}{Pop_{it}} > A\}$ is the set of participating countries at year t (participation is defined by a threshold value A of per capita GDP).

Interpretation: Countries participate if their per capita GDP is past a given threshold. Each participating country gets an allocation that is proportional to its reference emission rate. This approach is also called the sovereignty approach in some references (Rose et al., 1998).

Examples of implementation in the literature: *Variant CER.1:* This variant is implemented in Pan et al. (2017) and Pan et al. (2018) (see paragraph on the Capability rule for other details on the implementation).

In Pan et al. (2014), the implementation is described in the paragraph on the Equal Cumulative per Capita rule. The scenario used for population and GDP projections is the A1B scenario of the IPCC SRES. The participation threshold is 30% of the Annex I countries' average per capita GDP(ppp) in 1990. A 5-year policy delay is implemented.

Variant CER.2: In Robiou Du Pont et al. (2016), Robiou Du Pont et al. (2017) and Pan et al. (2018), there is no threshold: every country participates (see paragraphs on the Historical Responsibility and the Capability rules for other details on the implementation).

Common but differentiated convergence, CDC

Common but differentiated convergence rule Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which

$$\begin{cases} e_{it} = e_{it}^{BAU} & \text{if } i \notin P_t \\ e_{it} = Pop_{it} \times \left((epc - \frac{e_{it_i^*-1}}{Pop_{it_i^*-1}}) \times \tau + \frac{e_{it_i^*-1}}{Pop_{it_i^*-1}} \right) & \text{if } i \in P_t \end{cases}$$

where P_t is the set of participating countries at year t , t_i^* is the starting year of convergence for a country i , which is the year the country exceeds the threshold ($t_i^* = 0$ for the countries already above the threshold), epc is the common emission per capita target level.

Interpretation: The participation depends on a threshold and the participating countries converge to an equal per capita emissions level within a certain time period (because not all the countries exceed the threshold at the same time, the starting year of convergence depends on the country).

Examples of implementation in the literature:

Variant 1: $P_t = \{i \in N, \frac{GDP_{it}}{Pop_{it}} > A_t\}$ (participation is defined by a threshold value A_t of per capita GDP).

In Pan et al. (2017) and Pan et al. (2018), $epc = 0$ (see paragraph on the Historical Responsibility rule for other details on the implementation).

Variant 2: $P_t = \{i \in N, \frac{e_{it}}{Pop_{it}} > \bar{e}_{ct}\}$ (participation is defined by a threshold value of per capita emissions).

In Höhne et al. (2006), the convergence period is 2010-2050, the value epc depends on the scenarios and is computed so that the targets are respected (see paragraph on the Linear Convergence at National Levels rule for other details on the implementation).

Multi-Criteria Approach, MCA:

Multi-Criteria rule: Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which

$$\begin{cases} e_{it} = e_{it}^{BAU} & \text{if } i \notin P_t \\ e_{it} = e_{it} \times \left(1 - a \frac{GDP_{it-1}}{GDP_{t-1}^*} - b \frac{CI_{it-1}}{CI_{t-1}^*} - c \frac{\frac{e_{it-1}}{Pop_{it-1}}}{(\frac{E}{Pop})_{t-1}^*}\right) & \text{if } i \in P_t \end{cases}$$

where $P_t = \{i \in N, \frac{GDP_{it}}{Pop_{it}} > A\}$ is the set of participating countries at year t (participation is defined by a threshold value A of per capita GDP), GDP_{t-1}^* , CI_{t-1}^* , $(\frac{E}{Pop})_{t-1}^*$ are respectively the average GDP, carbon intensity of the economy and emissions per capita for the countries above the threshold.

Examples of implementation in the literature: This rule is implemented in Pan et al. (2017) and Pan et al. (2018) (see paragraph on the Historical Responsibility rule for other details on the implementation).

Multi-Stage Approach MSA:

Multi-stage rule: Variant 1: Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which

$$\begin{cases} e_{it} = e_{it}^{BAU} & \text{if } i \notin P1_t \text{ and } i \notin P2_t \\ e_{it} = GDP_{it} \times \frac{e_{it-1}}{GDP_{it-1}} \times (1 - \min(a \times \frac{GDP_{it}}{Pop_{it}}, EIR_{max})) & \text{if } i \in P1_t \\ e_{it} = e_{it-1} - \left(\sum_{c \in P2_t} e_{ct-1} - \left(\sum_{c \in N} e_{ct} - \sum_{c \notin P2_t} e_{ct}\right) \times \frac{S_{it}}{\sum_{c \in N} S_{ct}}\right) & \text{if } i \in P2_t \end{cases}$$

where $S_{it} = \frac{e_{it-1}^2}{Pop_{it-1}}$, $P1_t = \{i \in N, CRI_{it} > CRI_1\}$ is the set of countries at stage 2 at year t , $P2_t = \{i \in N, CRI_{it} > CRI_2\}$ is the set of fully participating countries. $CRI_i = \frac{GDP_{it} + e_{it}}{Pop_{it}}$ is a Capacity-responsibility index.

Variant 2:

$$\begin{cases} e_{it} = e_{it}^{BAU} & \text{if } i \notin P1_t \text{ and } i \notin P2_t \\ e_{it} = GDP_{it} \times \frac{e_{it-1}}{GDP_{it-1}} \times (1 - b) & \text{if } i \in P1_t \\ e_{it} = e_{it}^{BAU} - \left(\sum_{c \in N} e_{ct}^{BAU} - e_{ct}\right) C_{it} & \text{if } i \in P2_t \end{cases}$$

where b is a target of reduction of the carbon intensity, C_{it} is a per capita contribution to CO₂-induced temperature increase and is calculated following the Brazilian

approach, $P1_t = \{i \in N, GDP_{it} > A_1\}$ is the set of countries at stage 2 at year t , $P2_t = \{i \in N, GDP_{it} > A_2\}$ is the set of fully participating countries.

Variant 3:

$$\begin{cases} e_{it} = GDP_{it} \times \frac{e_{it-1}}{GDP_{it-1}} \times (1 - b) & \text{if } i \notin P1_t \\ e_{it} = e_{it}^{BAU} - \left(\sum_{c \in N} e_{ct}^{BAU} - e_{ct} \right) \frac{\frac{e_{it}}{Pop_{it}}}{\sum_{c \in P_t} \frac{e_{ct}}{Pop_{ct}}} & \text{if } i \in P1_t \end{cases}$$

where b is a target of reduction of the carbon intensity, $P1_t = \{i \in N, e_{it} > \bar{e}_{ct}\}$ is the set of countries at stage 2 at year t .

Interpretation: There are three stages: countries at stage 1 emit as usual, countries at stage 2 reduce the carbon intensity of their economy, countries at stage 3 reduce their emissions.

Examples of implementation in the literature: Variant 1 is used in Pan et al. (2017) and Pan et al. (2018), with $EIR_{max} = 7\%$, $CRI_1 = 10$, $CRI_2 = 20$ (see paragraph on the Historical Responsibility rule for other details on the implementation).

Variant 1 is used in Den Elzen and Lucas (2005), with $EIR_{max} = 3\%$, $CRI_1 = 5$, $CRI_2 = 12$ (see paragraph on the Brazilian Proposal for other details on the implementation).

Variant 2 and 3 are used in Berk and Den Elzen (2001), where $b = 0.04$, A_1 corresponds to 50% of the 1990 Annex I per capita income and A_2 to 75% of this income (see paragraph on the Brazilian Proposal for other details on the implementation).

5.2.8 Allocation rules following hybrid approaches

Some approaches are a combination of previously described rules.

Hybrid 'average' approach HY1:

Allocation rule: Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which e_{it} is the non-weighted average of the values obtained with the allocations CER.2, CPC.1, GDR.1, EPC.2 and CAP.

Examples of implementation in the literature: In Robiou Du Pont et al. (2017), the conditions are the same as for the cited allocation rules.

Hybrid 'entropy' approaches HY2, 3, 4, 5:

Entropy allocation rule: Here, $\Phi(d_L) = (e_{i,t})_{i \in N, t > 0}$, in which

$$e_{it} = e_{it}^{BAU} - \left(\sum_{c \in N} e_{ct}^{BAU} - e_{ct} \right) \frac{K_{it}}{\sum_c K_{ct}}$$

where K_{it} is the emission reduction factor of a country i.

We have

$$K_{it} = \sum_{j=1}^7 IW_{itj} \times DW_j \times I_{itj}$$

where IW_{itj} is the information weight associated to indicator j, country i at year t,

and $I_{itj} \in \left\{ \sum_{y=T}^t e_{iy}, \frac{e_{it}}{Pop_{it}}, e_{i0}, GDP_{it}, HDI_{it}, CI_{it}, PCC_{it} \right\}$

DW_j is a subjective weight given to indicator j, and the four hybrid approaches correspond to different weightings, detailed in the following table.

Indicator	I_{ijt}	HY2	HY3	HY4	HY5
Cumulative emissions	$\sum_{y=T}^t e_{iy}$	1/3	3/5	1/5	1/5
Per capita emissions	$\frac{e_{it}}{Pop_{it}}$	1/3	3/5	1/5	1/5
Emissions	e_{i0}	1/3	3/5	1/5	1/5
GDP	GDP_{it}	1/3	1/5	3/5	1/5
HDI	HDI_{it}	1/3	1/5	3/5	1/5
Carbon emission intensity	CI_{it}	1/3	1/5	1/5	3/5
Proportion of coal consumption	PCC_{it}	1/3	1/5	1/5	3/5

Interpretation: These approaches are partially based on the information entropy method and on subjective weights to calculate the weight of each of the seven indicators used. The indicators (cumulative CO2 emissions, per capita CO2 emissions, CO2 emissions, GDP, HDI, carbon emission intensity and proportion of coal consumption to global energy consumption) are grouped into 3 dimensions. HY2 corresponds to an average between the 3 dimensions, HY3 to a more responsibility-oriented approach, HY4 to a more capacity-oriented approach, HY5 to a more potential-oriented approach.

Examples of implementation in the literature: In Gao et al. (2019), the reference year is 2012, the target year is 2030 and $T = -22$ (the historical year is 1990). The project data comes from six BAU scenarios based on the Roadmaps towards Sustainable Energy Futures. The emission control scenario is determined using RCP 2.6 and the global required effort is the difference between each BAU scenario and the emission control scenario.

Bottom-up allocation HY6:

Allocation rule : The modelling of this allocation rule is bottom-up and consists in iterative steps to derive a global pathway consistent with the chosen emissions scenario (A_0). A bottom-up allocation of the pathway $BU(A_0)$ is constructed, where each country follows the least-ambitious of five effort-sharing approaches : **CAP**, **EPC.2**, **GDR.1**, **CER.2**, and **updated CPC.1**. The pathway is then iteratively updated with the following formula :

$$A_{n+1} = A_n - \frac{(BU(A_n) - A_0)}{2}$$

The steps are repeated until $BU(A_n) = A_0$ or $A_n = A_{n+1}$.

Examples of implementation in the literature: In Robiou Du Pont and Meinshausen (2018)), the reference year is 2010 and the target year is 2100. The modelling of the individual approaches follows Robiou Du Pont et al. (2016, 2017)).

5.2.9 Limits of a single-rule based approach

Sharing a carbon budget is blind to the economic consequences, for countries, of the choice of allocation rules. In fact, for a given country, and for a given allocation rule, mitigation costs will vary depending on whether allowance trading is permitted or not (Van Den Berg et al., 2020; Li and Duan, 2020). In addition, mitigation costs are complex and uncertain. Discussing the equitable character of the allocation of costs is thus much more difficult than discussing the equitable character of the allocation of emission allowances. It also requires more complex models (Li and Duan, 2020), as consequences can reliably be estimated only after the mitigation choices are implemented whereas the evaluation of fairness regarding emission quotas happens ex ante. This is why only a few studies discuss directly the fairness of the distribution of mitigation costs (Li and Duan, 2020; Van Den Berg et al., 2020). More generally, all matters related to the

implementation of the mitigation objectives, such as financial or technology transfers, are not encompassed within this framework. Yet, they are central to fairness considerations. For example, a given allocation can be considered fair in a context where the exchange of quotas is permitted, and not if it is prohibited (Godard, 2000).

Implicit in all the rules presented above is also the idea that emissions reduction is a "burden" to be shared. This completely erases the idea that there could be benefits associated with the mitigation efforts. A bottom-up approach, as it is based on voluntary commitments, can address mitigation from the perspective of creating opportunities (Heyward, 2007). With regard to this work's main subject, the level of development of countries is considered to some extent in some of the allocation rules, but there is no accounting for the synergies and tensions that exist between climate change mitigation and other development objectives.

Last but not least, the analytical presentation of each rule, and the listing of all the underlying assumptions, makes it clear that individual rules can yield a wide range of allocations depending on the underlying choices that are made. For example, the choice of the starting year, the choice of BAU emissions used as reference, or the choice of the threshold for participation can have significant impacts on the outcome (Lecocq, 2000; Van Den Berg et al., 2020). The diversity of the rules that we have reviewed also illustrates the wide range of competing views on fairness and equity that are present in the debate. As shown in some of the previously mentioned studies (Pan et al., 2018; Robiou Du Pont et al., 2017), implementing different rules can lead to very different allocations for countries. This is an obvious source of tensions in international negotiations (Bodansky, 2016), as there is no consensus in the literature, or among parties, as to what a "fair" distribution of allocation is. To illustrate this point, Parties use different and competing allocation rules to justify the fairness of their NDC (Cunliffe et al., 2019; Chan, 2016; Rajamani et al., 2021). The recent literature on assessing fairness takes stock of this lack of consensus, and offers assessments based on a variety of rules, as reviewed in the following section.

5.3 A review of the tools assessing national contributions' fairness

Since the Paris Agreement, every country produces a Nationally Determined Contribution (NDC), which sums up the country's voluntary commitments in terms of climate change mitigation and adaptation. In this context, it is tricky to assess the fairness of the countries' ambition levels. Indeed, such an assessment requires a normative vision of what an ambitious contribution from each country should be. No such vision of what is equitable has, however, been agreed upon internationally.

Yet, assessments tools are necessary:

- The current aggregated emission targets are not enough to maintain the global temperature under the 2°C target (United Nations Framework Convention on Climate Change (UNFCCC), 2016; Den Elzen et al., 2022): an increase in ambition at the global level is needed, which means an increase in ambition is also needed at some individual level.
- For stakeholders, being able to judge a country's level of ambition can be useful to push for more ambitious action. It is also a way to strengthen the accountability of governments to citizens, as shown in recent court decisions (Murdie and Urpelainen, 2015; Backes and van der Veen, 2020).
- Assessing the fairness of countries' NDCs also fuels positive emulation between countries: they could be more likely to contribute in an ambitious way if they believe other countries have ambitious targets too (Aldy, 2015). Indeed, as mentioned by Carattini et al. (2019b), an updated theory of international environmental agreements shows that the existence of an equity-preference and reciprocity might rationalize larger coalitions (Lange and Vogt, 2003), push countries to send an ambitious signal (Buchholz and Sandler, 2017) or decrease their ambition if few countries abate (Nyborg, 2018). This reciprocity depends on the countries' perceptions of fairness (Hadjiyiannis et al., 2012).

In this section, we list and compare the existing methods to assess the fairness of countries' mitigation contributions, which we call "judgement rules". A judgement rule associates, to any set of national pledges and characteristics (population, historical emissions, wealth etc.), a set of corresponding judgements (such as "fair", "indifferent", "rather unfair", etc.). All of the judgement rules that we review are based on one or several allocation rules - mostly among the ones reviewed in the previous section.

5.3.1 Framework

We consider a domain D as described in section 1 and a set of **national pledges** $E^{NDC} = (e_{it}^{NDC})_{(i,t) \in N \times N}$ of future yearly national emissions.

The **set of admissible assessment scales** \mathbb{J} includes all sets of statements which can be gathered among the three categories "fair", "unfair" and "undecided". Any elements $J \in \mathbb{J}$ is called a **assessment scale**. For instance $J = \{\text{"fair"}, \text{"rather fair"}, \text{"indifferent"}, \text{"rather unfair"}, \text{"unfair"}\}$. An assessment scale which only gathers statements in the "fair" and "unfair" categories is said to be **decisive**.

A **individualized assessment** on national pledges is a set of statements $(j_i)_{i \in N} \in J^n$ where $J \in \mathbb{J}$.

An **individualized assessment rule** on national pledge Γ associates to any $d \in D$ and national pledge E^{NDC} an individualized assessment $\Gamma(d, E^{NDC}) \in J^n$.

5.3.2 Existing assessment approaches

Existing assessment methods all rely on comparing individual countries' voluntary contribution in terms of GHG emissions reduction, to reference values computed for these countries. There are three broad categories of assessment, depending on how these reference values are computed. In some tools, the voluntary contributions are compared to a single emission reference, that may be defined with a single allocation rule or a hybridisation of different allocation rules. Other tools consist in comparing national targets to a range of emission references, each one depending on a different allocation rule.

Approaches based on a common fair allocation rule:

In these approaches, NDC targets are compared to a single reference value, either obtained with a single allocation rule, or by averaging values from several allocation rules (which is equivalent to having a single, ad-hoc rule, as the references for all countries are computed the same way). The assessments that derive from these methods are conclusive: the assessment scale only includes statements in the "fair" and "unfair" categories.

Reference value from a common allocation rule

$$\begin{cases} j_i = \text{"fair"} & \text{if } e_{it}^{NDC} \leq e_{it} \\ j_i = \text{"unfair"} & \text{if } e_{it}^{NDC} > e_{it} \end{cases}$$

Interpretation: The targets proposed in the NDCs are compared to an allocation, or a weighted average of several allocations.

Example 1: Pan et al. (2017) compares 8 countries' targets with an unweighted average of the allocations under 13 approaches: historical responsibility (HR), ability to pay (AP), emission intensity targets (EIT), equal per capita convergence (EPC.1), immediate per capita allocation (EPC.2), billion high emitters (BHE.1), greenhouse development rights (GDR.2), south-african approach (SAA), cumulative per capita convergence (CPC.2), common but differentiated convergence (CDC), constant emission ratios (CER.1), multi-criteria approach (MCA), multi-stage approach (MSA).

Example 2: Pan et al. (2018) compares 6 countries' targets with an unweighted average of the allocations under 16 approaches, including the 13 previous ones, CPC.3, CER.2 and EPC.1 with a convergence in 2100.

Example 3: Robiou Du Pont et al. (2017) compares the INDCs of all countries with an unweighted average of the allocations under 5 approaches: capability (CAP.1), equal emissions per capita (EPC.1), greenhouse development rights (GDR.1), equal cumulative per capita (CPC.1) and constant emission ratios (CER.1), which corresponds to the hybrid allocation rule (HY.1).

Example 4: The Climate Equity Reference Calculator (CERC, Holz et al. (2019)) enables the user to choose their own parametrization of the responsibility and capability rules, then choose the relative importance of each rule. It then compares the NDCs of all countries with the emission reference calculated from the greenhouse development rights (GDR.2) operationalization that derives from the chosen parameters.

Approaches based on differentiated allocation rules:**Hybrid bottom-up method 1**

$$\begin{cases} j_i = \text{"fair"} & \text{if } e_{it}^{NDC} \leq e_{it} \\ j_i = \text{"unfair"} & \text{if } e_{it}^{NDC} > e_{it} \end{cases}$$

where e_{it} is determined by an allocation rule that follows a bottom-up logic (where every country chooses, among a few allocation rules, the one for which the efforts are minimal, but the target is respected).

Interpretation: The targets proposed in the NDCs are compared to bottom-up determined allocations, in which each country follows the equity rule that benefits them the most, but where aggregated projections respect the global target.

Example 1: Robiou Du Pont and Meinshausen (2018) compares the INDCs of all countries with the allocations calculated under the HY.6 hybrid approach: each country follows the least ambitious out of five allocation approaches (capability (CAP.1), equal emissions per capita (EPC.1), greenhouse development rights (GDR.1), equal cumulative per capita (CPC.1) and constant emission ratios (CER.1)). The aggregated allocations have to be consistent with a target warming threshold.

The results are accessible online with the Paris Equity Check Vizualizing tool⁸ on the Pledged Warming Map.

Hybrid bottom-up method 2

$$\begin{cases} j_i = \text{"fair"} & \text{if } e_{it}^{NDC} \leq e_{it} \\ j_i = \text{"unfair"} & \text{if } e_{it}^{NDC} > e_{it} \end{cases}$$

where e_{it} is determined by a single allocation rule that takes into account the existing NDC targets in order to avoid over-allocation (see below).

Interpretation: Over-allocation happens when a country's ambition is high enough that its NDC emissions targets are lower than the initial reference value allocated. Considering the country's ambition, one might want, in this case, to set its allocation at the level of its NDC, while distributing the difference among other countries for which there is no over-allocation. This avoids over-ambition by reducing the commitment needed of countries if another country is more ambitious than its "fair share".

⁸<http://paris-equity-check.org/>

Example 1: Li and Duan (2020) compare the NDCs of some countries with the allocations calculated under one equity rule. The allocations are then updated as follows: the aggregated gap between the global target and the aggregated contributions is shared among NDCs that are not fair enough following another allocation rule based on responsibility, capability, responsibility and capability, grandfathering, and mitigation potential. (The article provides the operationalization of this method for seven starting allocation rules: Historical Responsibility (HR), Ability to pay (AP), South African approach (SAA), Common but differentiated convergence (CDC.1), grandfathering (CER.1), multi-stage approach (MSA.1) and equal cumulative per capita (CPC.2)).

The "Climate Action Tracker (CAT)" approach

General idea: In the method developed by Climate Analytics et al. (2016), the national targets are compared to a range of allocations that each derive from a different equity rule. The country's ambition is considered very high if its target is higher than any allocation, very low if its target is lower than any allocation. Otherwise, the tool is not entirely conclusive.

Climate Action Tracker CAT constructs a "Fair Share Range" for each country based on a set of reference allocations calculated with a comprehensive set of fair allocation rules existing in the literature.

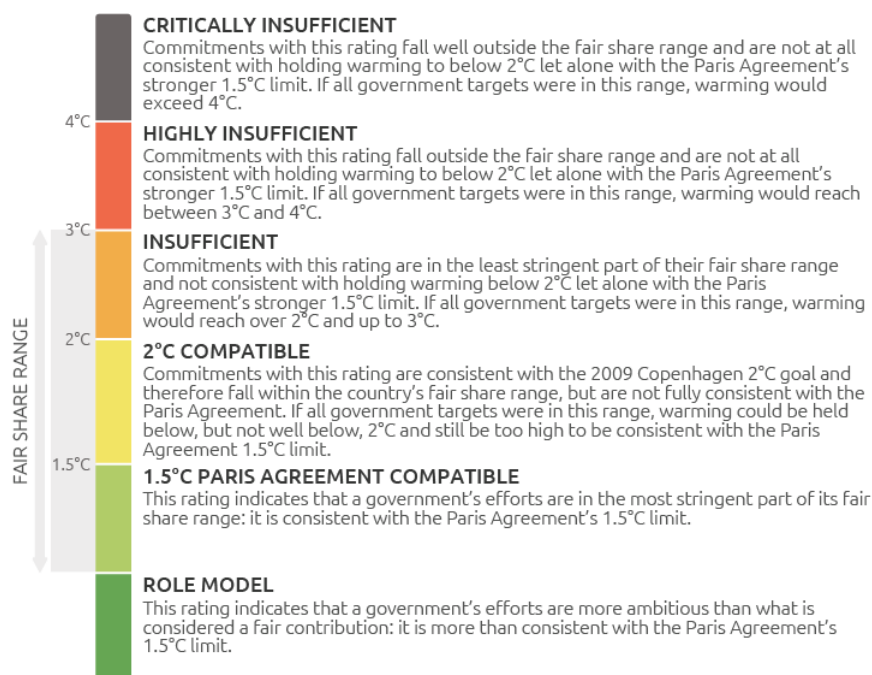
For each of the allocation rules' categories presented earlier, implementing the allocation rules forms a range of allocations. The category with the highest value(s) and the category with the lowest value(s) are excluded. The values of the remaining categories form the fair share range $[e_{itinf}; e_{itsup}]$, which is presented in Figure 5.2. It is divided in 3 categories: insufficient, 2°C compatible, 1.5°C compatible.

$$\left\{ \begin{array}{l} j_i = \text{"critically insufficient"}, \text{ if } e_{it}^{NDC} > e_{it4} \\ j_i = \text{"highly insufficient"}, \text{ if } e_{it4} > e_{it}^{NDC} > e_{itsup} \\ j_i = \text{"insufficient"}, \text{ if } e_{itsup} > e_{it}^{NDC} > e_{it2} \\ j_i = \text{"2°C compatible"}, \text{ if } e_{it2} > e_{it}^{NDC} > e_{it1.5} \\ j_i = \text{"1.5°C compatible"}, \text{ if } e_{it1.5} > e_{it}^{NDC} > e_{itinf} \\ j_i = \text{"role model"} \text{ if } e_{it}^{NDC} \leq e_{itinf} \end{array} \right.$$

Where e_{it4} , e_{it2} and $e_{it1.5}$ are calculated using the following method. A "global fair share range" is determined by a "best case scenario" where all countries choose to reduce

emissions to the lowest 10th percentile of their Fair Share range, and an opposite global "worst case scenario" where all countries choose to reduce emissions to the highest 10th percentile of their Fair Share range. $e_{it1.5}$ is determined considering that the relative level of emissions between the 1.5°C pathway and the best/worst case scenarios is the same as between $e_{it1.5}$ and the bounds of country i 's fair share range. The same reasoning is used with e_{it2} and 2°C pathways (and e_{it4} and 4°C pathways, outside of the global fair share range).

Figure 5.2: Presentation of the Climate Action Tracker assessment tool



Source: <https://climateactiontracker.org/>

If a country is at the border between two categories, several additional elements are taken into account for the rating (if the commitment is conditional on international financing for example). Adaptation and the contribution to international financing are not explicitly included in this range, but CAT provides another tool to assess the finance contribution of some countries.

Other approaches similar to CAT: Other approaches exist, in which the country's ambition is considered very high if its target is more ambitious than all reference allocations computed for the rules included in the tool, very low if its target is less ambitious than all reference allocations, but the judgment is not decisive in between.

Example 1: The Equity Map proposed by the Paris Equity Check tool ⁹ is based on reference allocations calculated in Robiou Du Pont et al. (2017). For a given country, the map displays the number of approaches with which the INDC is compatible among the 5 following approaches: capability (CAP.1), equal emissions per capita (EPC.1), greenhouse development rights (GDR.1), equal cumulative per capita (CPC.1) and constant emission ratios (CER.1).

Example 2: In Gao et al. (2019), a country's NDC is compared to a range of reference values calculated from the hybrid allocation rules HY2, HY3, HY4, HY5. Outside of the range, the country's ambition is sufficient or insufficient, inside, the tool is not conclusive and the country's ambition is deemed "moderate".

Example 3: In Holz et al. (2018), a country's NDC is compared to an "equity band" calculated from different parametrizations of the Climate Equity Reference Calculator earlier detailed. Outside of the range, the country's ambition is sufficient or insufficient, inside, the tool is not conclusive.

5.3.3 Comparing the approaches

The main features of each assessment approach are summed up in Table 5.1 (AR=Allocation Rule).

As noted above, some judgement rules use a single effort-sharing rule. These judgement rules are fully conclusive: the country is deemed sufficiently ambitious if its target is higher than the « fair contribution » proposed by the rule, insufficiently ambitious otherwise. Judgement rules based on a single allocation rule are, however, hard to legitimise in the current international context as no rule has been internationally agreed upon, nor is there a consensus among scholars on one rule rather than another.

Other judgement rules (e.g. Robiou Du Pont and Meinshausen (2018)) rely on a hybrid method based on several equity rules. These approaches are also conclusive, but they rely on out-of-the-hat aggregation procedures. They come down to creating a new

⁹<http://paris-equity-check.org/>

Table 5.1: Comparison of the three main approaches of the existing assessment tools to evaluate the ambition of a country's contribution

Characteristic	Single reference method	Differentiated AR	CAT or CAT-like method
Based on multiple AR?	Possibly	Yes	Yes
Conclusive?	Yes (single reference)	Yes (single reference)	No (range of values)
All countries follow the same AR ?	Yes	No (differentiation)	No (range)
If all NDCs are "fair", is their aggregation necessarily in line with the global target?	Yes	Yes	No
Results are sensitive to the parametrization of AR	Yes	Yes	Yes
Results are sensitive to which AR is included or not	Medium to high	Medium	High if extreme values are included

AR = Allocation Rule

"composite" allocation rule. Consequently, the legitimacy of such judgement rules is no higher than the legitimacy of judgement rules based on a single allocation rule.

Finally, some approaches (e.g. Climate Analytics et al. (2016); Gao et al. (2019)), compare a Party's target to a range of reference values, each determined by a different effort-sharing rule. Such judgement rules are more legitimate, as they account for the diversity of views on equity. They are also less conclusive, since when countries' engagements fall between reference values, no firm judgement is provided. Moreover, with these rules, all countries' contributions may fall in a Fair Share range, without the global aggregated contribution meeting the global target. The CAT itself proposes estimations of subranges that would indicate a compatibility with global targets. However, links between the global 1.5°C or 2°C climate targets and individual countries' emission pathways prove difficult to establish and also rely on many assumptions (Lecocq and Winkler, 2023).

5.4 Conclusion - Discussion

This chapter provides an extensive review of equity assessment tools, both emission allocation rules and judgement rules that refer to one or several allocation rules.

We show that when assessing the fairness of a country's contribution, there is a compromise to find between multiplying the viewpoints and providing a firm assessment. Indeed, the assessment methods reviewed in Section 5.3 compare a country's target to a value or a range of values based on the allocation rules reviewed in the first section. Given the absence of consensus among scholars and stakeholders in international negotiations on what a "fair" allocation is, there are theoretical reasons to leave aside any of the principles that underlie the calculation of the allocation rules. On the other hand, Dooley et al. (2021) argue that including all the allocation rules in an assessment gives it the illusion of being unbiased, placing a value-neutral gloss over normative perspectives. It also prevents us from providing a firm judgement: the bigger the "fair share range" is, the more risk there is for most countries to fall within an "indecisive" category.

This compromises the relevance of the assessment tools as their uses would require conclusive judgements while accounting for stakeholders' divergent values and beliefs and being fair in their treatment of opposing views. The former is a condition for salience and the latter for legitimacy, two conditions for knowledge systems to effectively contribute to sustainable development (Cash et al., 2003). In its latest report, the IPCC thus calls for updated tools to assess fairness (Patt et al., 2022). Among the new ideas in this direction is Rajamani et al. (2021) who link equity approaches with the principles of international law. The views of citizens could also be taken into account to motivate a more salient collective equity assessment. In Chapter 6, we thus gather, through a survey, empirical data on public intuitions on climate equity, aiming at improving the knowledge on the plurality of conceptions of what an equitable effort sharing is.

Although the current assessment methods have already helped pointing out a lack of individual ambition among countries, this present framework of assessment may also be too restricted. Indeed, a few aspects are not included.

First, on a technical aspect, the LULUCF (Land-Use, Land-Use Change and Forestry) sector is almost always excluded from the emissions calculations, mainly for practical reasons: it is difficult to quantify and compare emissions and emission targets amongst different countries. Thus, the assessment methods are mainly focused on energy-linked emissions. This way of calculating emissions and targets could be

detrimental for countries who rely on forestry as an opportunity to offset their emission levels, and advantageous for large LULUCF emitters. More generally, different ways of accounting for greenhouse gases emissions in equity can generate unfairness (Rogelj and Schleussner, 2019).

Another aspect comes with the new call to reach global net zero emissions by 2050 (Van Soest et al., 2021), which risks to be translated into a framework in which all countries have to individually reach net zero emissions - equity considerations would then be applied in the form of differentiated timelines to do so (Dubash et al., 2021), which is not explicitly the case in current existing allocation rules.

Finally, the change of paradigm operationalized in the Paris Agreement is not limited to a change from a top-down effort-sharing approach to a bottom-up mitigation approach. Indeed, the NDCs also contain targets in terms of adaptation to climate change, and international climate finance. Although the global climate mitigation target is fundamental, these dimensions should also be accounted for when assessing the climate ambition of countries: some countries may indeed be more ambitious in terms of adaptation to climate change, which may alter their ability to mitigate. Additionally, some developing countries' targets depend on an international financial support, and the subject of Loss and Damages has also made its way in the international agenda.

If we push these considerations further in the context of this thesis, the equity considerations within the climate change framework could even be extended from the current climate-change centered vision to a broader vision including other development targets. Overall, there are parallel and complementary needs to, on the one hand, find avenues to legitimize a more conclusive judgement on whether the countries "took their fair share" of mitigation or not - which would mean reducing the number of legitimized points of view on fairness - as well as, on the other hand, to gather more information on how fairness considerations evolve when put in the larger context brought by the Sustainable Development Goals. Integrating development pathways (Klinsky and Winkler, 2018) and the fact that countries pursue other Sustainable Development Goals in this climate-centered vision could indeed help strengthen the chances for a consensus to emerge with regard to equity considerations, but this approach has yet to be fully operationalized.

International climate justice: what the people think

*This chapter is adapted from joint work with Yann Kervinio and Aurélie Méjean
(CIRED)*

Abstract

To what extent do countries make equitable climate contributions within the Paris Agreement? The answer to this central question relies on the existence of explicit and shared views about fairness. Yet, studies on the range of fairness views are rare and often have a limited immediate policy-relevance. In this chapter, we discuss how using citizens' judgements can be relevant to discriminate among the large set of reasonable views that can define international climate justice. We design and administer a survey to elicit relevant judgements among French and US citizens. We find that in both countries, most respondents think that principles of climate justice should be settled internationally even if they go against some countries' interests, and express a preference for common (rather than differentiated) responsibilities - all the more so when they are concerned about climate change. We observe support for two effort sharing rules: convergence towards equal per capita emissions, and a version of grandfathering. Our survey also shows inconsistencies in fairness judgements, and that citizens have difficulties coordinating with others on simple judgements regarding existing nationally determined contributions. A development of standardised surveys to investigate citizens' views on fairness opens avenues for improving the existing fairness assessment tools.

Contributions:

Auriane Meilland: Conceptualization, Methodology, Investigation, Analysis, Data curation, Writing (original draft)

Yann Kervinio, Aurélie Méjean: Conceptualization, Methodology, Analysis, Writing (review and editing), Supervision

6.1 Introduction

In the Chapter 5, we showed that providing a judgement on whether each Nationally Determined Contribution is in line with the Paris Agreement goals or not is far from trivial. Because of the existence of a wide range of possible rules to share the mitigation effort, and no ex-ante agreement on how to allocate the remaining carbon budget, there is no international consensus on what would constitute a "fair" national contribution. Existing assessment tools all present a trade-off between taking into account the multiple, sometimes contradictory, views on equity, and providing a conclusive judgement.

The stakes around such an evaluation are high: an increase in ambition at the global level is still needed (United Nations Framework Convention on Climate Change (UNFCCC), 2016), which means an increase in ambition is also needed at the countries' level – and even, in the end, at regional or sectoral scales. The Intergovernmental Panel on Climate Change's sixth assessment report thus notes that the academic community needs updated tools to evaluate the fair character of individual contributions to the global issue, with constraints arising to translate collective judgements in the new international context (Shukla et al., 2022).

The work described in this Chapter intends to make a step in this direction. Our underlying hypothesis is that, in the absence of a philosophical rationale that everyone would agree on, and in the absence of a consensus amongst Parties, one might go back to the judgement of individuals. Stated opinions and preferences of citizens may, if not provide a consensus on what is a fair contribution to global mitigation, at least restrict the range of rules that should be considered when making the judgement. The question guiding this Chapter is then "What are the individual attitudes of the general population regarding international climate justice that could motivate conclusive and legitimate collective judgements?". We intend to enhance the conclusiveness and legitimacy of existing judgement tools by getting a refined understanding of citizens' relevant divergent values and beliefs on that matter. To do so, we conduct a survey on citizens from France¹ and the USA, two countries that hold contrasted positions in climate negotiations (Szarka, 2012). We follow the existing literature and use survey techniques to elicit public attitudes towards climate justice. However, we follow the original perspective of empirical social choice which intends on building a legitimate collective judgement out of the observation of separate individual judgements (Gaertner and Schokkaert, 2012; Yaari and Bar-Hillel, 1984). This implies observing the attitudes towards similar rules

¹as a part of the European Union

in different settings. We show that two allocation principles (convergence towards equal per capita emissions and grandfathering) are prioritized, and provide further insights on whether these judgements are relevant to found a legitimate collective judgement on normative grounds.

The remainder of this chapter is structured as follows. Section 6.2 reviews the existing literature around surveys on climate justice, discusses the normative scope of their results, and motivates specific aspects of our survey design. Section 6.3 presents the survey and methods. Section 6.4 displays raw survey results as well as in-depth data analyses. Section 6.5 discusses the significance and limits of our results, and presents leads for further improvements in using empirical social choice to address climate equity at the international level.

6.2 Literature review: public attitudes towards climate justice

6.2.1 Climate justice and equity rules

Ringius et al. (2002) define equity principles as “*generally acknowledged norms of fairness that have traditionally been seen as valid across a range of issue areas and at different levels*”. In our context, they are translated into allocation rules. An allocation rule associates, for any set of countries with their characteristics and a global climate target, an allocation of yearly target-emissions to each country, ensuring consistency with the achievement of the global target. They rely on specified formulas studied by a wide literature (Höhne et al., 2014), which we reviewed in-depth in Chapter 5.

Most of the rules in the literature belong to one of six categories described by the IPCC’s fifth assessment report (Fleurbaey et al., 2014):

- The *responsibility* approach is related to the polluter-pays principle, as countries’ past greenhouse gases emissions are accounted for (for example in den Elzen (1999)).
- The *capability* approach refers to allocation rules in which the more one is able to contribute (e.g. wealthier countries, countries where abatement costs are lower), the more one should (examples in Jacoby H. D. et al. (2008); Miketa and Schrattenholzer (2006)).

- The *equality* approach refers to allocation rules based on per-capita emissions converging towards an equal level compatible with the global target (examples in Berk and Den Elzen (2001); Höhne et al. (2006)).
- The *responsibility-capability-need* approach refers to allocation rules that put an emphasis on historical responsibility, capability and the need for countries to sustainably develop (examples in Kemp-Benedict et al. (2018); BASIC experts (2011)).
- In rules using an *equal cumulative per capita* approach, equal per capita emission budgets over a cumulative period are allocated to countries, then divided into yearly budgets (example in Bode (2004)).
- *Staged approaches* include other allocation rules where countries take differentiated commitments in various stages (e.g. rules based on the “grandfathering principle”, in which emission “rights” should be given in priority to historical emitters).

As discussed in Chapter 5, allocation rules provide a basis for “judgement rules”. A judgement rule associates, to any set of national pledges (for example NDCs) and characteristics (population, historical emissions, wealth etc.), a set of corresponding judgements (such as “fair”, “indifferent”, “rather unfair”, etc.). We showed that existing judgement rules all result in a trade-off between legitimacy and conclusiveness and can be classified into three groups:

- Some judgement rules (Pan et al., 2018, 2017; Robiou Du Pont et al., 2016, 2017) are based on a single allocation rule and are thus fully conclusive: a country is deemed sufficiently ambitious if its target is higher than the « fair contribution » proposed by the rule, insufficiently ambitious otherwise. But these approaches are hard to legitimise as no allocation rule has been internationally agreed upon.
- Other judgement rules (e.g. Robiou Du Pont and Meinshausen (2018)) rely on a hybrid method that combined several equity rules. While making sure the aggregated targets are in line with the 2°C goal, the « fair contribution » of each country is calculated using the most advantageous rule for that country. These approaches are conclusive, but they rely on out-of-the-hat aggregation procedures, which compromise their legitimacy.
- Finally, some approaches (e.g. Climate Analytics et al. (2016); Gao et al. (2019)) compare a Party’s target to a range of reference values, each determined by a

different allocation rule. If its targets exceed the higher values, the country is deemed unambiguously ambitious enough, and if they fall short of the lower values, it is judged unambiguously insufficiently ambitious. Such judgement rules are more legitimate, but also less conclusive, since when countries engagements fall between different reference values, no firm judgement is provided.

Improving our knowledge and understanding of citizens' perceptions of global climate justice could strengthen the existing judgement rules. For example, improving the conclusiveness of tools such as the Climate Action Tracker without compromising their legitimacy could be helped by removing allocation rules that are not supported by observed judgements.

6.2.2 Existing survey results

Existing studies on stakeholders' attitudes on international justice follow a diversity of approaches. Some review how fairness views are expressed by countries in national position documents feeding negotiations on climate mitigation (e.g. Tørstad and Sælen (2018)), or other stakeholders (e.g., for States, NGOs and experts in Pottier et al. (2017) or the media in Schmidt and Schäfer (2015)). Others conduct lab experiments emulating international negotiations, mostly on student samples (Anderson et al., 2017) with one notable exception on negotiators (Dannenberget al., 2010). Overall, these studies have limited external validity. Finally, a stream of literature uses survey methods.

A systematic review of survey results on individual attitudes towards international climate justice, conducted in february 2023 and detailed in Appendix D, shows that existing studies tackle a diversity of research questions and differ regarding their framing, sampling strategy, and administration. The framing and questionnaires vary: most questionnaires are elaborated on an ad hoc basis for each study, with little standardised approaches. These surveys also differ regarding the targeted population and the sampling strategy. Some target participants to climate negotiations (Lange et al., 2007, 2010; Hjerpe, M. et al., 2011; Kesternich et al., 2021), others citizens in the US, European countries or China (Carlsson et al., 2011, 2013; Bechtel and Scheve, 2013; Schleich et al., 2016), and one targets college students in China and the US (Kriss et al., 2011). They follow the full range of possible administration methods (paper or on-line, remotely or face-to-face). Finally, most reviewed surveys were conducted around 2010. Some recent ones also focus on citizens' attitudes towards climate policies (see Carattini et al.

(2018); Maestre-Andrés et al. (2019) for reviews of the literature as well as the more recent studies by Carattini et al. (2019a); Dechezleprêtre et al. (2022); Carlsson et al. (2021); Andor et al. (2022)). While they partially address our problem, their main focus is not on attitudes towards international fairness.

These differences in design entail differences in the scope and nature of what is observed. Some surveys provide descriptive information on individual support to different allocative rules, while others further analyse mechanisms in people's judgements. For example, the previous literature has shown a preference for rules relating to differentiated responsibilities but also finds evidence supporting the existence of a self-serving bias (which is a preference for visions aligning with the one's interests) in existing attitudes (e.g. Schleich et al. (2016)). While most surveys provide a descriptive account for stakeholders' divergent values and beliefs, they also gather limited information about how different ways to arbitrate or conciliate opposing views would be deemed fair. How the various rules should be accounted for when providing a judgement, based on the described preferences of citizens, is thus left open.

Most approaches to the study of people's judgements have a descriptive intent. In contrast, our endeavour is normative, as inspired by Miller, D. (2012), empirical social choice (Gaertner and Schokkaert, 2012; Yaari and Bar-Hillel, 1984) or empirical ethics (e.g., Appiah (2009) on experimental approaches). These approaches aim at using the observation of individual judgements as a basis for supporting a normative statement. With an observation of actual stakeholders' judgements, they complement the normative literature², mostly philosophical and theoretical, and possibly biased by the specific values of moral and political philosophers. However, they require specific care in avoiding taking social consensus as always right, and minority views as automatically mistaken, as this would contradict the very nature of moral judgements (Hausman D. M. (2000) quoted in Gaertner and Schokkaert (2012)).

This normative intent requires specifying which individual judgements are relevant in a normative perspective, and paying attention to survey design accordingly. As their intent is mostly descriptive, existing surveys on stakeholders' attitudes toward international climate justice do not enter into such considerations.

On the other hand, the existing literature in empirical social choice and ethics mostly focuses on decontextualized situations. This literature is thus limited and incomplete

²An abundant theoretical literature also exists on international climate justice. It is confronted with actual stakeholders' positions by Pottier et al. (2017)

to address the question of public adhesion to allocation rules. In this work, we specify which information would have normative relevance in the specific context of international climate justice, and adjust our survey design accordingly.

6.3 Methods

As previously detailed, the nature of the relevant information to be collected and the study design have to be consistent with a legitimate basis for collective decisions, that is explicitly justified both in terms of whose and what judgements are relevant. Such an informational basis will vary depending on the different understandings of the socio-political process through which legitimate judgements are built. In the context of international climate negotiations, two contrasted perspectives can be described (Pottier et al., 2017).

In an *internationalist perspective*, collective judgements are a product of negotiations between sovereign States. Principles of climate justice thus do not prevail over countries' national interests. In this context, Schelling (1981) argued for the relevance of identifying focal points, understood as outcomes that would be reasonable enough to crystallise an agreement while limiting feelings of unfairness. This perspective invites us to focus on the views of negotiators in a context of bargaining (not deliberation)³ and on the existence of a shared understanding regarding the fair level of countries' contribution, which could act as a focal point in negotiations.

In a *cosmopolitan perspective*, collective judgements are the product of deliberations (not bargaining) between citizens' representatives in idealised deliberative instances (Sen, 2006). Principles of climate justice can thus prevail over countries' national interests. In this context, we are interested in citizens' considered judgements over specific allocation rules. We define a considered judgement as arising when the judgement on a theoretical principle and the judgement on an illustrative case representing this principle mutually adjust and become consistent with one another: they are in a reflective equilibrium (Rawls, 1951). This perspective invites us to focus on the plurality of conceptions of a fair allocation, how existing judgements overlap and how stable they are, in order to identify the potential outcomes of deliberation and consensus-building.

³Bargaining is usually defined as a process between people with stable interests who decide to make concessions and use promises or threats, whereas deliberation uses rational arguments and features people who are open to changing their values in order to reach a "common interest".

We do not choose between these two competing perspectives, but rather aim at collecting data that would be potentially relevant for one and/or the other. Concerning the legitimate stakeholders, we choose to focus on ordinary citizens rather than actors involved in international climate negotiations. This can be justified in the cosmopolitan perspective as they are the source of legitimacy, but also in the internationalist perspective as the disagreement between Parties may reflect a stronger self-serving bias of their negotiators than their citizens due to strategic delegation (Lange and Schwirplies, 2017). Concerning the nature of the judgements observed, each perspective provides reasons to focus on specific information, as detailed hereafter. In the following, we first detail some broad research questions that guide the survey design, which we then present.

6.3.1 Broad research questions

To motivate the vision of a collective judgement, we first aim at eliciting isolated individual attitudes towards equity. This leads to our main research question: “*What are the individual attitudes of the general population regarding international climate justice that could motivate decisive and legitimate collective judgements?*”, specified by three sub-questions:

- **Q.1 Are people in favour of a cosmopolitan or an internationalist perspective on international justice?**
- **Q.2 How do people conciliate between common and differentiated responsibilities?** “Common But Differentiated Responsibilities” recognises the responsibility of all States in addressing climate change on the one hand, and acknowledges that different levels of development among countries need to be accounted for on the other hand. Allocation rules often result in a trade-off between the common and differentiated aspects.
- **Q.3 Among allocation rules listed by the IPCC, which ones are supported the most in the population?** Based on the existing literature (Schleich et al., 2016), we form the hypothesis that some rules might gather more support than others.

Our goal is to get a refined understanding of the plurality of existing conceptions of fairness regarding climate change among French and US citizens, and identify the potential to discriminate between these conceptions.

Considering previous survey results, it is unlikely that we observe convergent individual judgements on allocation rules in **Q.3**. Consistently with the cosmopolitan approach, we thus investigate the potential for judgements to evolve and adjust (for example during a deliberation process). For this, we collect information on the stability (whether judgements evolve through moral reasoning⁴) and consistency (whether judgements expressed over general principles and in particular cases are consistent overall) of the observed judgements. Consistently with the internationalist perspective, the survey also provides information on the existence of a shared understanding which could act as a focal point in a negotiation context (Schelling, 1981). This motivates a situation where respondents are incentivized to tacitly coordinate their judgements with others.

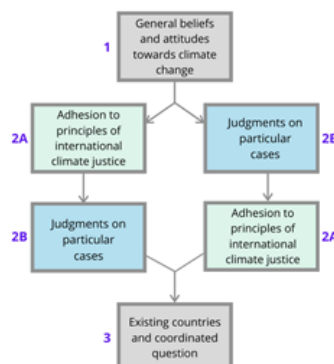
6.3.2 Questionnaire

The complete version of the questionnaire in English can be found in Appendix D. Apart from general socio-demographic questions, the survey is composed of four blocks. While the content of the blocks will be detailed later, their structure, depicted in Figure 6.1, is the following:

- **Block 1:** general beliefs and attitudes towards climate change.
- **Block 2A** (randomised with Block 2B): adhesion to principles of international climate justice.
- **Block 2B** (randomised with Block 2A): judgement on illustrative cases.
- **Block 3:** individual/coordinated judgements on four countries' NDCs.

The questionnaire is designed to answer the three research questions. Block 2A and 2B bring relevant information regarding existing attitudes in the general population with respect to these questions. To inform the discussion on question 3, the consistency of judgements is checked by using different approaches to get a better grip on citizens' opinions. The respondents are asked about their opinion on a general principle (Block 2A), but also on illustrative abstract cases (Block 2B). These two blocks are randomised in order to measure the stability of judgements - whether citizens respond differently depending on the order of the blocks or not. Statistical analyses then allow testing for

⁴We define moral reasoning as a quest for consistency between judgements over general principles and in illustrative cases, to achieve a reflective equilibrium (Rawls, 1951)

Figure 6.1: Structure of the survey

learning effects, the existence of which would suggest that observations do not reflect the stabilised judgements that could arise through deliberation and moral reasoning. Finally, Block 3 features a question in which respondents are asked to coordinate (with a reward if successful) on a judgement without communicating. This design has been proposed to elicit shared understandings (Schelling, 1981), including social norms (Krupka and Weber, 2013). This exercise intends to test for the existence of a widely shared understanding between French and US citizens on fairness in this context, and provides insights on the existence of potential focal points, further informing the discussion around question 3. With that in mind, the content of each section is detailed in the following paragraphs.

Block 1 is inspired by Douenne and Fabre (2020), and elicits some general beliefs and attitudes of respondents towards climate change. We ask how often they talk about climate change, then measure their knowledge with questions on its anthropogenic origin and the main gases causing it. We ask for their perception of the gravity of climate change and who will be most affected geographically and in time. We finish by eliciting the citizens' preference for an internationalist or a cosmopolitan perspective in climate justice.

In Block 2A, we determine respondents' adhesion to the CBDR principles (and what they would prioritise between the common and differentiated dimensions), and to the underlying principle of the « grandfathering » approach (where countries which emitted more in the past have a right to continue emitting more). We test their agreement with the fairness of five general principles sharing an intertemporal net carbon budget, belonging to four categories detailed in Chapter 5: responsibility (countries that emitted less have a right to less reduce their emissions), capability (poor countries or

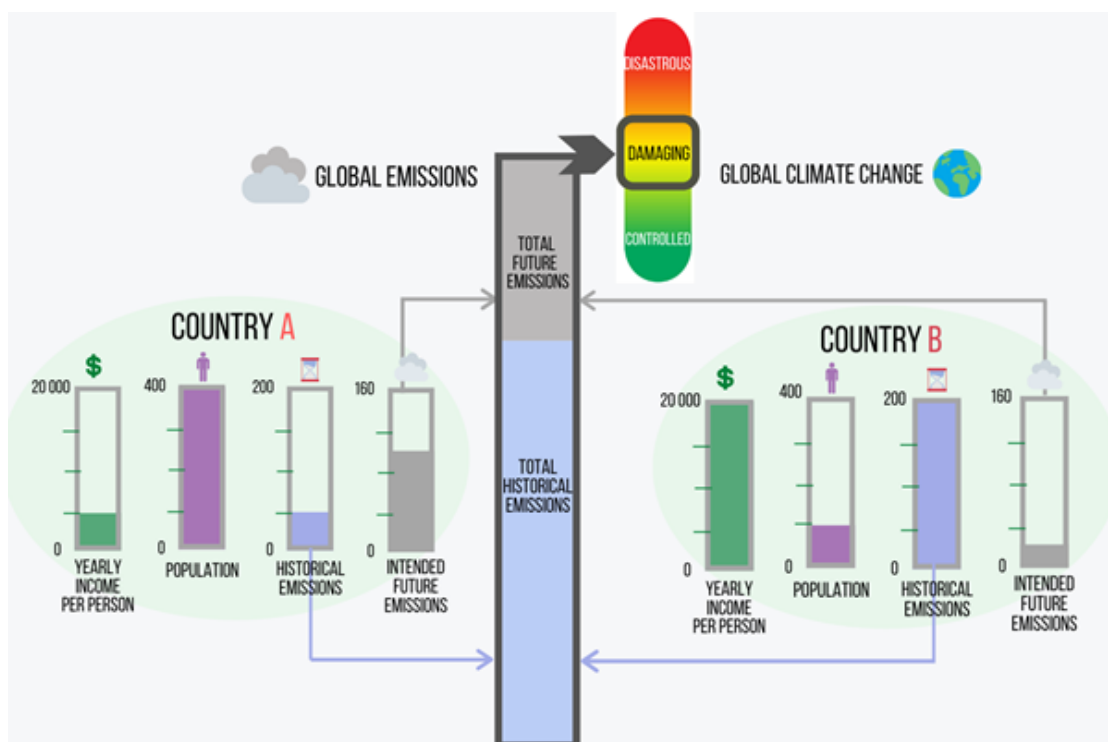
countries where reducing emissions is costly have a right to less reduce them), equality (countries' emissions converge towards an equal per capita value) or an operationalized version of grandfathering (countries reduce their emissions by the same percentage). Since we care about respondents' adhesion, but also about the principles they tend to prioritise, we then ask them to choose two out of the five listed above. Another question targets their agreement with the fairness of allowing some countries (poor, with large carbon sinks, funding projects abroad or sharing their low-carbon technologies) to reduce their emissions less than others. This block concludes by asking which geographical (territorial, or footprint) and historical (since 1850, 1990 or present times) emissions respondents would consider for judging a country's NDC.

In Block 2B, respondents are presented with particular cases where two countries differ by their GDP and/or past emissions and/or population and/or future intended emissions, and the resulting projected climate change varies. After a question in which their comprehension of a case is tested (Figure 6.2 shows the image displayed), all six cases described in Table 6.1 are displayed in a random order, and respondents are asked whether they think each country took its fair share or not. Cases are arbitrarily chosen so that answers bring information on the respondents' attitudes towards different allocation rules, to test for the consistency of their opinions. This design differs from discrete choice experiments in that we do not ask respondents to choose between two countries: by making it possible for them to agree that both contributions would be fair/unfair, we consider judgments as attitudes and not preferences.

Block 3 presents respondents with a question resembling Block 2B, on four existing Parties: China, India, the EU, the USA. In a second question, French and US respondents are asked to coordinate their judgements on the EU and the USA's NDCs with their counterpart of the other country. We compare the first answer in France to the first answer in the US, the second answer in France to the second answer in the US and so on, and give a reward to the respondents who successfully coordinate. The participants are also asked to estimate their chances of succeeding.

We finally display an open text field for comments.

Figure 6.2: Representation of the test case



In each case, countries differ by their yearly income per person, population and cumulated historical emissions. They intend to produce a given quantity of cumulated net future emissions. Each representation of a case also comes with a small text recapitulating what is visually described (common and different characteristics of the countries, resulting level of climate change), see Appendix D for the detailed survey.

Table 6.1: Summary of the cases proposed in Block 2B of the survey

Case	Country List				Country List				Climate change
	Pop	GDP/cap/yr	Historical	Pledge	Pop	GDP/cap/yr	Historical	Pledge	
C0	100	20000	200	100	100	20000	200	20	Damaging
C1	400	20000	200	100	100	20000	200	20	Damaging
C2	100	5000	200	100	100	20000	200	20	Damaging
C3	100	20000	50	100	100	20000	200	20	Damaging
C4	400	5000	50	60	100	20000	200	60	Damaging
C5	400	5000	50	60	100	20000	200	20	Controlled

Case 0 (in blue) is considered a reference case and is always presented first to the respondents. Case 1 to 3 deviate from the reference case by one characteristic of country A. In Case 4, countries differ by all their characteristics but implement the same pledge. Case 5 is similar to Case 4 except that country B adopts a more ambitious pledge, that leads to a global controlled climate change. The five following cases are randomised. In grey are highlighted the values that change from the reference case.

6.3.3 Survey implementation

The survey was implemented on LimeSurvey from the 15th to the 31st of July 2020. The samples and implementation are presented in further details in Appendix D.

For practical reasons (language, representativeness and panel quality), we focused on two countries in this study: France⁵ and the USA. While their populations are quite similar in terms of income and development, the EU and the USA hold different positions regarding climate equity in international negotiations (Lange and Schwirplies, 2017). Whether this opposition reflects fundamental differences in citizens' values, or whether specific principles of climate justice and related allocation rules could gather large support in both countries, is unclear.

We collected responses for 1004 US and 1001 French respondents, accessing panels via the survey company Lightspeed Research (Kantar) through a link sent by email. Screening questions were implemented to ensure that the final sample was representative of the national population for gender, age (6 brackets), income (4 in the US, 5 in France), region (5 in France, 4 in the US) and agglomeration category (5 in France, 3 in the US). Our tests show that the sample is representative in both countries (see Appendix D).

Lightspeed Research maintains representative panels in various countries and manages the rewards for respondents. The respondents are paid in "LifePoints", which can be converted into gifts or cashed out (the value of LifePoints varies). For our survey, for which the median time of completion was around 13m30 both in French and English, the individual reward was around 2.2 euros for a complete answer. The participants who successfully coordinated were rewarded with an additional 25 LifePoints (around 0.5 euros).

The resulting dataset, including all questions and response speed, is available in supplementary material.

⁵Here, France is targeted as a subset of the EU population for convenience in the survey implementation (language, etc.). The differences in public attitudes within the EU could be addressed in later studies.

6.4 Results

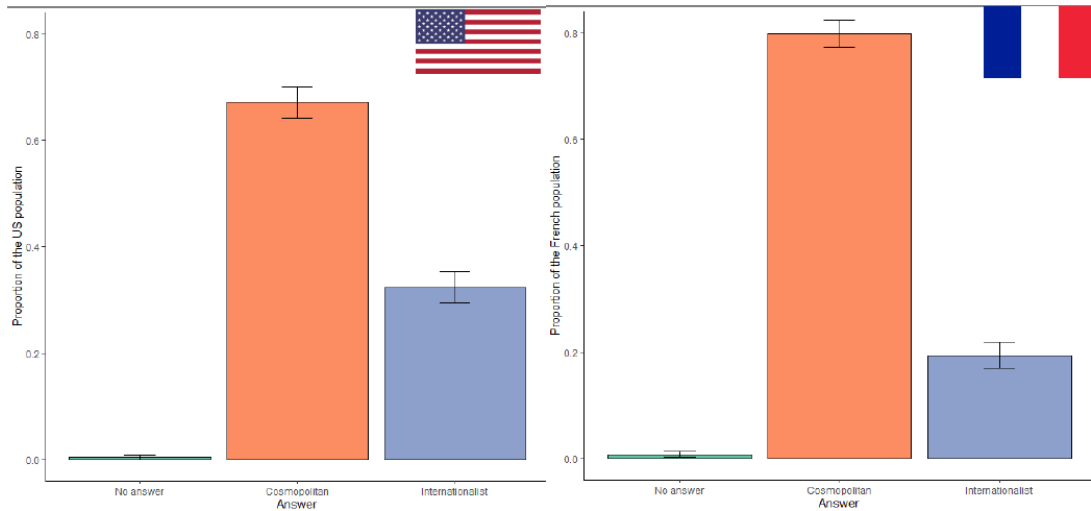
This section presents descriptive statistics answering the questions motivated in the previous section.⁶

French and US respondents have a close general understanding and set of beliefs about climate change (Block 1). Most respondents think that climate change is mainly caused by human activities (78% in France, 62% in the US), and more than 45% cite both carbon dioxide and methane as contributing to global warming.⁷ Most respondents think the effects of climate change could be significant or disastrous (90% in France, 75% in the US), affecting both countries indifferently (more than 70%), and around a third of respondents think people born in 2020 will be the first affected (which is not their own generation).

6.4.1 Main result 1: a majority of citizens favour a cosmopolitan perspective on climate justice, with a wider share among those most worried about climate change

Most respondents, in France as well as in the US, favour a cosmopolitan vision of climate equity over the States' sovereignty. This surprising result shown in Figure 6.3 answers research question **Q1**: “*Are people in favour of a cosmopolitan or an internationalist perspective on international justice?*”. The proportion is higher for French (around 80%) than US respondents (around 67%). In both countries, this preference does not significantly depend on basic socio-demographics (age, gender, income), but depends on the frequency with which respondents talk about climate change, as well as how serious they think climate change will be. **More than 80% of respondents who think that climate change will be disastrous and/or talk about it frequently are in favour of the cosmopolitan perspective (compared to around 73,5% for all respondents).**

Figure 6.3: Preference for a cosmopolitan or an internationalist approach on equity considerations, among the US (left) and French (right) populations



These figures display the distribution of answers when citizens were asked to choose between the following (with the possibility not to answer): (1) Principles of climate justice should be settled at the international level, even if that may prevent countries from pursuing the interest of their own people [label: Cosmopolitan] and (2) Principles of climate justice should never prevail over countries' own national interests, even if it may impede the fight against climate change [label: Internationalist]. Error bars represent a confidence level over 95%.

6.4.2 Main result 2: a majority of citizens prioritise the “common” aspect of CBDR, with a wider share among the more worried about climate change

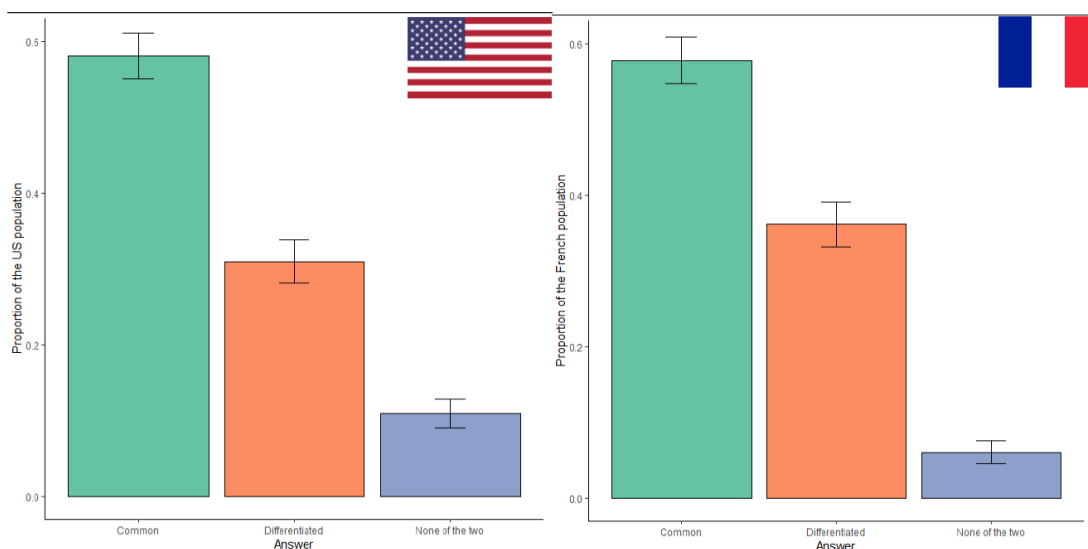
In response to research question **Q.2A**, both **French and US citizens tend to favour the common responsibility in the “Common But Differentiated Responsibilities” principle** (Figure 6.4). Around 58% of the respondents in both panels would prefer for every country to contribute to the fight against climate change without discrimination (common responsibilities) rather than accept exceptions (differentiated responsibilities).

The preference for common responsibilities is significantly correlated with a higher awareness of the climate crisis (frequent talk and knowledge

⁶A complete overall review, question by question, is provided in Appendix D. Further analyses mentioned in the discussion are also provided in Appendix D

⁷although around 60% of French people wrongly cite particulate matter, which is only the case for 32% of people in the US

Figure 6.4: Preference for the Common or Differentiated aspect of the CBDR principle, among the US (left) and French (right) populations



These figures display the distribution of answers when citizens were asked to choose between the following (with the possibility not to answer): (1) Countries share common but differentiated responsibilities. However, if I had to choose, I would consider that countries mostly hold common responsibilities, which means that all countries, without exception, should act to limit climate change. [label: Common], (2) Countries share common but differentiated responsibilities. However, if I had to choose, I would consider that countries mostly hold differentiated responsibilities, which means that some should make more efforts than others to combat climate change. [label: Differentiated] (3) None of the above [label: None of the two]. Error bars represent a confidence level over 95%.

about the subject, pessimism regarding its effects). Age, gender or income cannot be significantly linked to the answer, but with significance in both countries, people who talk about climate change frequently, and/or think its effects will be disastrous, and/or favour the cosmopolitan vision for principles of climate equity, also insist on common responsibilities. This tends to confirm that the anticipation of dramatic consequences could lead people to less accept exceptions, although establishing such a causal effect would require a specific questionnaire design and include respondents from other countries.

6.4.3 Main result 3: two allocation rules are largely favoured (individual judgements are stable, with moderate inconsistencies)

Two allocation rules draw a collective adhesion

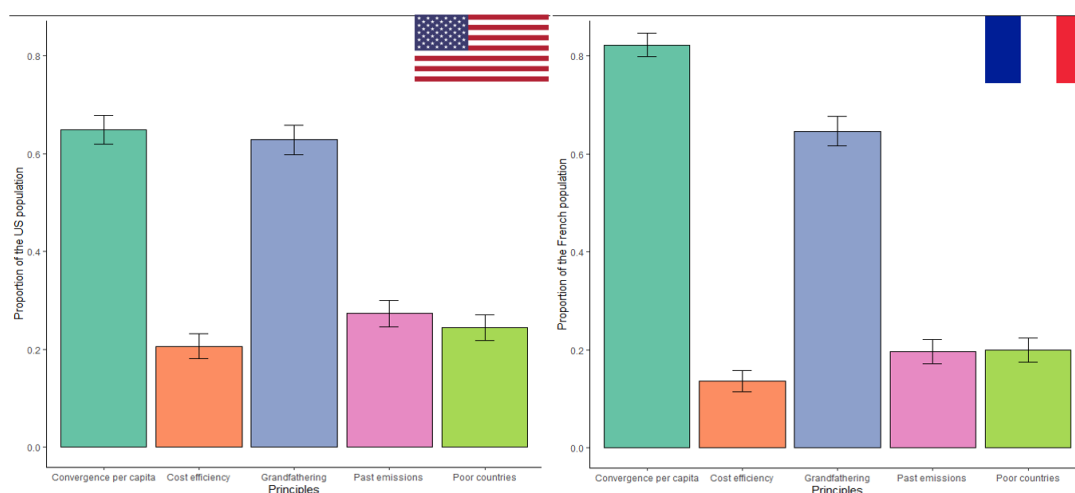
Our main research question (through **Q.3**) is mainly treated in Block 2A: “*What are the judgements of the general population regarding the relative fairness of allocation rules listed by the IPCC?*”. **Here, respondents show a strong adhesion to a long term convergence towards an equal per capita level of emissions** (80% and 90% of US and French respondents), **and a reduction of emissions by the same percentage** - which is an operational grandfathering (76% and 73% of US and French respondents). Both were also chosen by more than 60% of US and French respondents when asked to select two among the five proposed principles. The three other principles (as shown in Figure 6.5) were not chosen by more than 30 % of respondents in this question, and do not get the adhesion of respondents when they are asked about each principle individually.

These results are notable for several reasons. First, people tend to very largely favour a convergence towards equal per capita emissions (compatible with a 2°C target) when sharing future net cumulated emissions. This strong level of adhesion, for citizens of two developed countries, is interesting as it goes against a possible self-serving bias. It could however be explained by the fact that respondents may not have considered its full implications.

Second, an operational version of grandfathering in which all countries reduce their emissions by the same percentage also draws strong adhesion. This is surprising, as the first question of Block 2A shows that in both countries, more than 73% disagree with the principle underlying the grandfathering allocation rule.⁸

In the context of our study, the supportive attitudes displayed both for a common responsibility principle and two sharing rules are all the more interesting that people also display a preference for cosmopolitan justice. However, the adhesion to the two principles might be triggered by their wordings. Indeed, both preferred allocation rules refer to the notion of equity (use of the word “same”) and tend to be evocative of a harmonized treatment of countries, either perceived as more simple unlike other principles which tend to be evocative of a way to differentiate commitments, or leading to the respondents not

⁸See Appendix D, question 9

Figure 6.5: Preferred allocation principles in the US (left) and French (right) panels

In this question and out of five principles, respondents were asked to choose the two that they considered to be the fairest: (1) all countries commit to converge to the same average of total emissions per inhabitant [label: Convergence per capita], (2) countries where reducing the emissions is costly commit to reduce them less [label: Cost efficiency], (3) all countries commit to reduce their emissions by the same proportion [label: Grandfathering], (4) countries which emitted less in the past commit to reduce their emissions less [label: Past emissions], and (5) poorer countries commit to reduce their emissions less [label: Poor countries]. Error bars represent a confidence level over 95%. See Appendix D for the detailed question and an analysis of the adhesion of citizens to each principle individually.

having realised the implications of each rule. The next paragraphs further investigate the consistency and stability of observed judgements.

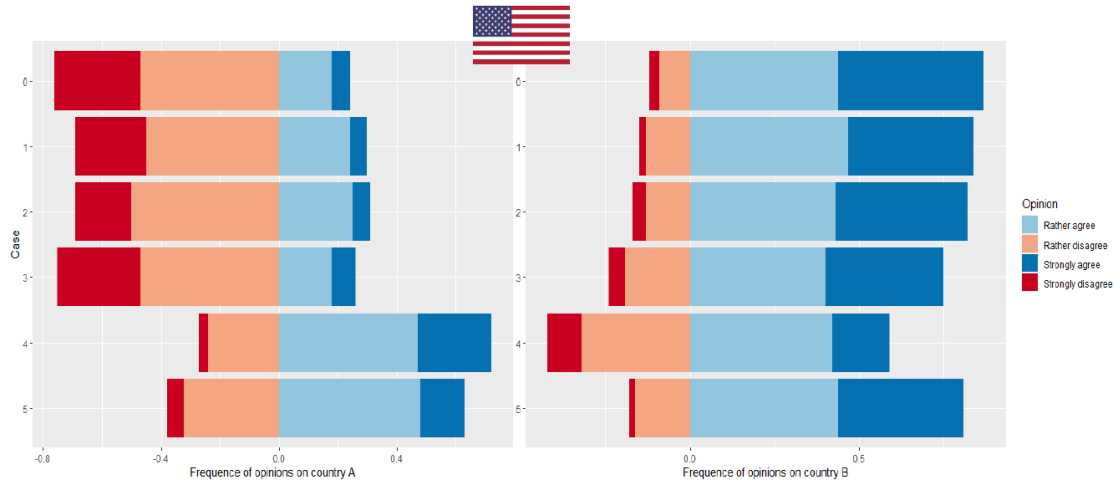
Judgements on particular cases are consistent with the preference for common responsibilities (with little consistency with judgements on generic rules)

The judgements of people on particular cases presented in Block 2B (see Table 6.1, Figure 6.6) shows that **respondents almost exclusively take into account the total future emissions of a country when judging its contribution.**

Indeed, in Case 0, the countries only differ by their level of future emissions (A will emit more than B)⁹, and climate change is predicted to be damaging. Unsurprisingly,

⁹Although it thus seems that future emissions are the main driver of the respondents' judgements, we cannot rule out that this result is explained by the design of the figures.

Figure 6.6: Judgement of US citizens on countries in illustrative cases presented in Block 2B



The respondents are presented with 6 simplified cases (see Table 6.1). They are then asked whether they think that the country A and the country B took their fair share or not, in cases 0 to 5. Case 0 is considered a reference case and is always presented first to the respondents. Case 1 to 3 deviate from the reference case by one characteristic of country A. In Case 4, countries differ by all their characteristics but implement the same pledge. Case 5 is similar to Case 4 except that country B adopts a more ambitious pledge, that leads to a global controlled climate change. Only Case 4 and country A in Case 5 show a significant difference with the equivalent value in Case 0 with a confidence level of 95 %. The distributions of answers to cases from question 3 are corrected to only account for the answers of respondents who succeeded the test. However, even though the proportions may change, the trends described are also valid among the global populations. Similar results for the French population, as well as the associated tables can be found in Annex D.

most US and French respondents think that B took its fair share and A did not. We compare the answers to other cases to this reference and get the following results, which hold in both countries:

- In cases which only differ from Case 0 by one of A's characteristics, the distributions of answers are not significantly different from the reference case.
- In case 4 where A and B are only similar by their future emission commitments, respondents' judgements are significantly different from the judgement provided in the reference case: both countries' pledges are positively judged.
- In case 5 where A and B completely differ, and climate change appears controlled, both countries' pledges are also positively judged.

The previous observations seem consistent with answers drawn from Block 2A, and the preference of people for common responsibilities: by not taking into account any past and present characteristic for the country but only their future contribution, the respondents choose to not make any difference or exception for a country with a specific characteristic.

Further tests for the consistency of individual judgements over sharing rules and particular cases, detailed in Appendix D, show that:

- *Judgements about a convergence towards equal per capita emissions display some level of inconsistency, in both panels.* Judgements are consistent in that people prioritising common responsibilities significantly tend to agree more with a convergence towards equal per capita emissions. The judgements on the principle and on A's contribution in case 1 (where A is more populated) are, however, not consistent. People who strongly agree with the principle significantly tend to either strongly agree or strongly disagree more with the fact that country A's contribution is fair. This last result could be explained by lack of attention, but we also show that careful respondents (who can read the situations without mistake) almost only take into account future pledges when judging countries' pledges.¹⁰
- *Judgements about the grandfathering principle(s) are inconsistent, in both panels.* Although people's opinions about both formulations of grandfathering are significantly dependent, respondents who strongly agree with one tend to either strongly agree or strongly disagree more than others with the other. This could signal the existence of heuristics – respondents' interpretations of the same principle might highly depend on its formulation. Moreover, respondents significantly tend to have the same opinion about a version of grandfathering and the principle that refers to an historical responsibility. This result is a marker of inconsistency as these principles would not be compatible with one another. However, some people could very well think that two incompatible principles are both fair in absolute terms (around 13 % of French and 19 % of US respondents never disagree with the principles).

Judgements are rather stable

In a cosmopolitan perspective, deliberation and consensus-building would involve an articulation between judgements on general principles and illustrative cases, and likely

¹⁰See Appendix D

induce the kind of moral reasoning leading to a reflective equilibrium. In this perspective, further investigation about the existence of learning effects could be useful to get a sense of whether observed judgements are likely to reflect considered and stable judgements or, on the contrary, to evolve through argument. This can be investigated by testing for the effect of the order of Blocks 2A and 2B on their respective answers.

We find that **judgements are rather stable, although some learning is observed**. However, it does not reflect a change in opinions, but mostly in their strength. We observe that specific cases can have an influence on general principles, not the opposite. The significant results on moral reasoning differ from one panel to another, and are displayed in Appendix D. Even though learning effects are observed, they do not make people drastically change their opinion about the principles of interest: people's adherence to equal per capita convergence is strengthened, and while respondents exhibit more moderate positions towards an operational grandfathering, they still globally agree with it. These conclusions are nuanced by the fact that none of these results is significant in the US panel.

No shared understanding emerges when studying interpersonal judgements

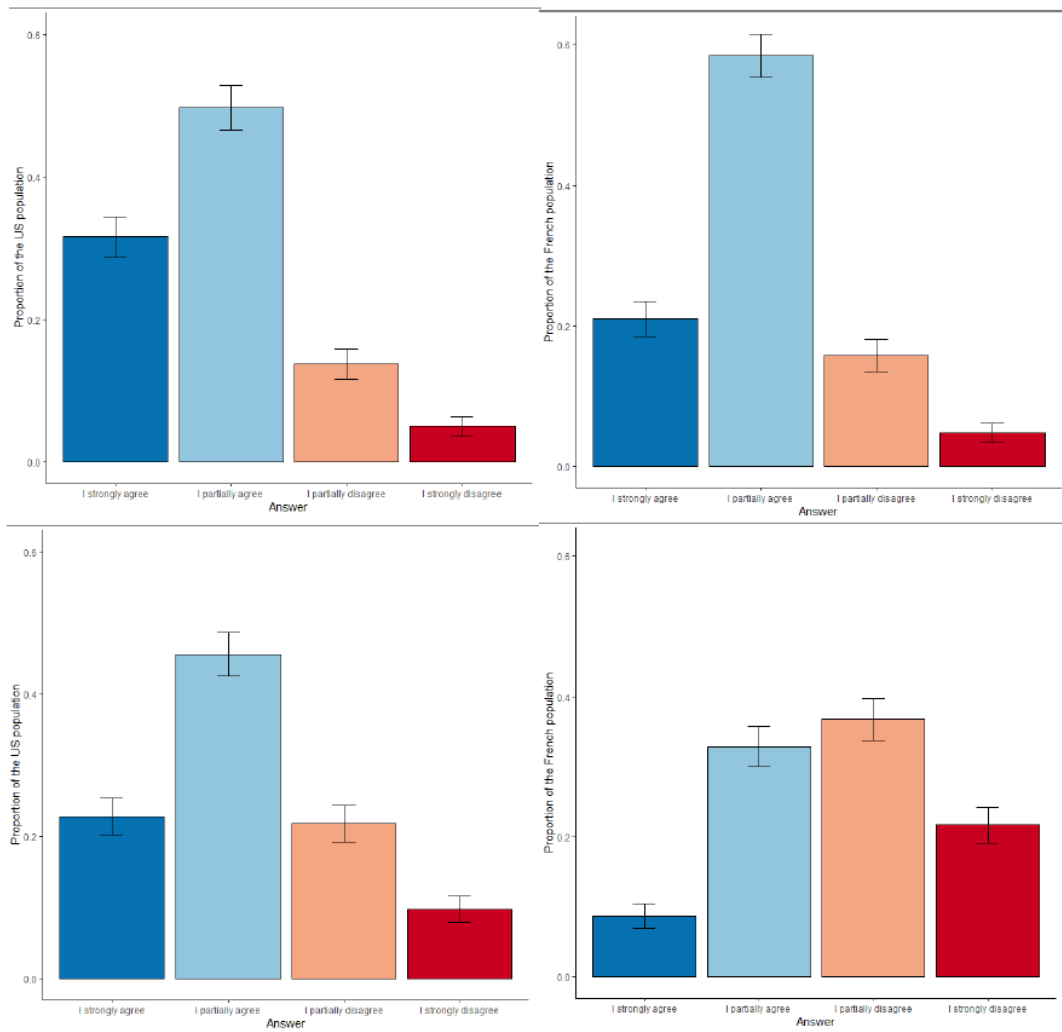
In the internationalist perspective, a collective judgement could also emerge from bargaining. This would draw interest on the potential existence of focal points, revealing the existence of a shared understanding among citizens regarding the natural outcomes in a negotiation process.

Block 3 first asks respondents, after presenting figures on the situations of China, India, the USA and the EU, whether those Parties took their fair share or not (Figure 6.7). We show that respondents from France and the US give similar answers when judging China and the EU, but differ when judging India and the USA. Respondents from both countries agree or strongly agree that the EU is taking its fair share (79 % in France, 80% in the US). US respondents agree or strongly agree that the USA (58%) is taking its fair share, whereas French respondents mostly disagree that the USA is taking its fair share (58%).¹¹ These judgements about the EU and the USA will serve as a reference for the coordination game.

In the coordination exercise, French and US respondents are asked to imagine they

¹¹The exact question and a detailed description of the answers are presented in Appendix D of this chapter

Figure 6.7: Respondents' judgement on the EU's (top) and the USA's (bottom) NDCs, among the US (left) and French (right) populations



In this question, respondents are shown a figure representing the characteristics and NDCs of China, India, the EU and the USA and are asked whether they think each of these countries took its fair share with no incentive to coordinate their judgements. Error bars represent a confidence level over 95%

have to coordinate their judgements on the EU and the USA with a counterpart from the other country. At first glance, the distributions of judgements on both Parties for both panels do not change compared to the reference. However, a majority of respondents (around 54%) change their minds for at least one country, when asked to coordinate.

In order to get a better understanding of how opinions changed, flowcharts of the evolution of the respondents' answers are presented in Figures 6.8 and 6.9. They confirm that there is no clear tendency in the evolution of opinions, in that for each group of people changing their opinion, there is an equally-sized one going for the opposite change. The respondents, when asked to estimate their probability to have successfully coordinated with others, consider it rather low (80% of French and 54% of US respondents estimate it at less than 50%), and only 137 pairs of respondents among the 1004 formed actually succeeded in coordinating their judgements.¹² **This shows the absence of a widely shared understanding, between French and US citizens, of what countries' fair shares should be.**

6.5 Conclusion - discussion

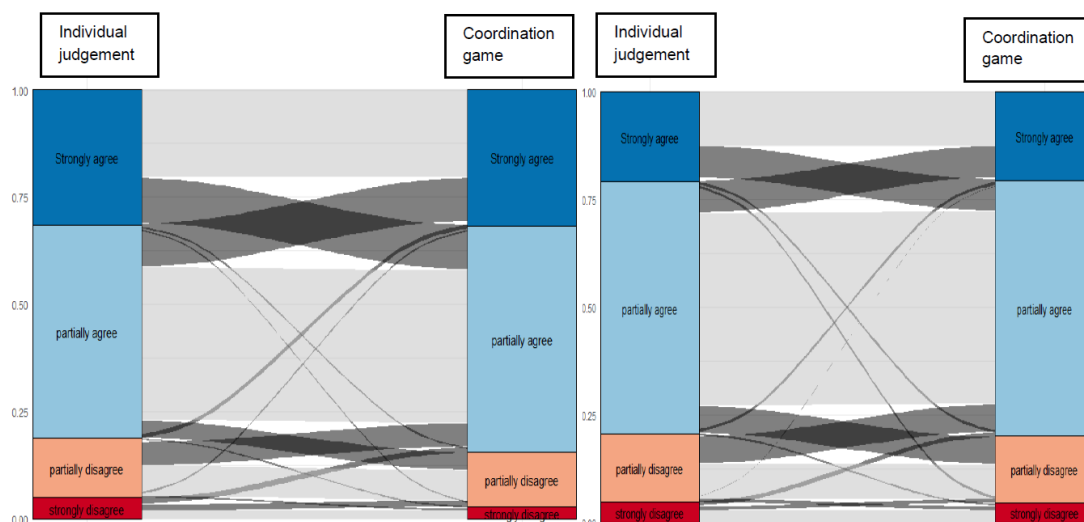
6.5.1 Main conclusions and policy-relevance of the study

In this study, we contribute to a limited literature on eliciting public attitudes towards international climate justice, and perform an innovative design informed by a discussion on the relevant empirical bases for motivating normative judgements. By specifically identifying what type of knowledge on citizens' views would be important within which perspective on cooperation, we aim at providing information to, for example, legitimize the use of some allocation rules drawing adhesion over others, when assessing the countries' ambition in real life. This endeavour is crucial, as stated in the IPCC's 6th Assessment Report: *“given the limited avenues for multilateral determination of fairness, several researchers have argued that the onus is on the scientific community to generate methods to assess fairness”*. The originality of our work lies in the methodology that is developed: we combine judgements on principles and allocation rules with judgements on specific cases, and complete this approach by eliciting both individual and interpersonal judgements on some countries' NDCs.

Three main results emerge from our analysis:

¹²Further analyses featured in Appendix D show that even though significant differences exist among the responses of individuals with different characteristics, no clear trend appears.

Figure 6.8: Evolution of the answers of US (left) and French (right) respondents about the EU’s NDC, when asked for their opinion in isolation and in the tacit coordination game

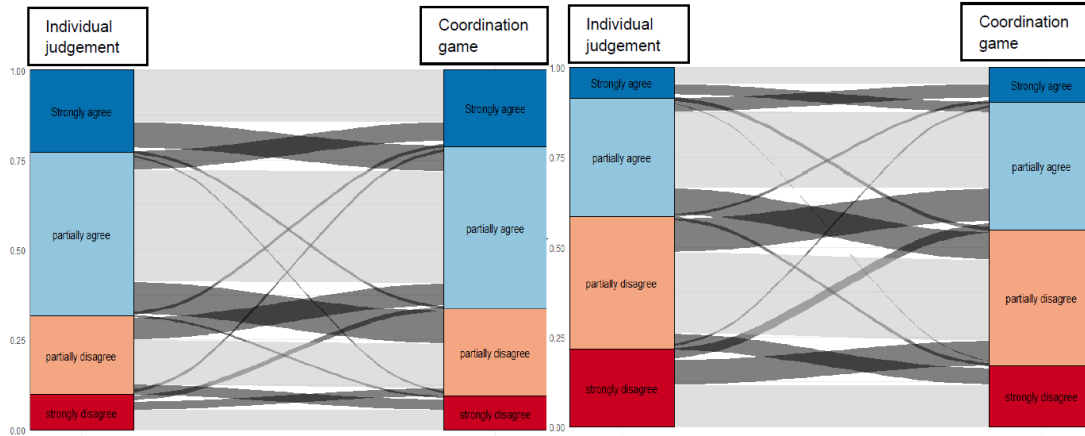


In the coordination game, respondents are given the following question: “Imagine that you have to coordinate with someone living in Europe. This person also tries to answer the same as you do. To what extent do you agree that each country is taking its fair share of the collective effort?”

- Both in France and in the US, most people favour a *cosmopolitan climate justice perspective*, and the *common aspect of the CBDR principle*, with a stronger share among people worried about climate change.
- People display preferences for the principles compatible with a convergence towards equal per capita emissions and a reduction of emissions by the same percentage for all countries. The judgements are stable but show some level of inconsistency.
- No shared understanding pre-exists among citizens of both countries on the question of countries’ fair contributions to global GHG emissions reductions.

There is little basis for comparison of our results in the literature. Equal per capita emissions are also preferred in Carlsson et al. (2011), with a very different design. Yet, results are strikingly different in Schleich et al. (2016) with a closer design, as they highlight a preference for responsibility and capability principles, then equal per capita emissions, and grandfathering coming last. This could be due to differences in samples or framing, depending on how the survey was introduced, or even context effects (e.g. this

Figure 6.9: Evolution of the answers of US (left) and French (right) respondents about the US's NDC, when asked for their opinion in isolation and in the tacit coordination game



In the coordination game, respondents are given the following question: “Imagine that you have to coordinate with someone living in Europe. This person also tries to answer the same as you do. To what extent do you agree that each country is taking its fair share of the collective effort?”

survey was conducted during the peak of a global pandemic necessitating an international response), which may have a strong influence on the respondents' answers (Stalans, 2012) and can be tested for in further studies.

6.5.2 Robustness and relevance of the results

This study shows interesting similarities among citizens from two countries with different positions on the international stage. However, these are two developed countries. For external validity, further studies should include a larger set of countries, with more diverse characteristics (including, as is not the case in this study, some developing countries). We could imagine, for example, that citizens from developing countries are in favour of more differentiated than common responsibilities.

We also focus on classical "burden-sharing rules" while, as mentioned in Chapter 5, in the current climate context, additional fairness considerations are becoming central (how to share adaptation costs, how to account for residual carbon sinks like forests or how to fund emerging technologies like offshore wind power or concentrating solar power). More specifically in the context of this thesis, current evaluation tools are still only centered around climate change mitigation. They include rules that take into

account some countries' characteristics that are linked to development, but the fact that countries produce other development targets in other international contexts (for example within the framework of the Sustainable Development Goals) is not taken into account here. This calls for the existence, in addition to a "burden-sharing" framework in which reducing the number of points of view is an important stake, of a broader framework to bring information on the fairness of countries' contributions in the context of their development priorities, as will be discussed in the conclusion.

Besides, international and cosmopolitan perspectives draw the focus on two contrasted informational bases, the understanding of which could be strengthened in future designs.

In the *internationalist perspective*, we are interested in the pre-existence of natural focal points which could serve to crystallise agreement in a negotiation context. Our main tool to assess this existence is the incentive for tacit coordination. This incentive could be increased in future designs, to confirm the conclusion of a lack of common understanding among citizens regarding countries' fair contributions.

In the widely preferred *cosmopolitan perspective*, direct observation is informative of existing attitudes. Ours reveals some inconsistencies and instabilities in the observed judgements on this unfamiliar issue. These observations might not reflect actual attitudes and the potential consensus which could emerge in actual deliberative arenas. As we expect that there is a pluralism of individual morals, more information should be gathered on the potential for existing judgements to evolve through reasoning (and converge to some consensus), possibly through the paths proposed below.

6.5.3 Future research avenues

This discussion suggests that survey methods could bring relevant knowledge regarding citizens' attitudes towards fairness. To the extent of our knowledge, this study is the first to explicitly discuss what informational basis and related design would be most relevant in a normative perspective. It also emphasises research avenues for our understanding of public attitudes toward climate justice.

Surveys could bring relevant and replicable observations on existing attitudes and their determinants. They are an efficient way to provide wide samples and representative panels, and when standardised, are replicable across countries. They can first improve our understanding of spontaneous citizens' attitudes, as these are likely to emerge in

public opinions. Robust knowledge in this perspective would require controlling for the multiplicity of biases observed in questionnaire studies (e.g. framing effects). Beyond this, they could help identifying robust attitudes, relevant *moral heuristics*¹³, systematic inconsistencies and the potential for existing judgements to evolve through reflection and argument.¹⁴ They could uncover possibilities for either consensus building in a cosmopolitan perspective, or for agreement in an internationalist perspective. A possible way forward would be the development of standardised questionnaire designs, allowing for a better control for framing effects, and for further learning about the linkages between attitudes and their consistency from general principles to specific cases. Insights from the psychology literature would be useful to inform these designs.

Despite these possibilities, surveys are still conducted in limited time and in isolation. Hence, they have fundamental limitations, especially to investigate reflected judgements on complex issues such as climate change. While survey methods conducted with some degree of experimental design could uncover some systematic inconsistencies in individual judgements, social psychologists have shown the importance of a social context to ensure the consistency of moral arguments (Haidt, 2001). Further investigation on the potential for consensus building would then benefit from survey designs involving learning and social interactions, and even real-world cooperation.¹⁵ In-depth individual interviews would also be an interesting complement to questionnaire studies, to fully embrace the complexity of individual fairness attitudes and their determinants.

Acknowledgements

We thank Adrien Fabre, as well as participants to the IEDES AuToMat seminar and to the Sorbonne “COP 21: 5 years later” conference for valuable exchanges that have enriched the article. We acknowledge funding from AgroParisTech (AO APT 2019), used to administer the survey.

¹³Sunstein (2005) defines theses as “moral short-cuts, or rules of thumb, that work well most of the time, but that also systematically misfire”.

¹⁴For instance, moral discoveries can be characterised as systematic and durable ways in which moral judgements are revised following an exposition to an argument (Daniels, 1996)

¹⁵Possible methods are numerous, including experimental replications of deliberations behind a veil of ignorance (Frohlich et al., 1987) to deliberative polls on real issues (Fishkin, 2003)

Conclusion

This thesis addresses the alignment between countries' climate and development targets, as well as ways to inform the evaluation of the fairness of countries' mitigation contributions (to the extent that this issue is important in responding to the outcomes of the first analysis). In retrospect, another perspective provided is on the articulation between international and national goals and frameworks, on both climate and development. Indeed, we examined the extent to which (global) SDGs could provide a good mapping of national development priorities. We also tackled the judgment of national mitigation targets within the context of the global goal(s) and architecture of the Paris Agreement. The present conclusion puts together the key results of this thesis, discusses limitations and research avenues, and opens a perspective for reframing climate equity issues within the context of SDGs.

On national priorities and Sustainable Development Goals

First, we created a mapping of over 121 national long-term development documents by manually collecting the featured development priorities and classifying them with their related Sustainable Development Goal(s). The SDGs had been theoretically discussed in the literature, but the academic contributions that look at the alignment between this global framework and the national priorities are scarce and fairly recent - to the extent of our knowledge, it had not been previously checked whether the SDGs provided an exhaustive mapping of existing national development priorities. Our findings support the idea that the SDGs are universal, as we find very few national priorities out of their scope, but they also confirm a form of silo treatment, in the sense that countries tend to not have all SDGs covered, to some extent, by their development priorities - SDG 13 on climate being absent in more than 15% of the documents.

The limit of this study, of course, is that we manually collect stated priorities in economy-wide documents. First, less represented SDGs (such as SDG 5 on gender,

SDGs 13, 14, 15 on climate change and ecosystems) might be absent from economy-wide documents but well represented in sectoral plans. In that sense, our results do not lead to the conclusion that 15% of the countries do not pursue SDG 13 enough. We rather conclude that if they do so, the formulation of national climate targets might be disconnected from other development priorities. Second, we collect stated priorities: as there might be implementation gaps, the question of whether development plans actually reflect national priorities or not is left open. Answering it would (at least) require the systematic exploration of a larger set of policy documents.

In addition to this result, our mapping led to the creation of a database and visualization tool that displays how SDGs are prioritized in national development documents, and which development priorities, related to which SDG(s), are present in each plan or vision. This database aims at being regularly updated to include newly adopted plans.

The database, in itself, can fuel further endeavours on many topics, as trends might emerge among national development priorities that fit under a same SDG: are there trends among transportation objectives, industry goals, targets on education, culture, migration, sports? Preliminary work by Liotta (2023) for example shows that more than 50% of the documents display explicit urban content, and more than 90% display content related to the urban sector, with mentions of the land use (in relation with the urbanization of territories), transportation (mostly in relation with mitigation goals) and building (mostly in relation with social development and poverty stakes) sectors.

Another notable preliminary result that we get, on the whole database, is that the SDG framework tends to blur the development narratives of development documents. When categorizing countries with multiple correspondence analysis and clustering techniques, the main cluster that emerges is the one formed by development documents that directly refer to and follow the structure of SDGs. This is not surprising, as using such a structure tends to lead to all SDGs appearing in the document, but does not lead to a clear highlight of which one is prioritized. This consequence of a national downscaling of SDGs would not necessarily be desirable, as development, especially in the long term, is as much a question of narratives as it is a question of quantified targets (Malone et al., 2017; Santos and Mourato, 2022). Rather than pushing for a "SDG-by-SDG" structure of development documents, we argue for the existence of a section translating the narrative and priorities they propose in terms of SDGs.

Finally, on this topic, artificial intelligence and natural language processing methodologies are being developed to understand the alignment between written

documents and the SDGs. For example, the SDG Prospector¹⁶ (Jacouton, J et al., 2022) helped analyse the annual reports of public development banks through the lens of the SDGs, giving insights on their extra-financial commitments and which SDGs are prioritized - an endeavour that is important as financial institutions are crucial to help achieving development and climate targets at the international scale. However, AI tools need to be pre-trained on a high number of texts to be able to distinguish which specific formulation(s) relates to which specific SDG(s). While they are well-trained on documents in english, and could ultimately be trained in well-represented languages such as french and spanish, the training material is less developed in other languages. We resorted to a manual mapping, to also allow for an analysis of development documents for which an official english translation did not exist. Yet, AI opens avenues for deepening our understanding of the prioritization of SDGs. Indeed, we looked at national development priorities displayed in countries' national long-term development plans and visions. This, of course, is not the only way to observe priorities and an automated analysis tool might help process a larger number of documents, such as existing laws, short-term plans, sectoral plans, political programs. After a first comparison between results of Chapter 1 and results obtained with this tool for documents that are featured in the database, an immediate extension of the work developed in this thesis would also be to analyse Nationally Determined Contributions, to determine the extent to which some SDG-related issues are featured in their targets. Indeed, a few studies highlight the potential of NDCs to foster integrated development and climate targets, for example on the Water-Energy-Food nexus (Paim et al., 2020; Matthews, 2023). Eventually, using AI tools might provide insights on the question of whether long-term development plans are actually representative of development priorities at the national level or not, which was raised in the above discussion.

On CGE modelling and the alignment between development and climate targets

To discuss the alignment between economic development targets and climate mitigation targets, we employ computable general equilibrium modelling. The numerical experiments on the stylized two-sector KLEM model developed in Chapter 3 show that the choice of macroeconomic closure (between 8 options) can have an important impact on E3 modelling outputs. In a static framework, depending on the closure option, the extent of the effect of energy demand control on welfare varies. First extensions of

¹⁶<https://sdgprospector.org/>

the results to cases where the tax on energy consumption is recycled also show that double-dividend potentials vary across closures.

However, a CGE model's outputs are also subject to parametric uncertainties. The value of elasticities of substitution is highly important for CGE models with CES functions (as shown for example by Okagawa and Ban (2008)). A general sensitivity analysis is thus currently being prepared on the KLEM static framework used in Chapter 3, to determine the importance of closures compared to parametric uncertainties.

KLEM, moreover, remains a very stylized model that captures few mechanisms. An analytical analysis of the impact of closures would be possible in a very stylized framework (ideally even more than KLEM) and would confirm our explanation of numerical results in very simple cases. But the implementation of closures and the extent of their impacts on E3 models when accounting for more complex mechanisms (such as financial transfers, or links with other sectors), in a dynamic framework, or in different regions, have yet to be discussed. And first explorations on the matter are easier to do numerically. First results for two closures on a dynamic KLEM framework can already be obtained. While the choice between the two does not have a large impact on economic growth in Chapter 4, different impacts might emerge for other indicators, and more closures are also being implemented in the dynamic model. Other numerical experiments, similar to the one presented in Chapter 3, but using more complex and dynamic CGE models, would now be a natural extension of our work.

This also calls for an explicit justification of the choice of closure in all future CGE modelling exercises, as well as, to the extent possible, sensitivity analyses with several closure options to ensure the robustness of results (as has been done with a limited number of closures in Chapter 4). In that sense, opening the debate on closures would help steer the discussion towards macroeconomic mechanisms, which often tend to be overlooked in applied studies that examine mitigation costs at country level.

These avenues raise two questions. First, from a very technical standpoint, a closure in the broadest sense is just a way to ensure that a model's equations are as numerous as its variables. As a result, the number of possible closures for a model is equal to the total number of its variables *squared* (Mitra-Kahn, 2008). Obviously, carrying out such an analysis for all possible closures for thousand-equation large models like those reviewed by the IPCC is a virtually impossible task. Closures must therefore be chosen amongst a pool of relevant ones, depending on the issue at stake and the research endeavours. This in turn poses the question of what criteria to summon to justify such choices. In Appendix B, we argue that empirics cannot help us beyond a gross pre-selection of relevant closures. We then ground the choice of closures in theory, acknowledging that

the 8 chosen closures represent competing views on the macroeconomic functioning of an economy.

In practice, resorting to detailed CGE models to give insights on the alignment between climate and development targets implies having access to a certain amount of data. The modelling literature on the matter is limited outside of large economies and large emitters. The methodology that we proposed in Chapter 4 aims to shed a first light on the compatibility between a country's climate and macroeconomic targets, outlined in their NDC and long-term development documents, using a stylized KLEM framework. The advantage is its ease of implementation on a potentially high number of countries. We test it on 3 countries – Malawi, Colombia, and Iraq. Despite limitations, notably the fact that by construction, the results cannot be as precise and detailed as in more complex modelling work, the methodology demonstrated flexibility, offering quick insights in many contexts.

For Malawi and Colombia, our methodology shows a large alignment between the modelled climate and development targets. Some conditions are needed for the two to be met, as the reference case (with no growth in the productivities of capital, energy and materials) does not meet the GDP targets, in both countries. However, the space of realistic productivities' growth rates, for which development and climate targets can be met, is large. One explanation might be that current NDCs in many countries do not display a high level of ambition, thereby not creating many trade-offs with economic development. To this regard, inconsistencies would be more likely within the development plan itself (as we find in Iraq). This could be the case for Malawi, for which the energy sector might not weigh enough on the economy for a moderate NDC-related shock to impede GDP growth. Colombia, however, has an important energy sector and targets net-zero emissions in 2050. In Colombia's case, the large alignment could very-well result from the extensive modelling work deployed to serve as a basis for the targets. To further test the explanation, the methodology would need to be applied in other countries, or in contexts where we artificially increase the level of ambition of NDCs. A second explanation might be that the tensions between the NDC and other development priorities are not fully captured in our current framework. This could be due to the fact that we take in available energy scenarios (whereas for Colombia, different scenarios for the evolution of international energy markets could be tested), and do so without two-way model-linking, which can have an impact on the model results. The tensions might also lie between development targets that are not encompassed within the stylized framework (such as poverty, inequalities or land use).

The first results on three different country cases, as well as the list of countries to possibly apply this methodology to, open immediate avenues for refinements in the methodology. These include a dynamic calibration of the model by introducing crisis factors to better fit existing time-series, the extension of the KLEM framework to an additional agricultural sector to adequately represent countries that plan to develop their agricultural sector, and the soft-linking of KLEM with national energy-systems models, in countries where they exist and are available.

One obvious limitation of this method comes with its national scale: there is currently no closure on international goods and energy markets. Yet, this could prove important for example for oil-exporting countries, since their targets in terms of oil exports may not be consistent with the oil consumption targets of the rest of the world. Similarly, international transfers are not modelled, and are yet central in reaching most developing countries' climate targets. This opens future avenues to expand the modelling framework to include these features, with challenges that will be linked with a need to harmonize the format (indicator, horizon, sector) of targets across countries. This might come with a loss of flexibility in the methodology, and an impossibility to model some countries.

Finally, the methodology is based on GDP targets. The use of GDP as a central indicator for economic development and as a measure of well-being has long been discussed in the literature (Stiglitz et al., 2018, 2010; Fleurbaey and Blanchet, 2013; Bleys, 2012), and more recently in the context of Sustainable Development Goals (Stewart, 2015), but remains standard practice in macroeconomic modelling. Moreover, some countries do not have quantified GDP target, which makes our methodology difficult to apply beyond Step 1 (see the case study of Iraq for an illustration). Using other indicators such as the human development index, capabilities, or multi-dimensional poverty measures, could also be considered in future modelling endeavours (with all associated limitations coming with data scarcity).

As detailed in this conclusion, the methodology is particularly adapted to offer quick insights in various contexts. In that sense, using it on a country could precede a more detailed modelling work, and provide a first alert on misalignments between climate and development targets. This use of the methodology is all the more relevant since NDCs are expected to be regularly updated. It is however currently limited by the fact that it depends on the existence of available energy scenarios for the country. This last constraint could be removed by developing simple energy-system national models, using the Open Source Energy Modeling System (Howells et al., 2011) and available "Starter Kits" (Allington et al., 2022), to soft-link with KLEM.

From improving the salience of current fairness evaluation tools to extending the framework to other development goals

Finally, the work developed in Part II gives insights on countries' policy integration. However, should inconsistencies be revealed in Part II, what could be the ways forward in terms of policy making? This could call for a revision of countries' targets, but discussing the compatibility between national climate and development goals does not, in itself, imply anything about the country's level of ambition in both regards. Judging the fairness of a country's mitigation contribution can thus be a first step. And, as presented extensively in the introduction and in Part III, in the context of international climate negotiations and specifically climate mitigation, new methods to assess fairness need to be generated or strengthened.

There is, on the one hand, a need to update existing tools to accommodate for evolutions in the current climate negotiations framework. Indeed, there are many different - and sometimes competing - visions of how to distribute climate mitigation targets among countries, and the bottom-up logic of the Paris Agreement implies that no single allocation rule has been agreed upon. There is thus no single reference to use to evaluate countries' ambition. We proposed, in Chapter 5, a new review of allocation rules that have recently been used in the literature, with a mathematical framework to explicit their formalization and parametrization. It enables rules to be compared more easily, but also allows for more transparency as to how implementation options can lead to different distributions of emissions allocations, even starting from a single underlying principle. We also reviewed the existing fairness evaluation tools, and discussed the fact that they all show a trade-off between multiplying the viewpoints and providing a conclusive assessment of the fairness of countries' targets.

We propose to improve the salience of these tools by using citizens' opinions as a basis for legitimizing some allocation rules over others. In Chapter 6, we thus designed and administered a pilot survey eliciting public attitudes towards international climate justice and equity rules in France and the USA. The originality of this work lies in its methodology adapted from the empirical social choice literature, which bridges a theoretical normative content and an empirical content by looking at the values of selected individuals to justify collective distributive choices. To do so, citizens' judgements need to be observed in various contexts, to also check for their stability and level of understanding of the distribution issue related to climate change mitigation. We thus designed an innovative survey to complement the limited literature on survey studies applied to climate change mitigation (reviewed in the appendices of this thesis).

We observe a strong support for two effort sharing rules, namely grandfathering and a convergence towards equal per capita emissions. Of course, the policy-relevance of these results is limited by the fact that the pilot survey was administered on citizens from two developed countries (for logistical and financing reasons). The results still show notable trends that would need to be confronted to further survey studies on citizens from developing countries. Other analyses on the data that we collected will also be developed, as we mainly focused on descriptive statistics and correlations, and did not engage in in-depth analysis of answers to all questions. More specifically, a future focus on the response times or on open-text questions could be of interest to our work, and provide other avenues for improving survey studies.

As mentioned in Part III, the IPCC also reports that the generation of entirely new methods to assess fairness is needed (Patt et al., 2022). Recent research has identified several avenues for future work on climate justice (Zimm et al., 2024), including on distributive justice, but also on other dimensions. Taking into account interactions between climate change mitigation and other development targets pursued could shed a new light on a climate equity debate that, in the UNFCCC context, has been somewhat stuck. The operationalization of these avenues could take the form of additional allocation rules to choose from, integrating more recent approaches, or ones that are based on the Sustainable Development Goals. In the general context of this thesis, an extension of the existing distributive justice framework also appears relevant. Integrating development pathways into equity considerations on climate change mitigation could even provide with new consensus opportunities (Méjean et al., 2015; Hourcade and Shukla, 2015). We highlight, as in Chapter 6, the potential of looking at citizens' opinions to inform these approaches.

- First, additional rules with thresholds based on recent development indicators such as the Decent Living Standard (Rao and Min, 2018) could be implemented, even though the principle behind such thresholds is not, in itself, new. Several of the new rules could also be based on the Sustainable Development Goals Index (Independent Group of Scientists appointed by the UN Secretary-General, 2023), a multidimensional indicator that is built for 193 countries based on around 90 SDG indicators, measuring countries' progress towards SDGs. Progress is tracked for each indicator, then aggregated at the scale of each SDG, finally averaged across SDGs to obtain the aggregated Index. This variety of levels also leaves the door open for a more complex aggregation of individual SDGs indices, using different weights. Using this metric, several allocation rules could be implemented. Ideas

behind it would for example be that countries which are more progressed towards reaching SDGs might be able to prioritize climate mitigation more, or, on the opposite, that countries for which SDG13 is not prioritized enough (compared to others) should be more ambitious.

- Bearing in mind that the focus on pathways and temporal targets (e.g. net-zero or zero-poverty horizon, emissions peaking horizon) gained and might continue to gain importance, another way to consider ambition and fairness would be to reframe the issue in a temporal way, e.g. consider climate and development targets along with the horizon at which they are pursued (as proposed in Dubash et al. (2021) for net-zero targets). A closer look on trade-offs between SDGs, such as the one developed by the SDG Synergies tool (built from Nilsson et al. (2016))¹⁷, might inform such an approach, by helping quantify, for a given country, if an increase in ambition on climate change mitigation might delay the reaching of other SDG targets.
- Finally, with regards to the policy implications of the analysis developed in Part II, should inconsistencies be revealed, this might call for an update of the countries' (climate or development) targets. In this thesis, we mainly observe the interactions between climate mitigation targets, and development goals falling under SDGs 8, 9 and 17. However, extensions of the modelling framework are envisioned. From the perspective of evaluating the countries' climate ambition at the international scale, the perspective of judging an update in climate targets raises new research questions, in relation with the integration of development goals in the climate equity framework. Would it be more fair to decrease ambition for climate mitigation if it is to ensure food security (SDG 2) than if it is for the development of the industry (SDG 9)? Looking at citizens' opinions might inform such a question and help propose a way forward.

We thus propose, on the one hand, to reduce the number of points of view in order to get more conclusive judgements on the countries' mitigation ambition, and on the other hand, to completely extend the framework by including more criteria. Pursuing both these endeavours, of course, could seem somewhat contradictory. In fact, and as proposed in the IPCC's 5th assessment report (Fleurbay et al., 2014), equity within the climate context can be thought of within three different scopes, that are summarized in Figure

¹⁷<https://www.sdgsynergies.org/>

Figure 6.10: Three frameworks for thinking equity within the climate context

Source: Contribution of the third working group of the IPCC to the fifth assessment report (AR5), Figure 4.1 in Fleurbaey et al. (2014)

6.10. Informing all of them is important. Within the framework of climate mitigation in itself, the first research endeavour tends to an identified need of conclusiveness within the new voluntary context, by reducing the number of "legitimate" perspectives on fairness. Indeed, no matter what, climate change mitigation needs to be accelerated at a global scale. On the other hand, taken within the broader context of development goals, it is also clear that information lacks on how targets interact and how equity would evolve should more development dimensions be integrated into the framework. In a first step in this framework, multiplying the viewpoints would be needed. Both these endeavours thus inform different but equally important frameworks and can very well be pursued in parallel.

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6 Bibliography

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Appendices to Chapter 1

The database as well as the data to reproduce all the figures can be found on the following link: <https://doi.org/10.5281/zenodo.7949159>

- 1 List of countries, accessible documents and their languages, featured in the base

Country	Source	Language
Afghanistan	https://ku.edu.af/sites/default/files/2020-12/National%20Document%2013%20January%202020_compressed_0.pdf	English
Algeria	https://planipolis.iiep.unesco.org/fr/node/6298	French
Angola	https://www.angonet.org/dw/sites/default/files/online_lib_files/angola_plan_2000-2025.pdf	Portuguese
Armenia	https://policy.asiapacificenergy.org/node/1492	English
Bahamas	https://observatorioplanificacion.cepal.org/en/plans/vision-2040-national-development-plan-bahamas	English
Bahrain	https://www.bahrain.bh/wps/wcm/connect/38f53f2f-9ad6-423d-9c96-2dbf17810c94/Vision%2B2030%2BEnglish%2B%28low%2Bresolution%29.pdf?MOD=AJPERES	English
Bangladesh	https://policy.asiapacificenergy.org/node/2654	English
Barbados	https://planipolis.iiep.unesco.org/sites/default/files/ressources/barbados_national_strategic_plan_2006-2025.pdf	English
Belarus	https://www.fao.org/faolex/results/details/en/c/LEX-FAOC189944/	Russian
Belize	https://med.gov.bz/horizon-2030-the-national-development-frame-work-for-belize/	English
Bhutan	https://www.gnhc.gov.bt/	English
Bolivia	http://www.planificacion.gob.bo/uploads/AGENDA_PATRIOTICA2025_MPD.pdf	Spanish
Botswana	http://www.vision2036.org.bw/publications	English
Brazil	https://www.gov.br/economia/pt-br/assuntos/gestao/estrategia-federal-de-desenvolvimento	Portuguese
Brunei	https://www.wawasanbrunei.gov.bn/Downloads%20Files/Infopack%20WB35%20(ENG).pdf	English
Darus-salam		
Bulgaria	https://www.minfin.bg/en/1394	English

1. List of countries, accessible documents and their languages, featured in the base

Country	Source	Language
Burkina Faso	http://mouvementcar.bf/wp-content/uploads/2015/12/Rapport-GENERAL-ENP-BURKINA-2025.pdf	French
Burundi	https://www.presidence.gov.bi/wp-content/uploads/2018/08/PND-Burundi-2018-2027-Version-Finale.pdf	French
Cambodia	http://cnv.org.kh/wp-content/uploads/2012/10/Rectangular-Strategy-Phase-IV-of-the-Royal-Government-of-Cambodia-of-the-Sixth-Legisla.pdf	English
Cambodia	https://ncsd.moe.gov.kh/sites/default/files/2019-06/CSDG_Framework_2016-2030_English_LAST_FINAL.pdf	English
Cameroon	https://minepat.gov.cm/fr/vision-horizon-2035/	French
Cameroon	https://effectivecooperation.org/content/cameroon-national-development-strategy-2020-2030	English
Canada	https://www.canada.ca/content/dam/esdc-edsc/documents/programs/agenda-2030/ESDC-PUB-050-2030Agenda-EN-v9.pdf	French
Chad	https://www.fao.org/faolex/results/details/fr/c/LEX-FAOC186305/	French
Chile	https://www.google.com/url?sa=t&rct=j&url=http%3A%2F%2Fwww.chileagenda2030.gob.cl%2Fstorage%2Fdocs%2FDiagnostico-Inicial_2.0_Agenda2030-ODS_2017.pdf&usg=AOvVaw3rf8Jo8VrDcZe5293Pt2uA	Spanish
China	http://www.chinadaily.com.cn/specials/China%27sNationalPlanonimplementationofagenda(EN).pdf	English
China	https://cset.georgetown.edu/publication/china-14th-five-year-plan/	English
Czechia	https://www.vlada.cz/assets/ppov/udrzitelny-rozvoj/projekt-OPZ/Strategic_Framework_CZ2030.pdf	English
Colombia	https://observatorioplanificacion.cepal.org/sites/default/files/plan/files/Documento_vision_colombia_2050.pdf	Spanish
Comoros	https://www.cpadcomores.com/fr/la-conference/documentation	French
Côte d'Ivoire	https://www.plan.gouv.ci/assets/fichier/RAPPORT-SYNTHESE-ENP-CI-2040-version-finale-du-10-mars-2017-1-5-.pdf	French
Croatia	https://hrvatska2030.hr/wp-content/uploads/2021/02/Nacionalna-razvojna-strategija-RH-do-2030.-godine.pdf	Croatian
Cuba	https://www.mep.gob.cu/es/pndesods-2030/plan-nacional-de-desarrollo-economico-y-social-2030	Spanish
Democratic Republic of the Congo	https://www.undp.org/fr/drcongo/publications/contextualisation-et-priorisation-des-objectifs-de-d%C3%A9veloppement-durable-odd-en-r%C3%A9publique-d%C3%A9mocratique-du-congo	French
Denmark	https://fm.dk/media/24837/handlingsplan-for-fns-verdensmaal_web.pdf	Danish
Djibouti	https://www.fao.org/faolex/results/details/en/c/LEX-FAOC169060/	French
Dominica	https://observatorioplanificacion.cepal.org/sites/default/files/plan/files/Dominica%2030The%20National%20Resilience%20Development%20Strategy.pdf	English
Dominican Republic	https://mepyd.gob.do/estrategia-nacional-de-desarrollo-2030/	Spanish
Ecuador	https://observatorioplanificacion.cepal.org/en/node/1675	Spanish
Egypt	https://mped.gov.eg/EgyptVision?lang=en	English
Equatorial Guinea	https://minhacienda-gob.com/wp-content/uploads/2022/10/ENDS-2035.pdf	Spanish
Ethiopia	https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiQgZ0vvgv7-AhWpQaQEHa0kDrQQFnoECBOQAQ&url=https%3A%2F%2Feuropa.eu%2Fcapacity4dev%2Ffile%2F109229%2Fdownload%3Ftoken%3DN_aSQQk&usg=AOvVaw1UavVncUEQUC4Mwa_BX_bc	English

A. APPENDICES TO CHAPTER 1

Country	Source	Language
Estonia	https://valitsus.ee/en/node/31?view_instance=0&current_page=1	English
Estonia	https://www.fao.org/faolex/results/details/fr/c/LEX-FAOC181629	English
Fiji	https://www.fiji.gov.fj/getattachment/15b0ba03-825e-47f7-bf69-094ad33004dd/5-Year-20-Year-NATIONAL-DEVELOPMENT-PLAN.aspx	English
France	https://www.agenda-2030.fr/feuille-de-route-de-la-france-pour-l-agenda-2030/documents-a-telecharger/article/telecharger-la-feuille-de-route	French
Gabon	https://www.cafi.org/sites/default/files/2021-02/Gabon_2015_SM_A_PlanStrategiqueGabonEmergent.pdf	French
Germany	https://www.bundesregierung.de/breg-en/issues/sustainability/germany-s-sustainable-development-strategy-354566	English
Ghana	https://www.climate-laws.org/document/long-term-national-development-plan-of-ghana-2018-2057_5ad3	English
Grenada	https://planipolis.iiep.unesco.org/en/2019/national-sustainable-development-plan-2020-2035-7099	English
Guatemala	https://siteal.iiep.unesco.org/bdnp/310/plan-nacional-desarrollo-katun-nuestra-guatemala-2032	Spanish
Guinea	https://www.fao.org/faolex/results/details/fr/c/LEX-FAOC208255/	French
Guinea-Bissau	https://prais.unccd.int/sites/default/files/2018-09/Plan%20Strategique%20GB%202025%20-%20Rapport%20Final%20-%202014-03-2015.pdf	French
Guyana	https://faolex.fao.org/docs/pdf/guy199315.pdf	English
Haiti	https://www.fao.org/faolex/results/details/es/c/LEX-FAOC145914/	French
Honduras	https://honduras.un.org/es/15238-republica-de-honduras-vision-2010-2038	Spanish
Hungary	https://www.nfft.hu/documents/127649/4101265/NFFT-ENG-web.pdf/f692c792-424d-4f5a-9f9d-9e6200303148?t=1580130885736	English
Indonesia	https://www.unicef.org/indonesia/media/1626/file/Roadmap%20of%20SDGs.pdf	English
Indonesia	https://policy.asiapacificenergy.org/sites/default/files/LONG-TERM%20NATIONAL%20DEVELOPMENT%20PLAN%20OF%202005-2025%20%28EN%29.pdf	English
Iraq	https://mop.gov.iq/en/min_publications/view/list?id=18&lastcontent=474	English
Ireland	https://npf.ie/wp-content/uploads/Project-Ireland-2040-NPF.pdf	English
Ireland	https://www.gov.ie/pdf/?file=https://assets.gov.ie/37937/12baa8fe0dcb43a78122fb316dc51277.pdf#page=null	English
Italy	https://www.mase.gov.it/sites/default/files/archivio_immagini/Galletti/Comunicati/snsvs_ottobre2017.pdf	Italian
Jamaica	https://www.vision2030.gov.jm/wp-content/uploads/sites/2/2021/04/vision-2030-jamaica-national-development-plan-1.pdf	English
Jordan	https://www.greengrowthknowledge.org/national-documents/jordan-2025-national-vision-and-strategy	English
Kazakhstan	https://strategy2050.kz/en/page/multilanguage/	Russian
Kazakhstan	https://www.akorda.kz/en/official_documents/strategies_and_programs	Russian
Kenya	https://vision2030.go.ke/publication/kenya-vision-2030-popular-version/	English
Kiribati	https://www.mfed.gov.ki/sites/default/files/KIRIBATI%2020-YEAR%20VISION%202016-2036%20.pdf	English

1. List of countries, accessible documents and their languages, featured in the base

Country	Source	Language
Kyrgyzstan	https://policy.thinkbluedata.com/sites/default/files/National%20Development%20Strategy%20of%20the%20Kyrgyz%20Republic%20for%202018-2040%20(EN).pdf	English
Lao People's Democratic Republic	https://data.laos.opendevelopmentmekong.net/library_record/vision-2030-and-tenyear-socioeconomic-development-strategy-20162025	Lao
Latvia	https://www.pkc.gov.lv/sites/default/files/inline-files/LIAS_2030_en_1.pdf	English
Lesotho	https://www.gov.ls/download/lesotho-vision-2020/	English
Liberia	https://mod.gov.lr/wp-content/uploads/2022/06/National-Agenda-for-Transformation-2030.pdf	English
Lithuania	https://e-seimas.lrs.lt/portal/legalAct/lt/TAD/TAIS.425517	Lithuanian
Luxembourg	https://mint.gouvernement.lu/dam-assets/circulaires/2020/janvier-juin/3764-PNDD.pdf	French
Malawi	https://npc.mw/wp-content/uploads/2021/02/ENGLISH-VERSION.pdf	English
Malaysia	https://www.epu.gov.my/sites/default/files/2020-02/Shared%20Prosperity%20Vision%202030.pdf	English
Mali	https://invenio.unidep.org/invenio/record/18825/	French
Malta	https://meae.gov.mt/en/Public_Consultations/MSDEC/Documents/Malta%27s%20Sustainable%20Development%20Vision%20for%202050.pdf	English
Marshall Islands	https://rmi-data.sprep.org/resource/rmi-national-strategic-plan-2020-2030	English
Mauritania	https://www.fao.org/faolex/results/details/fr/c/LEX-FAOC190616/	French
Mexico	https://archivo.cepal.org/pdfs/GuiaProspectiva/VisionMexico2030.pdf	Spanish
Micronesia	https://policy.asiapacificenergy.org/node/845	English
Mongolia	https://archive.un-page.org/files/public/20160205_mongolia_sdv_2030.pdf	English
Montenegro	https://www.fao.org/faolex/results/details/fr/c/LEX-FAOC180387/	English
Morocco	https://www.environnement.gov.ma/fr/strategies-et-programmes/sndd?showall=1&limitstart=	French
Mozambique	https://www.mef.gov.mz/index.php/publicacoes/estrategias/397-estrategia-nacional-de-desenvolvimento/file	Portuguese
Myanmar	https://themimu.info/sites/themimu.info/files/documents/Core_Doc_Myanmar_Sustainable_Development_Plan_2018_-_2030_Aug2018.pdf	English
Namibia	https://www.npc.gov.na/wp-content/uploads/2021/11/vision_2030.pdf	English
Nauru	https://nauru-data.sprep.org/system/files/nauru_development_strategy_2025_en_2005.pdf	English
Nepal	http://sdg.npc.gov.np/media/resources/items/0/bSustainable_Development_Goals_Status_and_Roadmap__2016-2030_46E6XzP.pdf	English
Niger	http://www.plan.gouv.ne/sddci-2035/	French
Oman	https://isfu.gov.om/2040/Vision_Documents_En.pdf	English
Pakistan	https://www.pc.gov.pk/uploads/vision2025/Vision-2025-Executive-Summary.pdf	English
Pakistan	https://www.fao.org/faolex/results/details/es/c/LEX-FAOC149943/	English
Panama	https://siteal.iiop.unesco.org/bdnp/392/plan-estrategico-nacional-vision-estado-panama-2030	Spanish

A. APPENDICES TO CHAPTER 1

Country	Source	Language
Papua New Guinea	https://policy.asiapacificenergy.org/node/867	English
Papua New Guinea	https://www.treasury.gov.pg/html/publications/files/pub_files/2011/2011.png.vision.2050.pdf	English
Paraguay	https://www.stp.gov.py/pnd/wp-content/uploads/2014/12/pnd2030.pdf	Spanish
Peru	https://www.ceplan.gob.pe/visionperu2050/	Spanish
Philippines	https://2040.neda.gov.ph/wp-content/uploads/2022/02/2162022_A-Long-Term-Vision-for-the-Philippines.pdf	English
Qatar	https://www.gco.gov.qa/wp-content/uploads/2016/09/GCO-QNV-English.pdf	Arabic
Romania	http://dezvoltaredurabila.gov.ro/web/wp-content/uploads/2019/03/Romanias-Sustainable-Development-Strategy-2030.pdf	English
Rwanda	https://www.minecofin.gov.rw/fileadmin/user_upload/Minecofin/Publications/REPORTS/National_Development_Planning_and_Research/Vision_2050/English-Vision_2050_Abridged_version_WEB_Final.pdf	English
Saint Vincent and the Grenadines	http://finance.gov.vc/finance/index.php/economic-planning-industry-and-social-development/national-economic-a-social-development-plan	English
Samoa	https://www.mof.gov.ws/wp-content/uploads/2021/03/Samoa-2040-Final.pdf	English
Saudi Arabia	https://www.vision2030.gov.sa/media/rc0b5oy1/saudi_vision203.pdf	English
Senegal	http://www.senegal-emergent.com/sites/default/files/documents/plan_senegal_emergent_1.pdf	French
Seychelles	http://www.finance.gov.sc/vision-2033	English
Sierra Leone	http://www.sierra-leone.org/Agenda%20%20Prosperity.pdf	English
Slovenia	https://www.gov.si/assets/vladne-sluzbe/SVRK/Strategija-razvoja-Slovenije-2030/Slovenian-Development-Strategy-2030.pdf	English
Solomon Islands	https://solomons.gov.sb/wp-content/uploads/2020/02/National-Development-Strategy-2016.pdf	English
South Africa	https://www.gov.za/issues/national-development-plan-2030	English
South Sudan	https://documents.pub/document/southern-sudan-vision-2040-2017-2040-south-sudan.html?page=3	English
Sudan	https://planipolis.iiep.unesco.org/sites/default/files/ressources/sudan_twenty_five_year_national_strategy_2007-2031.pdf	English
Suriname	https://observatorioplanificacion.cepal.org/sites/default/files/plan/files/MOP-2022-2026-Volledig-FINAL-DNA-approved-Engels.pdf	English
Tajikistan	https://nafaka.tj/images/zakoni/new/strategiya_2030_en.pdf	English
Thailand	https://www.dga.or.th/wp-content/uploads/2018/08/file_32600e26a233b3fc9c88e48300c10334.pdf	Thai
Timor-Leste	http://timor-leste.gov.tl/wp-content/uploads/2011/07/Timor-Leste-Strategic-Plan-2011-20301.pdf	English
Tonga	https://policy.asiapacificenergy.org/node/2688	English

1. List of countries, accessible documents and their languages, featured in the base

Country	Source	Language
Trinidad and Tobago	https://www.planning.gov.tt/sites/default/files/Vision%202030-%20The%20National%20Development%20Strategy%20of%20Trinidad%20and%20Tobago%202016-2030.pdf	English
Tuvalu	https://www.gov.tv/wp-content/uploads/2022/05/Te-Kete.pdf	English
Uganda	http://www.npa.go.ug/wp-content/uploads/2021/02/VISION-2040.pdf	English
United Republic of Tanzania	http://www.tzonline.org/pdf/theTanzaniadevelopmentvision.pdf	English
Uruguay	https://www.fao.org/faolex/results/details/fr/c/LEX-FAOC194130/	Spanish
Vanuatu	https://planipolis.iiep.unesco.org/en/2016/vanuatu-2030-peoples-plan-national-sustainable-development-plan-2016-2030-7062	English
Viet Nam	https://openknowledge.worldbank.org/handle/10986/23724	English
Viet Nam	https://vietnam.un.org/index.php/en/4123-national-action-plan-implementation-2030-sustainable-development-agenda	English
Yemen	https://andp.unescwa.org/sites/default/files/2020-10/Yemen%20Strategic%20Vision%202025.pdf	English
Zambia	https://www.nor.gov.zm/?wpfb_dl=44	English
Zimbabwe	http://www.zim.gov.zw/index.php/en/government-documents/category/1-vision-2030	English

2 Description of the columns in the database

2. Description of the columns in the database

Title	Content
Country	Name of the country - text
Source	Link to the plan - text
Reason for inclusion in database	Justification of the inclusion of the document in our corpus
Population (2020)	National population for the year 2020 according to the World Bank data - numerical (x1000)
Continent	ISO continent code (AF: Africa; AS: Asia; EU: Europe; NA: North America; OC: Oceania; SA: South America)
LDC	Y/N
OECD	Y/N
NDC	Whether the country has produced a NDC within the Paris Agreement (Y/N)
Annex 1	Y/N (Annex 1 to the UNFCCC)
Document name	Official name of the plan - text
Language	Language in which the plan was analyzed
Year of publication	Starting year of the plan - date
Horizon	End year of the plan - date
Institution	Name of the institution from which the plan emanates - text
Nature of the document	How the plan is displayed (3 categories: sustainable development plan, vision or development plan)
Reference to 2030 Agenda	How Agenda 2030 is mentioned/incorporated in the plan (3 categories: Yes, No, and Basis if the plan uses the SDG structure)
Civil society implication	Whether a consultation process is mentioned or not (Y/N)
SDG 1: poverty	Content of the plan regarding SDG 1 - text
SDG 1: priority	Priority level accorded to SDG 1 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 2: Hunger	Content of the plan regarding SDG 2 - text
SDG 2: priority	Priority level accorded to SDG 2 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 3: Health	Content of the plan regarding SDG 3 - text
SDG 3: priority	Priority level accorded to SDG 3 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 4: Education	Content of the plan regarding SDG 4 - text
SDG 4: priority	Priority level accorded to SDG 4 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 5: Gender	Content of the plan regarding SDG 5 - text
SDG 5: priority	Priority level accorded to SDG 5 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 6: Water and sanitation	Content of the plan regarding SDG 6 - text
SDG 6: priority	Priority level accorded to SDG 6 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 7: Energy	Content of the plan regarding SDG 7 - text
SDG 7: priority	Priority level accorded to SDG 7 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)

Title	Content
SDG 8: Work and economy	Content of the plan regarding SDG 8 - text
SDG 8: priority	Priority level accorded to SDG 8 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 9: industry, innovation, infrastructure	Content of the plan regarding SDG 9 - text
SDG 9: priority	Priority level accorded to SDG 9 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 10: inequalities	Content of the plan regarding SDG 10 - text
SDG 10: priority	Priority level accorded to SDG 10 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 11: sustainable cities	Content of the plan regarding SDG 11 - text
SDG 11: priority	Priority level accorded to SDG 11 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 12: responsible prod and cons	Content of the plan regarding SDG 12 - text
SDG 12: priority	Priority level accorded to SDG 12 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 13: Climate	Content of the plan regarding SDG 13 - text
SDG 13: priority	Priority level accorded to SDG 13 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 14: Marine/water life	Content of the plan regarding SDG 14 - text
SDG 14: priority	Priority level accorded to SDG 14 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 15: Life on land	Content of the plan regarding SDG 15 - text
SDG 15: priority	Priority level accorded to SDG 15 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 16: Peace, justice, institutions	Content of the plan regarding SDG 16 - text
SDG 16: priority	Priority level accorded to SDG 16 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
SDG 17: partnerships	Content of the plan regarding SDG 17 - text
SDG 17: priority	Priority level accorded to SDG 17 in the plan (4 categories: Absent, Barely mentioned, Mentioned, Priority)
Targets that fit nowhere	Content of the plan that do not fit into the framework - text
Nature of the change	Description of the change envisioned in the plan (General improvement, sustainable development and environment, Agriculture/fisheries, Reconstruction, Poverty/inequalities, Peace and reconciliation, Tourism development, Industrial development)
Quantitative targets ?	Whether future targets are quantified (Y/N)
Quantitative data ?	Whether the plan contains data on the present or past (Y/N)
Nature of the data	3 categories (Absent, Based on macroeconomic modeling, No detail of the modeling but institutional data)

Appendices to Chapter 3

3 Calibration data and substitution elasticities

All variants of the KLEM model mobilised in this chapter are calibrated on data in the form of an aggregate 2-sector 2-factor input-output table (Table B.1). The table proceeds from the straightforward aggregation of the 65-sector IOTs of current (post-Brexit) European Union member states of the GTAP 10 database (available from www.gtap.agecon.purdue.edu) for its latest available year, 2014. The table is converted from 2014 dollars to 2014 euros using the World Development Indicators conversion between current USD and current Euro. The energy sector aggregates sectors 15 (coal), 16 (oil), 17 (gas), 32 (petroleum products), 46 (electricity) and 47 (gas manufacture) of all EU member states. The non-energy sector aggregates the remaining 59 sectors. Capital payments aggregate all non-labour value-added components that are not taxes, i.e. include land and natural resource rents. Output taxes aggregate all factor taxes and production taxes.

Excises were extracted from EUROSTAT data in October 2020, and the unemployment rate was collected in January 2021 from the World Development Indicators ('national' estimate) for the EU in 2014 (without correction of Croatia and the UK), at 10.8%.

The substitution elasticities used in the KLEM production structure for all variants are drawn from the literature and detailed in Table B.2.

Table B.1: Input-Output table of the European Union in KLEM format for the year 2014

Bn 2014 euros	Non-E	E	C	G	I	X	
Non-Energy	10 885	151	6 246	2 539	2 395	2 308	24 524
Energy	552	475	397	-	-	62	1 486
Labour payments	3 209	32					
Labour taxes	1 835	18					
Capital payments	4 880	156					
Output taxes	137	3					
Imports	1 782	450					
Sales taxes	1 243	201					
	24 524	1 486					

Source: GTAP database, World Bank euro to dollar exchange rate, authors' aggregation.

Table B.2: Substitution elasticities of a ‘KLEM’ model of the European Union

Elasticity	Notation	Value, non-energy production	Value, energy production
Substitution of capital K_i to labour L_i	σ_{KL_i}	0.4200 ^a	0.4501 ^d
Substitution of value-added KL_i to energy $\alpha_{E_i}Y_i$	σ_{KLE_i}	0.3518 ^a	0.2374 ^d
Substitution of KLE_i aggregate to non-energy $\alpha_{Q_i}Y_i$	σ_{Y_i}	0.6678 ^b	0.2378 ^d
Substitution of domestic variety D_i to imported variety M_i on domestic markets	σ_{S_i}	2.0000 ^c	3.7610 ^d
Transformation of domestic production Y_i into either supply to domestic markets D_i or exports X_i	σ_{CET_i}	-2.000	-2.000

^a The elasticity computed by Van Der Werf (2008) for the aggregate French economy on time-series analysis.

^b The average of the elasticities computed by Burniaux and Truong (2002) for several activity sectors weighted by the contributions of these sectors to non-energy output of France 2010.

^c Inspired by the Armington elasticities of the non-energy sectors of the GTAP model (Hertel et al., 2008).

^d The average of the corresponding elasticities of the GTAP model for 6 energy goods weighted by the contribution of these goods to the sum of domestic production and imports of energy goods in 2010 France.

^d The average of the elasticities computed by Burniaux and Truong (2002) for the Mining and the Electricity, gas & water sectors weighted by the contribution of these sectors in their KL , KLE and $KLEM$ aggregates.

- The σ_U elasticity is calibrated to accommodate a .6579 own-price elasticity of households’ energy consumptions, as inferred by weighting the GTAP model elasticities for housing utilities and transport and communications (Hertel et al., 2008) with the budget shares of domestic and private transportation energy consumptions in total household energy expenses.

4 Why are alternative closures worth exploring?

From a very technical standpoint, as we saw above, a closure in the broadest sense is just a way to choose pairs of variables, one endogenous, one exogenous. As a result, the number of possible closures for a model is equal to the total number of its variables *squared* (Mitra-Kahn, 2008). Obviously, carrying out such an ideal analysis for thousand-equation large models like those reviewed by the IPCC is a virtually impossible task. Closures must therefore be chosen amongst a pool of relevant ones, depending on the issue at stake and the research endeavours. This in turn poses the question of what criteria to summon to justify such choices. So far, three have been mobilised by the literature.

4.1 Empirics

A first, quite neutral approach to closures, is to gauge them in light of their empirical relevance, be it statistical, or derived from historical or institutional studies. This approach was endorsed by Rattsø (1982) who did not see much interest for practitioners in framing closures in economic-theory terms. And indeed, most of the literature has thereafter adopted this view Dervis et al. (1989). Albeit seemingly very reasonable, relying only on empirics brings its lots of blind spots and conceptual dead ends. As put by Taylor and Von Arnim (2007):

Applied economists are well aware that certain models and their assumptions fit certain situations, periods, and countries and might not add insight in other circumstances. (Taylor and Von Arnim, 2007)

However, the authors follow by arguing that:

For a model on a global scale [...] it simply seems prudent to look at the issues from different perspectives. Suppose empirical research could show (or have shown) that the exchange rate is a highly flexible international price that adjusts to guarantee balanced trade with 50 per cent probability. Should policy analysis not address the other 50 per cent as well? (Taylor and Von Arnim, 2007)

Explained somehow, these objections are the following:

- If there is not enough spatial or temporal variation, there is simply no way to determine whether a causality structure is adequate or not. For the problem of climate, a typical global issue, this is all the more relevant.
- Econometrics is also a science of uncertainty. Econometric results are always formulated in terms of probabilities, and confidence intervals, whatever their degree of reliability, can be very large. And there is *a priori* no reason why we should not explore the whole spectrum they draw. This is all the truer in the case of macroeconometrics, in which uncertainties are higher than in the realm of microeconometrics Summers and Pritchett (1993), where stronger inference methods have been developed in the past decade (*e.g* Random Controlled

Experiments). It is also well possible that many hypotheses made in economics cannot be univocally falsifiable, experimental conditions being extremely hard to create.

- And we add that any empirical exploration, econometric or historical, is based on working hypotheses which derive, at least to a minimal extent, from some theoretical preconceptions. Be it in the realm of statistics or historical analyses, empirical ventures and their “proofs” are by no means definite, due to the uncertainties highly similar to that found in prospective modelling.

There is therefore, at some point, no getting away with theoretical thinking, and therefore conceptual assumptions. To the extent that there is no pure empirics, and that empirical studies are themselves fraught with uncertainties, confining the closure question to a pure empirical debate looks like replacing one uncertainty by another, hardly a solution from a heuristic standpoint. Another caveat relates more specifically to E3 prospective studies, which usually involve exploring very long-term trajectories (up to a century). Relying on empirics to justify one closure would actually be tantamount to assuming that what is true now will be true long afterwards. Although this is definitely done for some key parameters (or driver trends), it seems rather inappropriate in terms of causality structures, especially in view of the recent narrativist approaches to mitigation pathways (Riahi et al., 2017). It looks much more prudent to explore different closures as theoretical assumptions belonging to different economic views, as long as they are tractable. Note that the study by Chisari and Miller (2015), that resembles ours, does not frame its closures in empirical terms, but rather criticises sometimes strong assumptions made by traditional IAM modellers like Nordhaus, for instance on the smoothness of adjustments on some key markets and the perfect foresight of their representative agents.

This is not to say that empirics have no role to play. In our opinion, they do have a selection role, but only by default. Indeed, institutional or statistical analyses can provide a first screening of all possible closures by eliminating “implausible” or “unclear” causality structures that have little chance to be found in the real world. However, the chances that this would leave us with one univocal causality structure are weak.

4.2 Time horizon of the analysis

A second point was raised by Dervis et al. (1989), Dewatripont and Michel (1987) and Robinson (1989), and relates to the term of analysis.

Most CGEs being written for comparative statics, it is rather unclear whether analyses talk about short- or long-term changes. It is all too legitimate to question the relevance of a closure in that light, since some closures may therefore be more adequate for short-run studies than for long-run ones.

For Dervis et al. (1989), non-neoclassical closures prioritise income effects over relative price effects in driving macroeconomic dynamics — for instance, Kaldor’s

“forced savings” mechanism explained earlier relies entirely on an income effect in the determination of the investment-savings equilibrium. Robinson (1989) argues that such effects, which are the theoretical grounds of most non-neoclassical closures, are relevant for short-run considerations, but not in the medium or long-run. His argument is that short-run equilibria cannot be characterised the same way as medium or long-term ones:

Neoclassical CGE models are best suited for looking at medium-run issues. The longer the time horizon, the more appropriate are the assumptions of the neoclassical paradigm, with prices adjusting to clear markets in an environment of mobile factors and reasonable substitution possibilities in demand and supply. Macro structuralist models often justify some of their structural rigidities (e.g. assuming a fixed nominal wage, markup pricing, or lack of supply constraints) on the basis of short-run considerations, but then are applied to analyze the impact of shocks over the medium run. [...] The types of assumptions and equilibrium specifications appropriate for a short-run analytic model are quite different from those appropriate for a medium-run model [...] (Robinson, 1989).

This remark is sensible, but quite sketchy on the differences between “long-term” and “short-term” characterisation of equilibrium. Taylor (2004) provides some elements in that direction, arguing that long-term considerations belong to the realm of growth, while short-term considerations relate to macroeconomic adjustments. Building on that, he holds that closures are, regardless of their theoretical anchorage, *all* short-term concerns. Robinson’s claim that neoclassical closures are more adequate for long-run equilibria is therefore a bit fragile. Yet, Taylor suggests that different short-term closures can serve to sustain a variety of different long-term growth views — or “long-term equilibrium characterisations” in the words of Robinson. No doubt that Robinson had in mind traditional growth theories while writing this remark, but it is unclear why growth should only be a supply-side consideration, as in Solow (1956) or Ramsey (1928). Post-Keynesian authors for instance, have emphasised the role of aggregate demand in conditioning growth dynamics, beyond the short-run considerations of most modern macroeconomics models (Lavoie, 2015). Robinson’s remark is not easy to uphold in view of these arguments.

As a result, it is unclear whether we should dismiss non-neoclassical assumptions for considerations beyond the short run. There is therefore no getting away with theoretical uncertainty revolving around closures in E3 modelling on the basis of the horizon of analysis.

4.3 Legitimate and competing theoretical positions

This does not leave us with many avenues for evaluating the status of possible closures. If empirics cannot help us beyond a gross pre-selection of relevant closures, and if neoclassical causality structures cannot be chosen *a priori* based on the long-term view of most E3 studies, then there only remains to acknowledge *that these closures represent competing views on the macroeconomic functioning of an economy.*

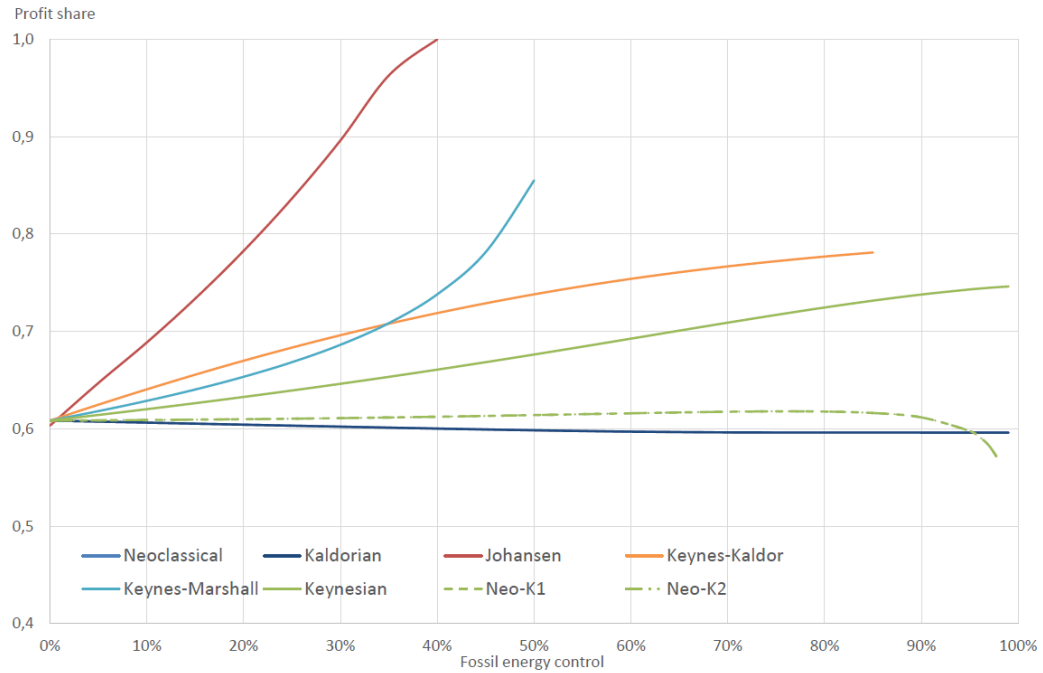
This acknowledgement of competing views in macroeconomics is fully made by Lance Taylor (2004), in a bid to criticise neoclassical assumptions. We do not go that far on our part, as we still consider neoclassical assumptions as a legitimate view of the economy — and to the extent that it covers 85% of the economic profession (Lavoie, 2015), rejecting it right would severely limit the range of our study. However, we do give room to other theoretical views that had so far been limited to empirical propositions, and in fact, never implemented so much by most practitioners in spite of this rather neutral approach to closures (Mitra-Kahn, 2008).

A last caveat is in order before we move on. Different closures can be given a theoretical content and be understood in such light.¹ However, as sketched above, this may not be the case for all of them. Sound and important choices of exogenous/endogenous variables may not be easily relatable to theoretical insights, for instance choosing whether the current account or the real exchange rate should be held constant (Zalai and Révész, 2016). To the extent that such “technical” choices within a CGE framework are relatively theoretically neutral, they can serve to explore different variants of a theoretically sound closure, but also assess the degree of equivalence between these choices.

¹Chisari and Miller (2015) do not use theoretical labels, but clearly compare neoclassical full-employment views with Keynesian assumptions allowing for unemployment.

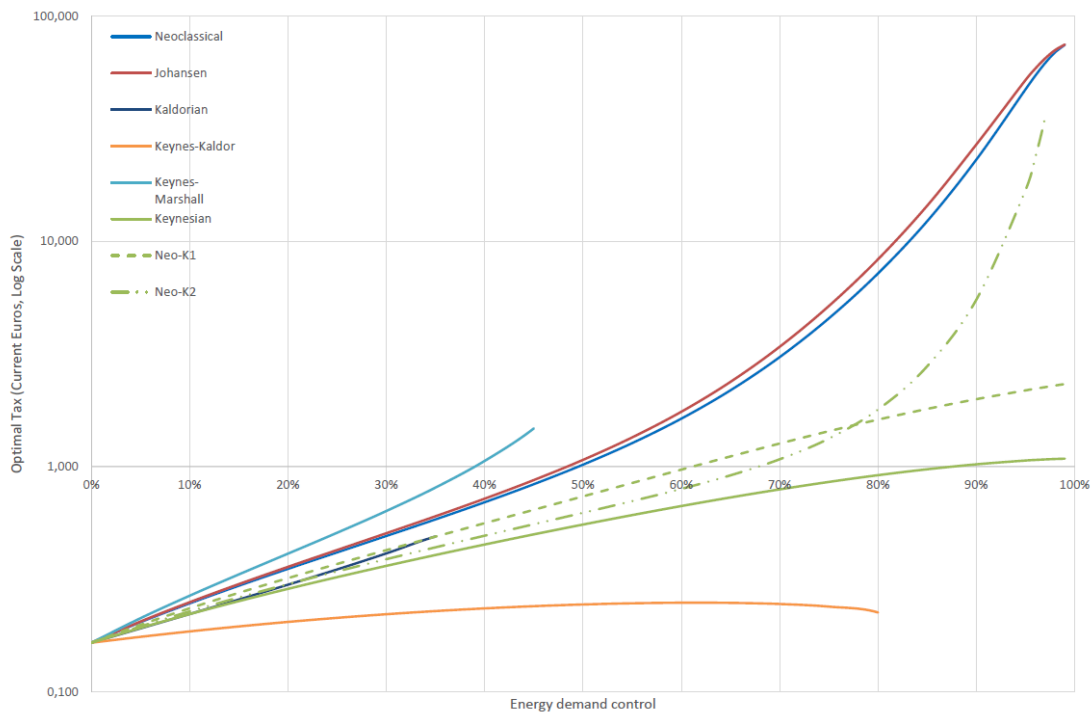
5 Results on other indicators

Figure B.1: Profit share evolution given the domestic polluting energy consumption reduction target for 8 closures of the KLEM model



Here, energy demand control represents a reduction of energy demand compared to the initial calibration value. This figure shows the evolution of the profit share compared to an initial value with no energy demand control, which represents the utility costs of such a control.

Figure B.2: Optimal carbon tax evolution given the domestic polluting energy consumption reduction target for 8 closures of the KLEM model



Here, energy demand control represents a reduction of energy demand compared to the initial calibration value. This figure shows the evolution of the associated Pigouvian tax level compared to an initial value with no energy demand control, which represents the utility costs of such a control.

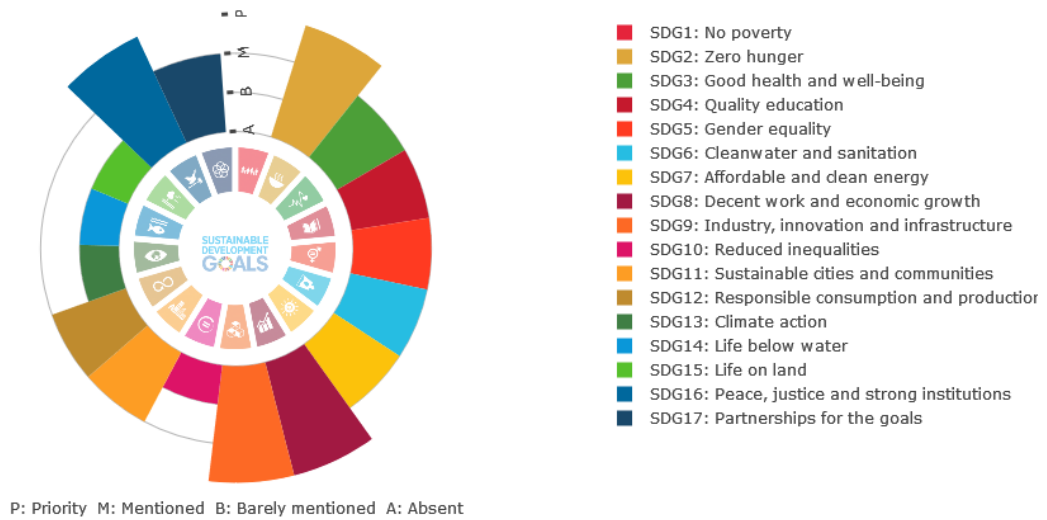
Appendices to Chapter 4

Data and model results are available on request.

6 Additional details on Malawi

6.1 Priorities of Malawi’s development vision

Figure C.1: Level of priority given to each SDG in Malawi’s national long-term development document (Malawi 2063)



As visualised in Chapter 1, SDGs are represented in the position they occupy in the SDG logo and the size of the bar indicates the level of priority accorded to a given SDG in the document according to our analysis – Absent (no bar), Barely mentioned (small bar), Mentioned (medium bar) and Priority (large bar).

6.2 Step 2 - Details

Model calibration

To calibrate the model in 2014, we use the following quantities, obtained from the UNSD Energy Balance tables for 2014 in Malawi (United Nations Department of Economic and Social Affairs, 2017) :

- Energy consumption of households: 0,579918 Mtoe
- Energy consumption of non-energy firms: 0,939763 Mtoe
- Energy consumption of energy transformation and losses: 0,799273 Mtoe
- Energy exports: 0,007213 Mtoe
- Energy imports: 0,317235 Mtoe

To hybridize the IOT, we also build energy prices for 2014, using the same methods as to build price projections, in order to maintain consistency. Electricity prices are built up from estimations on the Levelized Costs of Energy (LCOE, including Transmission and Distribution) of power technologies for firms and households (using the industry-related LCOE for firms and the unspecified LCOE for households), as well as their mix in the electricity sector (Miketa and Merven, 2013; United Nations Department of Economic and Social Affairs, 2017). For calibration year, the power mix of Malawi is composed of 12% oil products and 88% hydroelectricity (IRENA data is here consistent with the UNSD Balance which we use to calibrate the model, as the only input for the electricity sector is oil). Electricity costs in 2014 are then estimated at 1297\$/toe for the industry sector and 1917\$/toe for households.¹ End-use energy prices for energy firms, non-energy firms and households in 2014 are then determined by averaging the electricity and fuel prices computed from IRENA Miketa and Merven (2013) (assuming fuel prices are equal to their import prices) – and adding a value added-tax of 16.5%² except for exports –, weighting each source of energy by its share in each end-use as displayed in the UNSD 2014 energy balance. Prices for 2014 are thus:

- Energy import price: 845\$/toe
- Energy export price: 490 \$/toe
- Energy price for energy firms: 202 \$/toe
- Energy prices for non-energy firms: 456 \$/toe
- Energy prices for households: 196 \$/toe

The resulting hybridized IOT for Malawi, calculated as detailed in Section 4.2, is displayed in Table C.1.

¹These figures do not include the value-added tax, which is later included in the calculations of end-use energy prices.

²Source: Malawi Revenue Authority

Table C.1: Hybridized Input-Output table for Malawi used to calibrate the KLEM variant for the year 2014

Bn 2014 USD	Non-E	E	C	G	I	X	
Non-Energy	5893	122	4853	769	737	1828	14203
Energy	428	162	114	-	-	4	707
Labour payments	3 025	24					
Labour taxes	88	1					
Capital payments	2035	76					
Output taxes	-2	0					
Rent	326	52					
SM use in Q	-	142					
SM use in E	-	-81					
SM use in C	-	-62					
SM use in G	-	-					
SM use in I	-	-					
SM use in X	-	0					
Imports	1989	268					
Sales taxes	421	3					
	14203	707					

Source: GTAP database (Center for Global Trade Analysis, Purdue University et al., 2019), UNSD Energy Balance (United Nations Department of Economic and Social Affairs, 2017), IRENA SAPP report (Miketa and Merven, 2013), authors' aggregation.

Exogenous parameters and evolution

As presented with the model in Chapter 2, aside from the energy sector, the KLEM model relies on exogenous data and assumptions that we either derive from institutional sources, or from targets featured in Malawi's Vision 2063. All assumptions and data sources are summarized in Table C.2.³

For unemployment, there is a high discrepancy between data available in the plan and International Labour Organization (ILO) Data or World Bank Data. As detailed in the 2013 Labor Force Survey on which the development plan data is based (National Statistical Office, 2014), this is due to two different ILO definitions of unemployment, one being more restrictive than the other. As mentioned in the survey, the true unemployment situation in Malawi (and other developing countries) is better reflected by the broader definition. To match historical data with targets from the plan, we compute unemployment from the Survey value in 2013, and assume its growth is similar to the stricter definition of unemployment as proposed by the World Bank and ILO.

Energy scenarios

To build the reference and NDC-target scenarios for the energy system, a few studies propose projections of the evolution of Malawi's energy system or power mix, as the modelling work proposed by Ioannis Pappis in European Commission Joint Research Centre (2019) and Pappis (2022) using the TEMBA model for the power system and exogenous assumptions on other fuel demands, or in an IRENA report for the Southern African Power Pool IRENA (2021) using the SPLAT model for Malawi's power system. While the former proposes trajectories for the energy system and data on Malawi's power system, the associated reference growth of energy demand is lower than what is envisioned in Malawi Vision 2063. In the 2021 IRENA report, which updates results from the Southern African Power Pool (SAPP) Master Plan with new information on the costs of renewables, the electricity demand is projected to be multiplied by 2,6 between 2020 and 2030, and by 6,5 between 2020 and 2040, which is closer to the demand projected from the plan in Step 1.

Reference scenario We thus create a reference energy scenario for the KLEM model, based on this projected evolution of the power mix proposed in IRENA's reference scenario, and assuming that the rest of the energy mix is similar to the one proposed in European Commission Joint Research Centre (2019) in its reference scenario for the SAPP, with higher overall demands.

We assume that the energy consumption of households grows with the population (with a growth target featured in the plan), and that the energy consumption of non-energy firms grows like the final consumption of the economy projected in Step 1. For

³GDP and labour endowment (both projected from Vision 2063's targets) are used to compute an evolution of the productivity of labour, with an annual growth rate that averages 2,8% over the 2014-2040 period.

Table C.2: Sources and assumptions for exogenous drivers of the KLEM model

Exogenous Data	Before 2022	After 2022
Unemployment (%)	World Bank Data (% of labour force) adjusted to match development plan levels in 2013	Linear evolution following plan targets
GDP PPP (bn 2017 intl \$)	World Bank Data	/
Projected GDP PPP index 1 in 2015	/	Computed from plan targets
Labour endowment	ILO modeled estimates (Labour force by sex and age)	Computed assuming a 2,1% growth until 2030, a 1,8% growth after (population plan targets)
Trade Balance (current US \$)	World Bank Data (Net trade in goods and services, BoP)	Following modelling practice and in the absence of a plan target, forced to reach 0 in 2040
GDP (bn current US \$)	World Bank Data	/
Gross Fixed Capital Formation (% of GDP)	AFDB Socio-Economic Data Base	Adjusted to warrant that the capital stock grows at the pace of all volumes when the economy is growing according to its potential
Gross domestic savings (bn current US \$)	AFDB Socio-Economic Data Base	Adjusted to ensure balance with the trade balance and investment assumptions
Real Effective Exchange Rate index (2010 = 100)	World Bank Data	/
Energy rents (% of GDP)	World Bank Data	/

the energy sector, we assume that the charcoal industry consumption is multiplied by respectively 1,7 and 2,9 from 2020 to 2030 and 2040 (to adjust the evolution of energy demand to the biomass share in the energy mix). To follow the 2021 IRENA report's projections, we assume that the growth in electricity demand between 2020 and 2030 is exclusively met by an expansion in fossil fuel generating capacity, but that the growth between 2030 and 2040 is met by renewable energy capacity and imports (with no additional fossil energy consumption of the electricity industry). We ensure that the reference energy mix projected by the JRC is consistent with the global final consumption (by ensuring that the projected share of electricity applied to our scenario's final energy consumption is consistent with the total projected electricity consumption in IRENA's scenarios), then calculate the volume of imports by considering that all

coal, oil and gas are imported, as well as a share of electricity as projected in IRENA's reference scenario.⁴ Finally, following the JRC reference projections, we consider that energy exports stay constant.

We then compute prices with a similar approach as for calibration. For electricity, we use each projected technology share in the power mix and LCOE featured in the IRENA report (differentiating households and firms, and including transmission and distribution). For non-energy firms and households, we assume a similar energy mix as in the entire economy (as proposed in the JRC's report), and fossil fuel prices equal to their import price. For imports and exports, we weight prices by the share of traded fuel/electricity. We also apply a value-added tax of 16,5% (assuming it stays at its current value) to all prices except exports. Between 2014 and 2020, 2020 and 2030, and 2030 and 2040, we assume a linear growth in the model inputs. The figures of the reference scenario for Malawi's energy system are summarized in Table C.3.

⁴Although the plan targets are to reach 100% of electricity generation to demand, there is no modelling exercise of Malawi's energy system for which this target is applied as a constraint in the reference scenario.

Table C.3: Evolution of energy quantities and prices under Malawi's Reference scenario

Input	2020	2030	2040
E Imports (Mtoe)	0,544401	2,286590	4,017491
E Exports (Mtoe)	0,001624	0,001624	0,001624
E consumption of E firms (Mtoe)	0,843054	2,092460	3,063658
E consumption of non-E firms (Mtoe)	1,182191	2,141367	3,961101
E consumption of Households (Mtoe)	0,585888	0,764004	0,940488
E Imports (\$/toe)	928	789	934
E Exports (\$/toe)	251	251	251
E consumption of E firms (\$/toe)	114	506	385
E consumption of non-E firms (\$/toe)	791	602	698
E consumption of Households (\$/toe)	248	698	833

NDC targets scenario Malawi's NDC proposes a large reduction of energy-related emissions, with a potential reduction of 15,1 $MtCO_{2e}$ in 2040. Compared to the 2040 reference level of energy related emissions which is 19,83 $MtCO_{2e}$, this represents a 78% reduction in emissions. According to the document, around 50% of this reduction should be covered by CCS technology on coal plants, around 30% by changes in the energy mix and around 20% by a decrease in energy demand. This implies around a 15% reduction of the final demand in energy in 2040, that we ventilate on all consumers. We then compute energy prices in a similar way as proposed for the reference scenario, using the power mix of the High Renewable Energies scenario in the IRENA report (with CCS production costs for coal generation) and the energy mix of the 2°C scenario from the TEMBA report. The figures used are summarized in Table C.4.

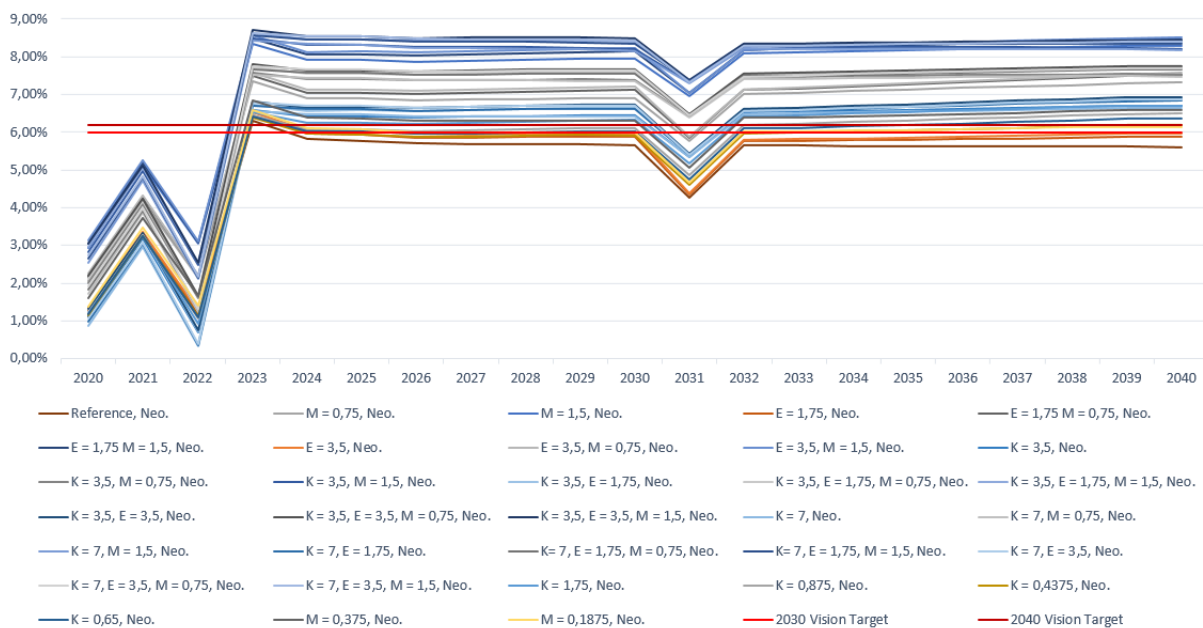
Table C.4: Evolution of energy quantities and prices under Malawi's NDC_targets scenario

Input	2020	2030	2040
E Imports (Mtoe)	0,544401	1,897363	2,573608
E Exports (Mtoe)	0,001624	0,001624	0,001624
E consumption of E firms (Mtoe)	0,843054	1,886080	2,828952
E consumption of non-E firms (Mtoe)	1,182191	1,713094	3,168880
E consumption of Households (Mtoe)	0,585888	0,611203	0,752390
E Imports (\$/toe)	928	772	934
E Exports (\$/toe)	251	251	251
E consumption of E firms (\$/toe)	114	608	435
E consumption of non-E firms (\$/toe)	791	626	850
E consumption of Households (\$/toe)	248	725	1052

6.3 Sensitivity of results to the choice of closure

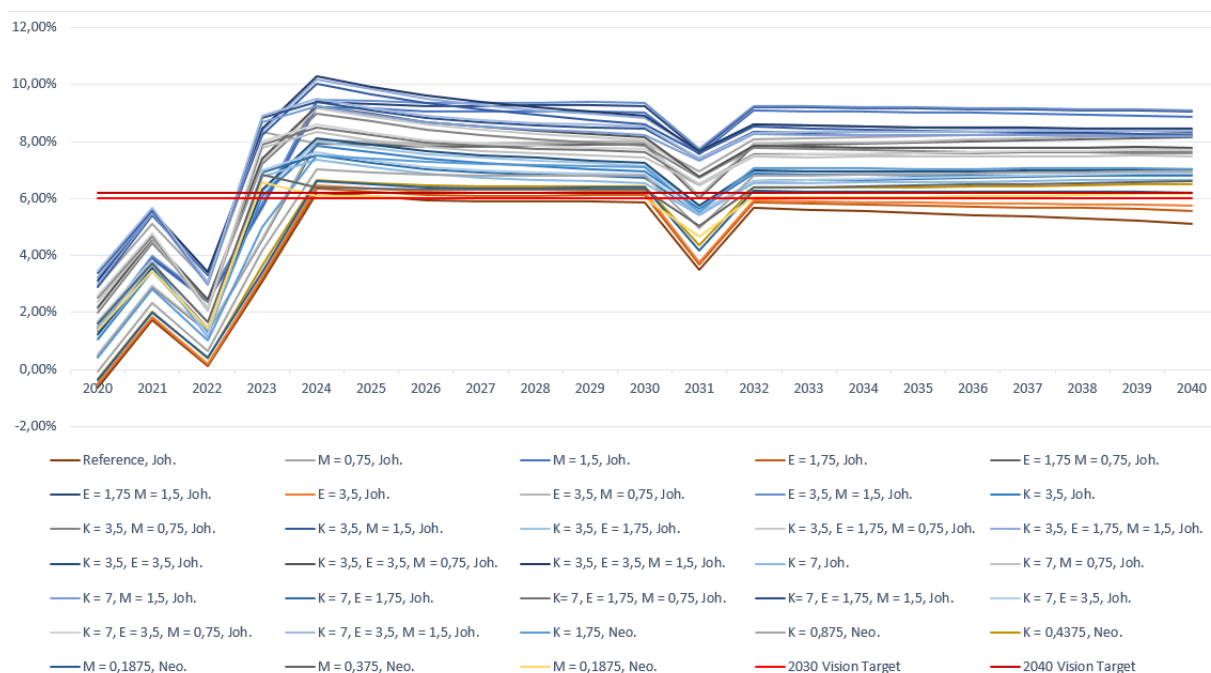
We show that the results hold under a Johansen closure. Indeed, even though for a given set of parameters, growth is not identical under a neoclassical and under a Johansen closure, the differences are small, and the number of sets that meet the GDP targets under a Johansen closure and under a neoclassical closure are similar. Further analyses will help point out specific numerical differences among both closures, and the mechanisms by which they are caused.

Figure C.2: GDP growths evolutions under the Reference scenario of Malawi, depending on evolutions of capital, energy and materials productivities in the non-energy sector, under a neoclassical closure



Each line represents a different set of growths of capital, energy and materials productivities in the non-energy sector. In green, results are obtained using a Johansen closure whereas in blue, results are obtained using a neoclassical closure. The name of the scenario includes the growth considered for each parameter in the scenario (K for capital productivity, E for energy productivity, M for materials productivity). If the parameter does not evolve, it is not mentioned. Discrepancies before 2022 are due to the fact that the model takes real data for exogenous assumptions up until this year. In 2031, there is a slight discrepancy due to the change of slopes between 2020-2030 and 2030-2040 exogenous targets.

Figure C.3: GDP growths evolutions under the Reference scenario of Malawi, depending on evolutions of capital, energy and materials productivities in the non-energy sector, under a Johansen closure



Each line represents a different set of growths of capital, energy and materials productivities in the non-energy sector. In green, results are obtained using a Johansen closure whereas in blue, results are obtained using a neoclassical closure. The name of the scenario includes the growth considered for each parameter in the scenario (K for capital productivity, E for energy productivity, M for materials productivity). If the parameter does not evolve, it is not mentioned. Discrepancies before 2022 are due to the fact that the model takes real data for exogenous assumptions up until this year. In 2031, there is a slight discrepancy due to the change of slopes between 2020-2030 and 2030-2040 exogenous targets.

7 Additional details on Colombia

7.1 Step 2 - Details

Model calibration

To calibrate the model in 2014, we use the following quantities, obtained from the UNSD Energy Balance tables for 2014 in Colombia (United Nations Department of Economic and Social Affairs, 2017):

- Energy consumption of households: 0,579918 Mtoe
- Energy consumption of non-energy firms: 21,857146 Mtoe
- Energy consumption of energy transformation and losses: 28,748615 Mtoe
- Energy exports: 94,34795 Mtoe
- Energy imports: 4,851915 Mtoe

To hybridize the IOT, we also build energy prices for 2014. We use electricity prices proposed in Ministerio de Minas y Energía (2015), and, like for Malawi, compute average energy prices for exports, energy firms, non-energy firms, households and imports, using the share of each fuel/electricity obtained from the UNSD energy balance (we take fossil fuel prices from Cannone et al. (2021)).⁵ Prices for 2014 are thus:

- Energy import price: 655\$/toe
- Energy export price: 312 \$/toe
- Energy price for energy firms: 453 \$/toe
- Energy prices for non-energy firms: 576 \$/toe
- Energy prices for households: 778 \$/toe

The resulting hybridized IOT for Colombia, calculated as detailed in Section 4.2, is displayed in Table C.5.

⁵adding a value-added tax of 19%

Table C.5: Hybridized Input-Output table for Colombia used to calibrate the KLEM variant for the year 2014

Bn 2014 USD	Non-E	E	C	G	I	X	
Non-Energy	229 009	5 766	195 409	65 597	95 865	52 276	643
							932
Energy	12 590	13 023	3 775	-	-	29 437	58 824
Labour payments	103 299	2 137					
Labour taxes	23 631	489					
Capital payments	170 637	23 867					
Output taxes	4 696	243					
Rent	7 003	7 409					
SM use in Q	-	3 224					
SM use in E	-	1 038					
SM use in C	-	1 603					
SM use in G	-	-					
SM use in I	-	-					
SM use in X	-	-5 865					
Imports	60 835	3 108					
Sales taxes	32 233	2 773					
	643	58 824					
	932						

Source: GTAP database (Center for Global Trade Analysis, Purdue University et al., 2019), UNSD Energy Balance (United Nations Department of Economic and Social Affairs, 2017), Cannone et al. (2021), and Ministerio de Minas y Energía (2015), authors' aggregation.

Exogenous parameters and evolution

As presented with the model in Chapter 2, aside from the energy sector, the KLEM model relies on exogenous data and assumptions that we either derive from institutional sources, or from targets featured in Colombia's Vision 2050. All assumptions and data sources are summarized in Table C.6.⁶

Table C.6: Sources and assumptions for exogenous drivers of the KLEM model

Exogenous Data	Before 2021	After 2021
Unemployment (%)	World Bank Data (% of labour force)	Linear evolution following plan targets
GDP PPP (bn 2017 intl \$)	World Bank Data	/
Projected GDP PPP index 1 in 2015	/	Computed from plan targets
Labour endowment	ILO modeled estimates (Labour force by sex and age)	ILO modeled estimates (Labour force by sex and age)
Trade Balance (current US \$)	World Bank Data (Net trade in goods and services, BoP)	Following modelling practice and in the absence of a plan target, forced to reach 0 in 2050
GDP (bn current US \$)	World Bank Data	/
Gross Fixed Capital Formation (% of GDP)	World Bank Data	Adjusted to warrant that the capital stock grows at the pace of all volumes when the economy is growing according to its potential
Gross domestic savings (bn current US \$)	World Bank	Adjusted to ensure balance with the trade balance and investment assumptions
Real Effective Exchange Rate index (2010 = 100)	World Bank Data	/
Energy rents (% of GDP)	World Bank Data	/

⁶GDP and labour endowment projections are used to compute an evolution of the productivity of labour, which yields a growth rate over the 2020-2050 period that equates what is envisioned in the Vision 2050.

Energy scenarios

Only Plazas-Niño et al. (2023b) is up to date with Colombia’s current mitigation target: most other trajectories either translate the targets of the initial NDC, or are in line with the current 2030 target, but do not lead to net-zero emissions in 2050. The implications of the Paris Agreement for Colombia’s energy exports are also systematically overlooked.

For our analysis, we use the energy trajectory built by Plazas-Niño et al. (2023b) with the OseMOSYS model. We compute the volumes of energy imports, energy consumption of households and non-energy firms directly from this study, and as crude oil and coal exports are not part of the projections,⁷ we assume that they remain constant in volume from 2021 onward (which would be in line with the recent pledge of Colombia to halt the signing of new hydrocarbon exploration contracts). We also assume that the intermediate energy consumption of the energy sector remains constant (the electricity sector grows but to include more renewables, and we assume that the extracting and refining activities remain constant, in line with the constant exports).

To compute electricity prices based on production costs, we calculate LCOEs for all technologies using the technico-economic dataset supporting the study (Plazas-Niño et al., 2023a)⁸, and the discount rate used in the study, which is 6,4% (based on the National Energy Plan for 2050 of Colombia). We also include transmission and distribution costs. We then compute an average electricity cost by averaging these LCOEs, weighting the average by each share in the final electricity mix. We compute export prices based on fuel prices from the dataset, and assuming a constant share of crude oil and coal in the exports from 2021 onward. We compute import prices based on fuel prices from the dataset, and fuel shares in the imports as proposed by Plazas-Niño et al. (2023b).⁹ We compute end-use prices using fuel prices from the dataset, electricity prices computed earlier, and the energy mix proposed in Plazas-Niño et al. (2023b).¹⁰ The figures used are summarized in Table C.7.

7.2 Sensitivity of results to the choice of closure

We show that the results hold under a Johansen closure. Indeed, even though for a given set of parameters, growth is not identical under a neoclassical and under a Johansen closure, the differences are small, and the number of sets that meet the GDP targets under a Johansen closure and under a neoclassical closure are similar. Further analyses will help point out specific numerical differences among both closures, and the mechanisms by which they are caused.

⁷The authors make no assumptions on the evolution of oil and coal exports, as it is highly dependent on the future mitigation pathways of Colombia’s trading partners.

⁸Including capital costs, fixed costs, variable costs, and assuming fuel prices detailed in the dataset.

⁹adding a value-added tax of 19%, assuming the rate is constant from 2021 on

¹⁰adding a value-added tax of 19%, assuming the rate is constant from 2021 on

Table C.7: Evolution of energy quantities and prices under Colombia’s Vision 2050 scenario

Input	2021	2030	2040	2050
E Imports (Mtoe)	1,958536	0,7165	0,812076	3,582688
E Exports (Mtoe)	62,678	62,678	62,678	62,678
E consumption of E firms (Mtoe)	34,9431	34,9431	34,9431	34,9431
E consumption of non-E firms (Mtoe)	27,4384	30,7310	33,8041	43,9454
E consumption of Households (Mtoe)	6,0230	6,7458	7,4204	9,6465
E Imports (\$/toe)	502	549	1546	1624
E Exports (\$/toe)	292	382	427	478
E consumption of E firms (\$/toe)	164	164	164	164
E consumption of non-E firms (\$/toe)	423	445	474	440
E consumption of Households (\$/toe)	466	512	574	560

Figure C.4: Comparisons of GDP growths evolutions under the Vision 2050 Scenario of Colombia, depending on evolutions of capital, energy and materials productivities in the non-energy sector, and the choice of closure



Each line represents a different set of growths of capital, energy and materials productivities in the non-energy sector. In green, results are obtained using a Johansen closure whereas in blue, results are obtained using a neoclassical closure. The name of the scenario includes the growth considered for each parameter in the scenario (K for capital productivity, E for energy productivity, M for materials productivity). If the parameter does not evolve, it is not mentioned. Discrepancies before 2022 are due to the fact that the model takes real data for exogenous assumptions up until this year. In 2031, there is a slight discrepancy due to the change of slopes between 2020-2030 and 2030-2040 exogenous targets.

8 Substitution elasticities

Table C.8: Substitution elasticities of a generic ‘KLEM’ model

Elasticity	Notation	Value, non-energy production
Substitution of capital K_i to labour L_i	σ_{KL_i}	0.2162 ^a
Substitution of value-added KL_i to energy $\alpha_{E_i}Y_i$	σ_{KLE_i}	0.3635 ^a
Substitution of KLE_i aggregate to non-energy $\alpha_{Q_i}Y_i$	σ_{Y_i}	0.8190 ^a
Substitution of domestic variety D_i to imported variety M_i on domestic markets	σ_{S_i}	2.7804 ^b

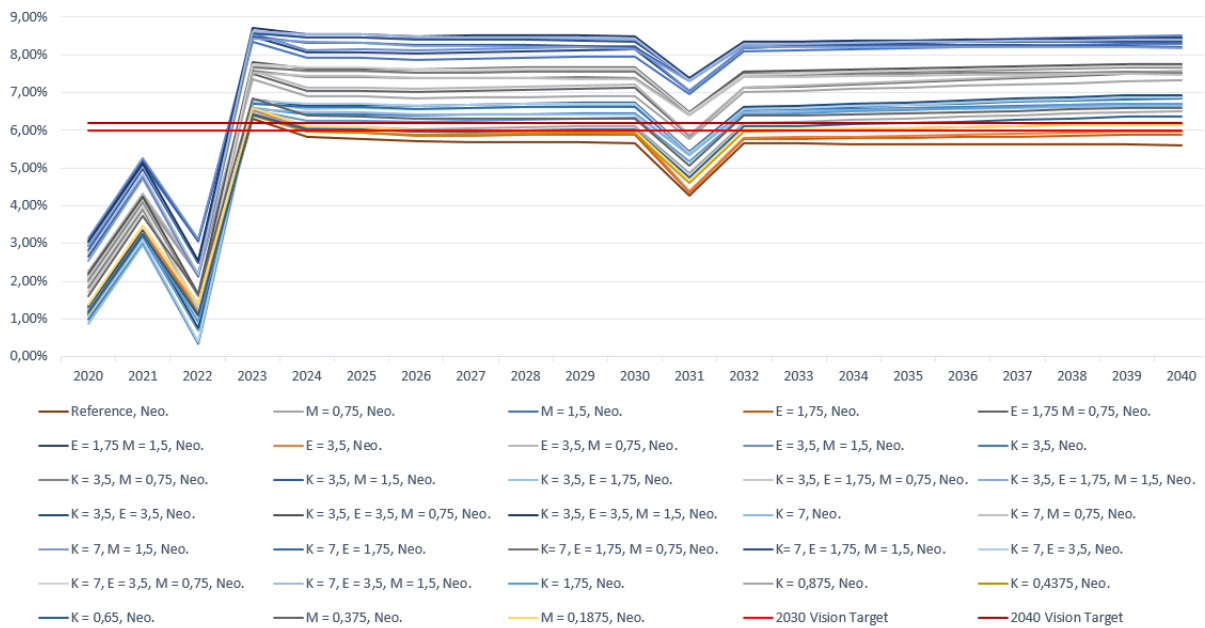
^a The elasticity computed for non-energy sectors from Antoszewski (2019).

^b Inspired by the Armington elasticities of the non-energy sectors of the GTAP model (Hertel and van den Mensbrugge).

8.1 Sensitivity of results to elasticities of substitution

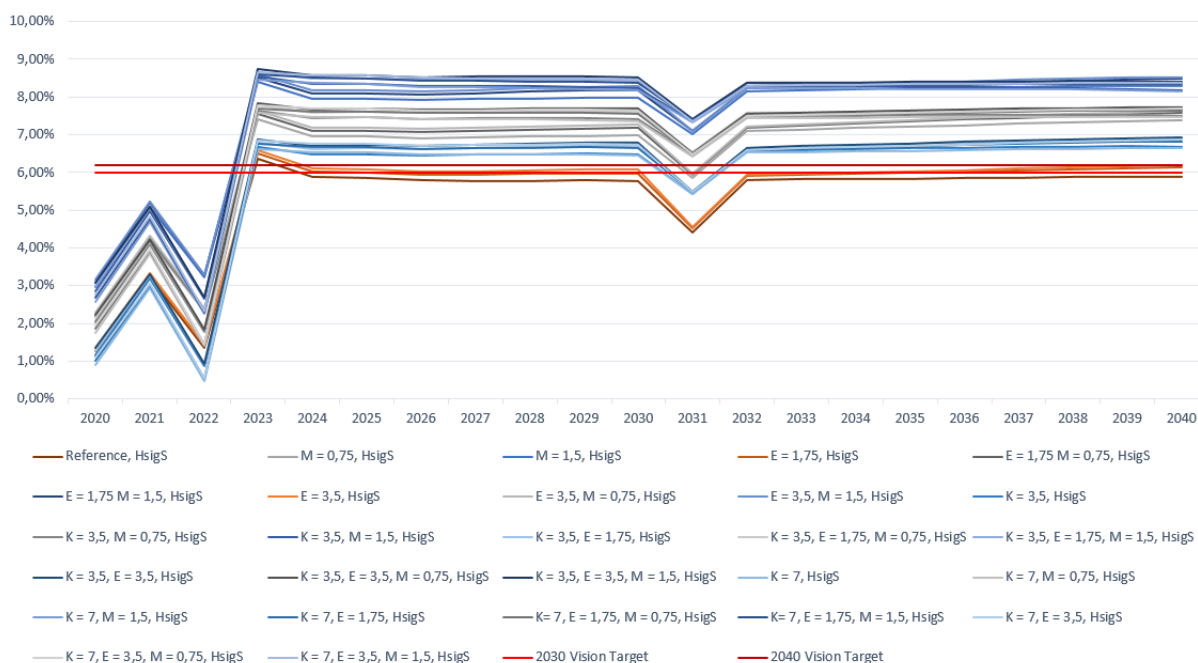
This section presents figures of the GDP trajectories for Malawi’s reference scenario, depending on the choice of elasticity of substitution Sigma S. Others similar analyses were conducted for the other elasticities. Their effect in detail on all variables of the model have yet to be sorted out. However, for all CES functions, while the effect of elasticities of substitution on GDP growth is visible, the global result - which is that there is a large space of parameters for which Vision 2063’s growth targets are met - is not changed.

Figure C.5: GDP growths evolutions under the Reference scenario of Malawi, depending on evolutions of capital, energy and materials productivities in the non-energy sector, under a neoclassical closure



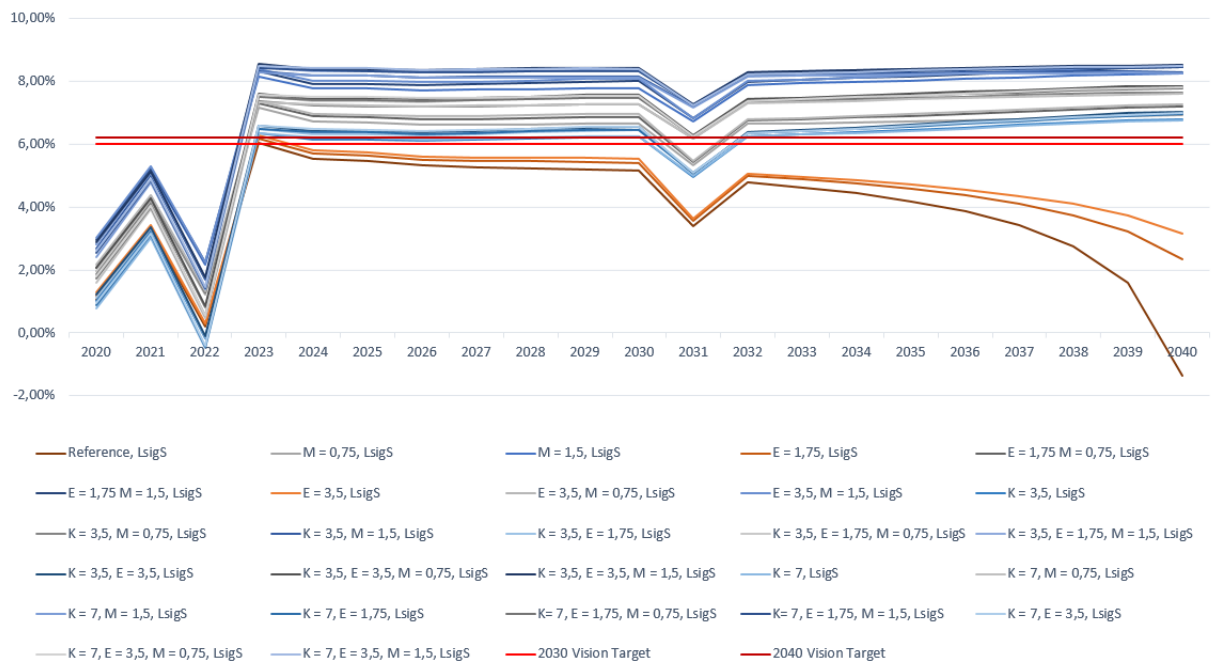
Each line represents a different set of growths of capital, energy and materials productivities in the non-energy sector. In green, results are obtained using a Johansen closure whereas in blue, results are obtained using a neoclassical closure. The name of the scenario includes the growth considered for each parameter in the scenario (K for capital productivity, E for energy productivity, M for materials productivity). If the parameter does not evolve, it is not mentioned. Discrepancies before 2022 are due to the fact that the model takes real data for exogenous assumptions up until this year. In 2031, there is a slight discrepancy due to the change of slopes between 2020-2030 and 2030-2040 exogenous targets.

Figure C.6: GDP growths evolutions under the Reference scenario of Malawi, depending on evolutions of capital, energy and materials productivities in the non-energy sector, calibrated with a high elasticity sigma S



Each line represents a different set of growths of capital, energy and materials productivities in the non-energy sector. In green, results are obtained using a Johansen closure whereas in blue, results are obtained using a neoclassical closure. The name of the scenario includes the growth considered for each parameter in the scenario (K for capital productivity, E for energy productivity, M for materials productivity). If the parameter does not evolve, it is not mentioned. Discrepancies before 2022 are due to the fact that the model takes real data for exogenous assumptions up until this year. In 2031, there is a slight discrepancy due to the change of slopes between 2020-2030 and 2030-2040 exogenous targets.

Figure C.7: GDP growths evolutions under the Reference scenario of Malawi, depending on evolutions of capital, energy and materials productivities in the non-energy sector, calibrated with a low sigma S



Each line represents a different set of growths of capital, energy and materials productivities in the non-energy sector. In green, results are obtained using a Johansen closure whereas in blue, results are obtained using a neoclassical closure. The name of the scenario includes the growth considered for each parameter in the scenario (K for capital productivity, E for energy productivity, M for materials productivity). If the parameter does not evolve, it is not mentioned. Discrepancies before 2022 are due to the fact that the model takes real data for exogenous assumptions up until this year. In 2031, there is a slight discrepancy due to the change of slopes between 2020-2030 and 2030-2040 exogenous targets.

Appendices to Chapter 6

All replication data for the figures and analysis can be found following this link: <https://zenodo.org/badge/latestdoi/587822851>

9 Systematic review of survey and experimental results on individual attitudes towards international climate justice

The literature was reviewed by conducting a systematic search on the platform Scopus in February 2023. We aimed at isolating articles and documents that tackled survey or lab experiment designs on climate equity rules at the scale of international climate negotiations and UNFCCC processes. To target these designs, we looked for the presence of variations of the words “game”, “survey” and “experiment” in the title, abstract or keywords. The word “climate” also had to be mentioned. To target the global scale, we looked for “international”, “country” or “negotiations” in the title, abstract or keywords. Finally, as we wanted the documents to specifically tackle distributive justice and equity rules, we looked for the presence of “fairness”, “equity” or “burden-sharing”, and for the presence of variations of the words “rule”, “principle”, “distribution”, or “preference” in the title, abstract or keywords.

We thus used the “advanced search” feature with the following search equation:

TITLE-ABS-KEY ((game OR games OR survey OR surveys OR experiment OR experiments) AND climate AND (international OR country OR negotiations) AND (fairness OR equity OR burden-sharing) AND (rule OR rules OR principle OR principles OR distribution OR distributions OR preference OR preferences))

This search equation isolated 82 articles, from which we manually removed articles which weren't about climate change issues and the global climate context, articles which didn't feature surveys or lab experiments and articles which weren't about fairness and equity rules. This led us to identify 17 studies, most of them being conducted around 2010.

The following table summarizes the main features of each of these 17 studies (survey/game, year of the study, type of questionnaire, observed features, length, administration, targeted groups, countries, sample size, sampling strategy, representativity, main results as mentioned in the abstract).

Ref	Type	Year	Survey	Observed features	Length of survey	Administration	Targeted group	Country	Sample size	Sampling strategy	Representativity	Main result(s) (from the abstract)
Lange et al. (2007)	Survey	2004	Ad hoc (Results on half the survey)	Individual declared views on equity/equity rules	not mentioned	Login for an internet questionnaire sent via e-mail, answers: online/e-mail/postal mail	people involved in international climate policy	World	230 (183 excl. some incomplete answers)	Direct emailing (1695 addresses taken from official UN documents e.g. workshops)	Not checked (no evidence of non-representativity of the targeted group)	<ul style="list-style-type: none"> - Equity issues are considered highly important - The most widely accepted principles are "polluter-pays" and "accompanying poor losers" - The economic or emission performance of the respondent's country has a strong influence on the answers (results are compatible with a self-serving bias, except: people from richer countries support an egalitarian principle more in the long run)
Lange et al. (2010)	Survey	2004	Ad hoc (Results on half the survey)	Perception of some regions' negotiating position/attitude towards equity rules (EU, G77/China, Russia, the USA)	not mentioned	Login for an internet questionnaire sent via e-mail, answers: online/e-mail/postal mail	people involved in international climate policy	World	230 (incl. some incomplete answers)	Direct emailing (1695 addresses taken from official UN documents e.g. workshops, corresponding to around 1500 persons)	No evidence of non-representativity of the targeted group	<ul style="list-style-type: none"> - The perceived support of different rules by regions may be explained by the ranking of their economic costs - Despite being self-interested, equity arguments may be perceived as being used for different reasons - Individuals are more likely to state positive reasons if they evaluate their region or regions that support the equity rule they prefer
Schleich et al. (2016)	Survey	2013	Ad hoc	Individual declared views on equity/equity rules, ranking of equity rules	~30 min (31.8 in GER, 28.5 in CHN, 30.4 in USA on average)	USA/GER: Login for an internet questionnaire sent via e-mail (by a market research company) CHN: face-to-face interviews (by a market research company)	citizens	China, Germany, US	3445 (1430 in China, 1005 in Germany, 1010 in the US)	GER/USA: sample drawn from representative panel (by the company) CHN: respondents recruited by employees in 11 regions (half the people from rural areas, half from metropolitan areas)	Weighted to ensure offline representativeness of the results	<ul style="list-style-type: none"> - in the three countries, the ranking of the burden-sharing principles is: accountability, then capability, egalitarianism and sovereignty. - citizens seem to have a common normative understanding of fairness

Ref	Type	Year	Survey	Observed features	Length of survey	Administration	Targeted group	Country	Sample size	Sampling strategy	Representativity	Main result(s) (from the abstract)
Lange and Schwirplies (2017)	Survey	2004; 2013	Same as Schleich et al 2016, Lange et al 2010	Equity preferences - perceived view on the position of their respective countries	cf Schleich et al 2016, Lange et al 2010	cf Schleich et al 2016, Lange et al 2010	citizens and people involved in international climate policy	citizens: China, Germany, US delegates: EU, G77/China, US	delegates: 161 citizens: (936 US, 1389 CHN, 914 US)	cf Schleich et al 2016, Lange et al 2010 (only keeping the responses from citizens and delegates who answered to the questions selected for the analysis)	cf Schleich et al 2016, Lange et al 2010	- While parties tend not to overrepresent their citizens' preferences for their own cost-efficient rule, they still do only partly deviate to come closer to the observed position of other parties
Carlsson et al. (2011)	Survey	2009	CE methods	WTPs associated with equity rules (discrete CE between distributions of the abatement among countries, imagining what each distribution would cost for the respondent's household)	not mentioned	Mailed with a lottery ticket	citizens	Sweden	411 questionnaires returned (397 sufficiently complete)	Direct mailing (random sample of 1200 citizens aged 18-75 drawn from the swedish census registry) along with a lottery ticket	Over-representation of people with university education and retirees	- the results show no evidence for ingroup bias in preferences for effort-sharing rules (the responses are not significantly different between a treatment where respondents are informed about the countries' names and a treatment where the names are replaced by anonymous labels)
Carlsson et al. (2013)	Survey	2009	CE methods	WTPs associated with equity rules (discrete CE between distributions of the global cost among countries, imagining what each distribution would cost for the respondent's household)	not mentioned	US: online (via survey company recruiting by telephone) CHN: on-site in special rooms with laptops	citizens	China, US	2173 (909 in the US, 1264 in China)	US: random selection in a representative panel CHN: four cities representative of Chinese cities in size, location and income - random selection in neighborhood-based databases used in previous surveys	Yes in the US, some biases in China	- respondents favored the rule that was least costly for their country - the WTP was much higher in China - the ranking of the two most preferred rules are generally robust across all socioeconomic groups within each country

Ref	Type	Year	Survey	Observed features	Length of survey	Administration	Targeted group	Country	Sample size	Sampling strategy	Representativity	Main result(s) (from the abstract)
Bechtel and Scheve (2013)	Survey	2012	conjoint analysis methods	Choice between two agreements depending on various characteristics (incl. distribution of costs)	not mentioned	Online (via YouGov)	citizens	France, Germany, UK, US	8500 (2000 in Fr, Ger, UK and 2500 in the US)	opt-in panel together with matched sampling to approximate a random sample of the adult populations	Yes (with some weighing)	- Distributing the costs of emissions reductions proportional to current or historical emissions increases support compared with an agreement in which only rich countries pay - opinion responds similarly to changes, in all four countries
Hjerpe et al (2011)	Survey	2009	Ad hoc	Declared views on equity rules	2-pages long	in-person on paper given to COP participants	people involved in international climate policy	Worldwide	170 delegates, 300 observers	to the 2009 COP (delegates and observers): 507 surveys administered in person at the venue	No (small number of Oceania/North America representatives)	- voluntary contribution, indicated as willingness to contribute, was the least preferred principle among both groups - agreement was strongest for basing a country's mitigation level on its capacity to pay in terms of GDP per capita and on its historic greenhouse gas emissions since 1990
Kriss et al. (2011)	Survey	not mentioned	Ad hoc	Choice of allocation of an economic burden between two countries	~15 min	in computer labs, or on computers provided by researchers	college students	China, US	292 in China, 332 in the US	recruitment in a university in China (class announcement) and a university in the US (class announcement + in the student center) - non-nationals were later excluded from the sample	Not of the populations	- students display a nationalistic self-serving bias - by disguising the problem, it is possible to elicit perceptions of fairness that are not influenced by national interests - the disagreement over what constitutes fair climate policy does not appear to be due to cross-national differences
Kesternich et al (2021)	Survey	2012	partially inspired from Lange et al (2007, 2010)	Views on international equity, combination and weighting of burden-sharing rules	not mentioned	Login for an internet questionnaire sent via e-mail, answers: online/e-mail/postal mail	people involved in international climate policy	Worldwide	329 complete answers (498 participations)	Direct emailing (5840 addresses taken from the official lists of participants to COP-16 in Cancún, COP-17 in Durban, keeping only delegation members of Parties or observer states)	No	- delegates from different groups of countries show a general willingness for concessions - the individual assessment of the polluter-pays rule shows differences between Annex B/non Annex B delegates but also between G77/BASIC delegates - there are tendencies for a more harmonized view towards the ability-to-pay rule

Ref	Type	Year	Survey	Observed features	Length of survey	Administration	Targeted group	Country	Sample size	Sampling strategy	Representativity	Main result(s) (from the abstract)
Mahajan et al (2022)	Game	not mentioned	/	The game is designed to match the climate stakes but for players, a neutral framing is used. Each bargaining game happens between two randomly paired players, on how to split a global cost, with alternating offers. Treatments vary in the players' initial endowment level(s), the collective risk or the termination probability after each round.	not mentioned	In-person: the experimental sessions were computerized (participants got a show-up fee + payments from the experiment itself), subjects were paired randomly and anonymously	college students	Nationality not detailed (study administered in the US)	182	recruitment among the undergraduates of a public university in the Northeast United States	No	- less vulnerable parties tend to be more generous with more vulnerable parties - parties with greater capacities are less generous in their offers
Feige et al (2018)	Threshold public goods game	2016	/	The game is designed to match the climate stakes but for players, a neutral framing is used. A threshold public goods game with uncertain threshold value serves as the stage game for the repeated interaction of the same group of players who choose their own individual contributions in terms of cost in each of ten independent rounds. Four treatments differ in the presence of a non-binding unanimous vote on contribution vectors before each contribution choice, as well as to the marginal contribution costs of the players.	about 1h30	In-person: the experimental sessions were computerized (participants earned on average 15.27 euros)	college students	Nationality not detailed (study administered in Germany)	132	recruitment via ORSEE from a student pool at the Karlsruhe Institute for technology (KIT)	No	- a non-binding unanimous voting procedure on contribution vectors leads to frequent agreement on an optimal total contribution and high rates of compliance, even in the case of heterogeneous marginal contribution costs - groups that do not reach agreement perform worse than the baseline treatments without a voting procedure. - the results point to a predominant burden-sharing rule that equalizes individual contribution costs, even at the cost of the group's total payoff.
Anderson et al (2017)	Ultimatum game	2015	inspired by Gampfer (2014)	Two players distribute the costs of mitigation - a proposer makes an offer that a Responder has to accept or not. Each player starts with a wealth and an historical responsibility (depending on the treatment, these features are chosen by the players or exogenously set)	not mentioned	Online on the software NodeGame after recruitment via AMT (showup fee of 1 USD + results of the game), if 4 participants were connected at the same time	citizens	Not explicitly mentioned, but the sample is compared to the US population	414	Recruitment via AMT, an online crowd-sourcing platform	Weighted to ensure representativeness of the results	- participants paid more attention to other players' capacity and historical responsibility when proposing a particular cost allocation and more attention to their own capacity and responsibility when responding to proposals by others

Ref	Type	Year	Survey	Observed features	Length of survey	Administration	Targeted group	Country	Sample size	Sampling strategy	Represe	Main result(s) (from the abstract)
Brick et Visser (2015)	Survey/Threshold public goods game	not mentioned	Coordination game	Test for evidence of strategically-motivated use of burden-sharing principles. There are 5 participants (each national to a different country), parties in the game are heterogeneous in terms of wealth, historical absolute emissions, per capita emissions, projected future emissions and vulnerability to climate change. Each one must select a preferred rule to share emissions cuts (each translating into different obligations for the countries). There are two treatments: players either represent their country, or are randomly assigned a country after playing.	not mentioned	Login for an internet questionnaire sent via e-mail, answers: online/e-mail/postal mail (with participation fees + earnings of the game)	students and people involved in international climate policy	US, EU, India, South Africa, China	Students: 255 (51 of each nationality) Practitioners: 70 (14 of each nationality)	Students: Recruitment via advertisements diffused differently on the universities (NYU, LSE, Peking University, UCT, Jadvapur), the first 51 respondents were kept in order to equalize the number of participants from each country. Practitioners: recruited via direct emailing from a database compiled using online attendance lists to IPCC and UNFCCC workshops and meetings.	No	- the use of the historical and future polluter-pays rules by American and Chinese participants is consistent with a self-interested use of burden-sharing principles
Gampfer (2014)	Ultimatum game	2012-2013	/	Two players distribute the costs of mitigation - a Proposer makes an offer that a Responder has to accept or not. Treatment conditions vary players' ability to pay, vulnerability, and historical responsibility (4 treatment groups + a control)	not mentioned	In-person interactive lab experiments (payouts are determined by the game)	students	Nationality not detailed (study conducted in Switzerland)	234 for a first experiment, 135 for a second	Participants were recruited from the ORSEE Zurich pool, which contains predominantly students from Zurich universities	No	- Capacity strongly affects burden sharing (richer players ending up paying more). - Vulnerability differences reduce the influence of fairness, leading to suggested cost distributions more unfavorable to vulnerable players. Vulnerable responders still reject many "unfair" offers. - Differences in historical responsibility result in cost distributions strongly correlated with players' relative contributions to climate change

Ref	Type	Year	Survey	Observed features	Length of survey	Administration	Targeted group	Country	Sample size	Sampling strategy	Representativity	Main result(s) (from the abstract)
Dannenberg et al (2010)	Survey/ Game	2007 and 2009	inspired by Blanco et al (2008)	Measurement of advantageous or disadvantageous inequality aversion. Games neutrally framed as two persons sharing a pie. Questions about the perceived position of their country.	~30 min	Login for an internet questionnaire sent via e-mail (expected gain 8 USD per participant)	people involved in international climate policy	Worldwide	155 participants (69 consistent in both games)	Direct emailing (around 2000 addresses taken from official UN documents e.g. workshops)	Good representativity of the UN participants' nationalities	<ul style="list-style-type: none"> - participants show an aversion to advantageous inequality to a considerable extent while the aversion to disadvantageous inequality is moderate - no significant differences in the degree of inequality aversion between different regions in the world - regional differences in addressing climate change are driven more by national interests than by different equity concerns.
Cai et al (2010)	Survey	2001	Existing extensive climate survey	Attitudes towards equity rules, and stated adherence to different policy options (from which a WTP for mitigation is obtained)	not mentioned	Online	students	Nationality not detailed (students recruited in the USA and Canada)	1770	Respondents were recruited by 114 different instructors from classes at 92 different colleges and universities throughout the U.S. and Canada	Not mentioned	<ul style="list-style-type: none"> - WTP is higher when larger cost shares are borne by parties deemed to bear a greater responsibility for mitigation, and when respondents believe (and care) that the impacts of climate change may be borne disproportionately by the world's poor.

10 English questionnaire

Here, horizontal lines delimit elements displayed on the same page of the survey. An asterisk at the end of a question means that the proposed answers are randomized, and an “x” at the beginning, that answering is mandatory. Illustrative cases are randomized.

Climate justice survey

There are 41 questions in this survey.

This survey is conducted for scientific research purposes. It aims at getting a better understanding of the judgment of citizens on the countries' effort regarding climate change action. There is no right or wrong answer. Your answers will be anonymous, and will be exclusively used for research purposes.

This survey is around fifteen minutes long. Many thanks in advance for your time and contribution.

x You are:

Please choose **only one** of the following:

- A man
- A woman

x What is your age?

Please choose **only one** of the following:

- Under 18
- 18-24
- 25-34
- 35-44
- 45-54
- 55-64
- 65+

x What is the annual income of your household?

Please choose **only one** of the following:

- Less than \$20,000
 - \$20,000 to \$39,999
 - \$40,000 to \$74,999
 - More than \$75,000
-

x Which State do you live in?

Please choose **only one** of the following:

- Alabama - AL
- Alaska - AK
- Arizona - AZ
- Arkansas - AR
- California - CA
- Colorado - CO
- Connecticut - CT
- Washington - DC
- Delaware - DE
- Florida - FL
- Georgia - GA
- Hawaii - HI
- Idaho - ID
- Illinois - IL
- Indiana - IN
- Iowa - IA
- Kansas - KS
- Kentucky - KY
- Louisiana - LA
- Maine - ME
- Maryland - MD
- Massachusetts - MA
- Michigan - MI
- Minnesota - MN
- Mississippi - MS
- Missouri - MO
- Montana - MT
- Nebraska - NE
- Nevada - NV
- New Hampshire - NH
- New Jersey - NJ
- New Mexico - NM
- New York - NY
- North Carolina - NC
- North Dakota - ND
- Ohio - OH
- Oklahoma - OK
- Oregon - OR
- Pennsylvania - PA
- Rhode Island - RI
- South Carolina - SC

- South Dakota - SD
- Tennessee - TN
- Texas - TX
- Utah - UT
- Vermont - VT
- Virginia - VA
- Washington - WA
- West Virginia - WV
- Wisconsin - WI
- Wyoming - WY
- Other - abroad

x Where do you mostly live?

Please choose **only one** of the following:

- In an urban area of a big city
- In a suburban area on the outskirts of a big city, or in a medium-sized city
- In a rural area or a small town

How often do you talk about climate change?

Please choose **only one** of the following:

- Several times a week
- Several times a month
- Several times a year
- Almost never

In your opinion, climate change...*

Please choose **only one** of the following:

- is not a reality
- is mainly due to natural climate variability
- is mainly due to human activity

**x in your opinion, which of the following contribute to global warming?
(Several answers possible) ***

Please choose **all** that apply:

- Carbon dioxide (CO₂)
- Methane (CH₄)
- Oxygen (O₂)
- Water vapor (H₂O)

- Nitrous oxide (N₂O)
- Particulate matter

x In your opinion, how would the effects of climate change be, if nothing was done to limit it?

Please choose **only one** of the following:

- Insignificant
- Small
- Significant
- Disastrous

x In which of these regions do you think climate change will have the worst consequences?

Please choose **only one** of the following:

- The European Union
- The USA
- Similar consequences in both regions

x In your opinion, in your country, which generations will be severely impacted by climate change? (Several answers possible)

Please choose **all** that apply:

- People born in the 1960s
 - People born in the 1990s
 - People born in the 2020s
 - People born in the 2050s
 - None of the above
-

Which of the following statements do you most agree with? *

Please choose **only one** of the following:

- Principles of climate justice should be settled at the international level, even if that may prevent countries from pursuing the interest of their own people
- Principles of climate justice should never prevail over countries' own national interests, even if it may impede the fight against climate change

x Which of the following statements do you most agree with?

Please choose **only one** of the following:

- Countries share common but differentiated responsibilities. However, if I had to choose, I would consider that countries mostly hold common responsibilities, which means that **all countries, without exception, should act to limit climate change.**
- Countries share common but differentiated responsibilities. However, if I had to choose, I would consider that countries mostly hold differentiated responsibilities, which means that **some should make more efforts than others to combat climate change.**
- None of the above

x To what extent do you agree with the statement that countries which emitted a lot of carbon in the past have a right to continue emitting more than others in the future?

Please choose **only one** of the following:

- I strongly agree
- I rather agree
- I rather disagree
- I strongly disagree

x The countries' commitments are voluntary: countries are invited to submit targets for their own emission reduction plans. To what extent do you agree with each of the following statements? *

Please choose the appropriate response for each item:

	I strongly agree	I rather agree	I rather disagree	I strongly disagree
It would be fair that: countries which emitted less in the past commit to reduce their emissions less than other countries				
It would be fair that: all countries commit to converge to the same average of total emissions per inhabitant, compatible with a controlled climate change				
It would be fair that: all countries commit to reduce their emissions by a same proportion				
It would be fair that: poorer countries commit to reduce their emissions less than richer countries				
It would be fair that: countries where reducing emissions is more costly commit to reduce their emissions less than other countries				

In the following question, emissions refer to overall emissions from a country, not per capita emissions, and the commitments are measured as total emissions in the future

x Among the statements of the previous question, select the two you agree with the most* Please choose all that apply:

- It would be fair that countries which emitted less in the past commit to reduce their emissions less than other countries
- It would be fair that all countries commit to converge to the same average of total emissions per inhabitant, compatible with a controlled climate change
- It would be fair that all countries commit to reduce their emissions by a same proportion
- It would be fair that poorer countries commit to reduce their emissions less than richer countries
- It would be fair that countries where reducing emissions is more costly commit to reduce their emissions less than other countries

x To what extent do you agree with the following statements? *

Please choose the appropriate response for each item:

	I strongly agree	I rather agree	I rather disagree	I strongly disagree
It would be fair that: countries with forests that sequester large quantities of carbon commit to reduce their emissions less than other countries				
It would be fair that: the poorest countries do not commit to reduce their emissions now				
It would be fair that: countries that fund low-carbon projects in other countries commit to reduce their emissions less than others				
It would be fair that: rich countries that share their low-carbon technologies with others commit to reduce their emissions less than others				

x Which of the following statements do you most agree with? *

Please choose **only one** of the following:

- Countries should only be held accountable for the carbon emissions that occur on their territories
- Countries should be held accountable for the carbon emissions of all the products they consume, including the emissions of imported products that occur abroad

x Which of the following statements do you most agree with?

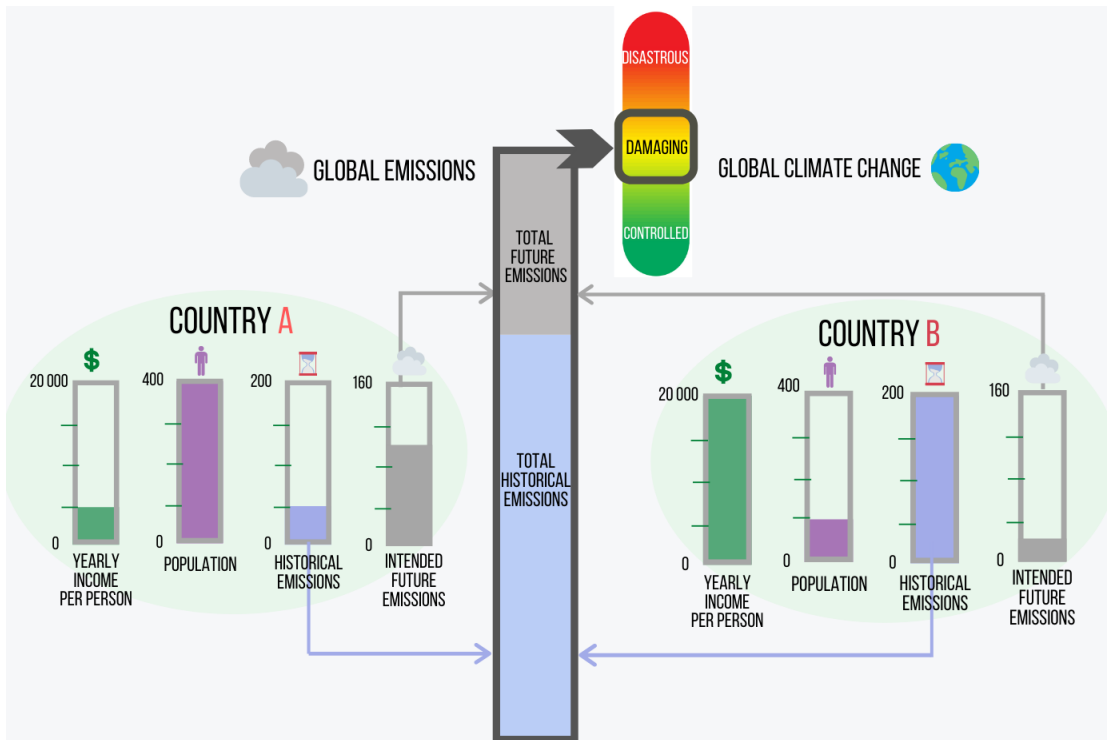
Please choose **only one** of the following:

- Countries should only be held accountable for their current emissions
- Countries should be held accountable for their historical emissions since 1990, when it was scientifically established that climate change was real and caused by human activities
- Countries should be held for their historical emissions since 1850, when humans started emitting large quantities of carbon in the atmosphere

x Let us consider a hypothetical world. Two countries, A and B, have both emitted carbon in the past (their "historical emissions"). In order to mitigate climate change, **global emissions should be significantly downsized.** A and B have expressed commitments for the future (their "intended future emissions"). The resulting level of climate change is displayed on the next figure.

Countries A and B are different in terms of population, yearly income per person, historical emissions and intended future emissions. They are similar in all other aspects.

This situation is represented here:

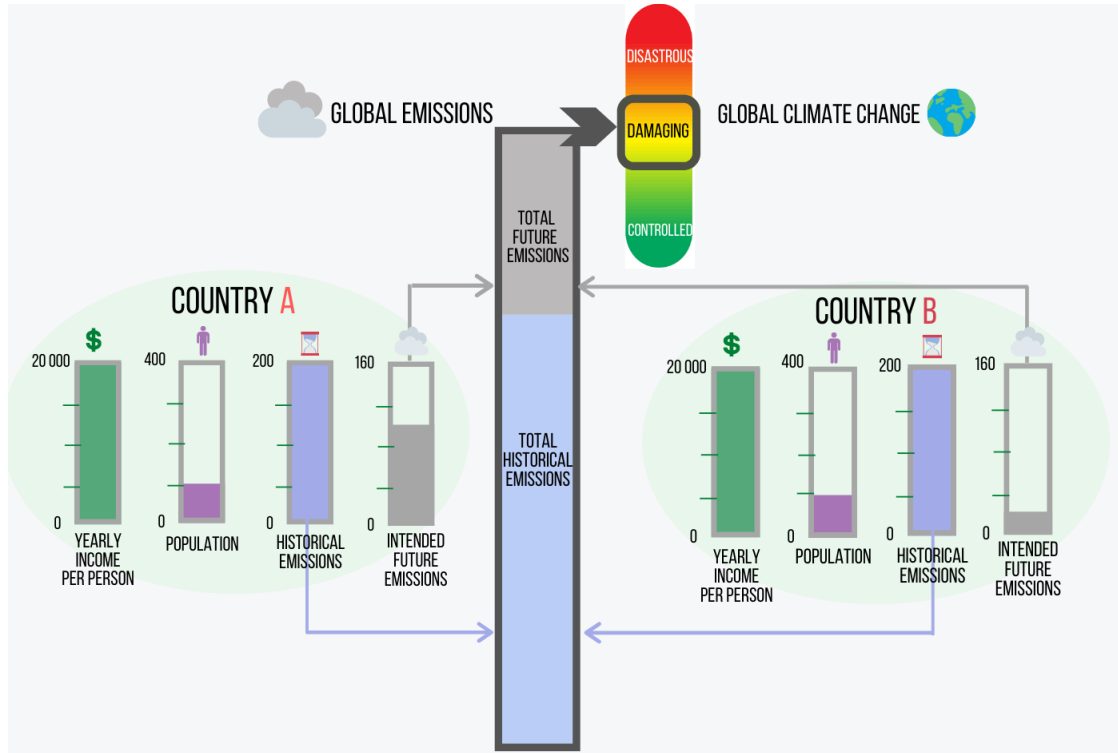


This sketch will be used to present different situations in the next questions. It is essential that you get a good sense of the situation: the following question is not a "trick question", but is rather intended to help you get familiar with the figure. **True or false?***

Please choose the appropriate response for each item:

	True	False
Country A has emitted more in the past than country B		
Country A will emit more in the future than country B		
The intended future emissions of countries A and B will be sufficiently low to avoid damaging climate change		
People in country A are poorer and more numerous than in country B		

x In this new situation, countries are different from one another in terms of intended future emissions only. Their combined emissions lead to damaging climate change.

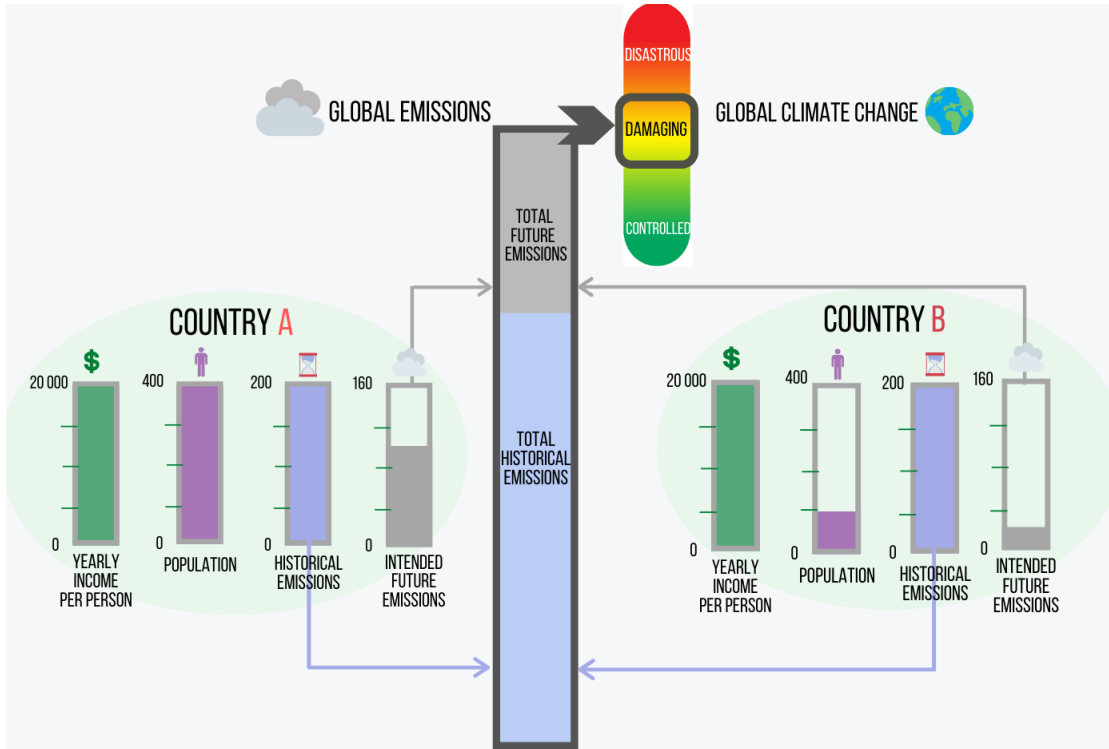


To what extent do you agree that each country is taking its fair share of the collective effort?

Please choose the appropriate response for each item:

	I strongly agree	I rather agree	I rather disagree	I strongly disagree
Country A				
Country B				

x In this new situation, countries are **different from one another in terms of intended future emissions and population only**. Their combined emissions lead to **damaging climate change**.

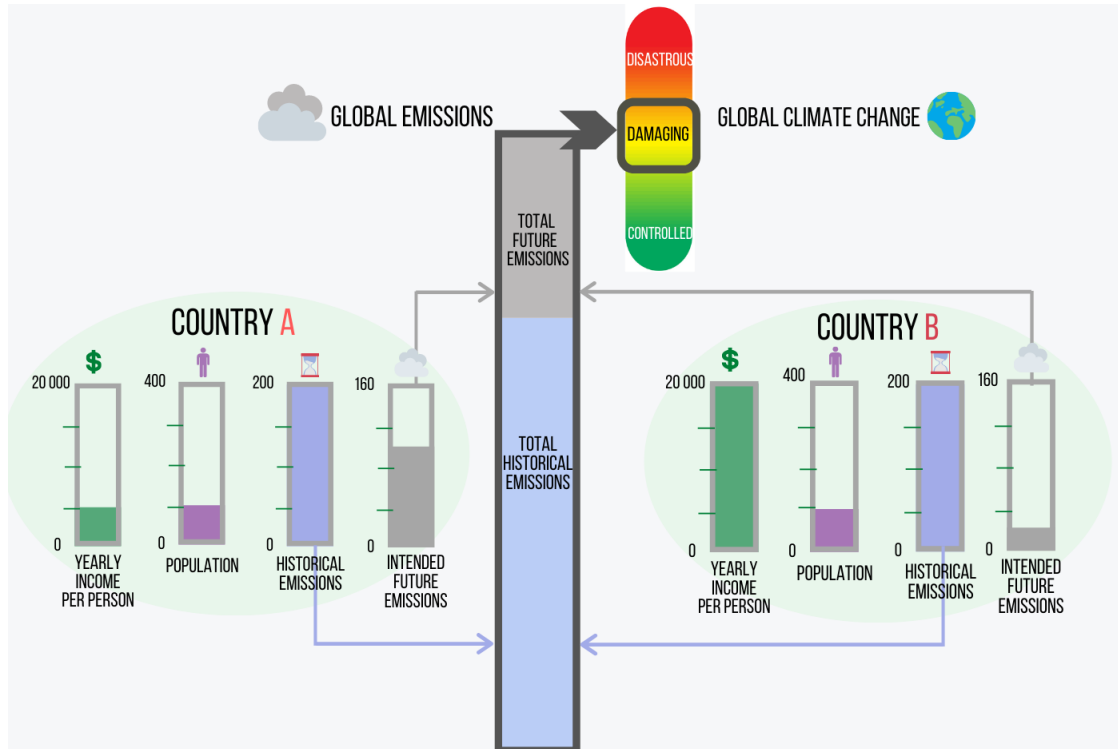


To what extent do you agree that each country is taking its fair share of the collective effort?

Please choose the appropriate response for each item:

	I strongly agree	I rather agree	I rather disagree	I strongly disagree
Country A				
Country B				

x In this new situation, countries are different from one another in terms of intended future emissions and wealth (yearly income per person) only. Their combined emissions lead to **damaging** climate change.

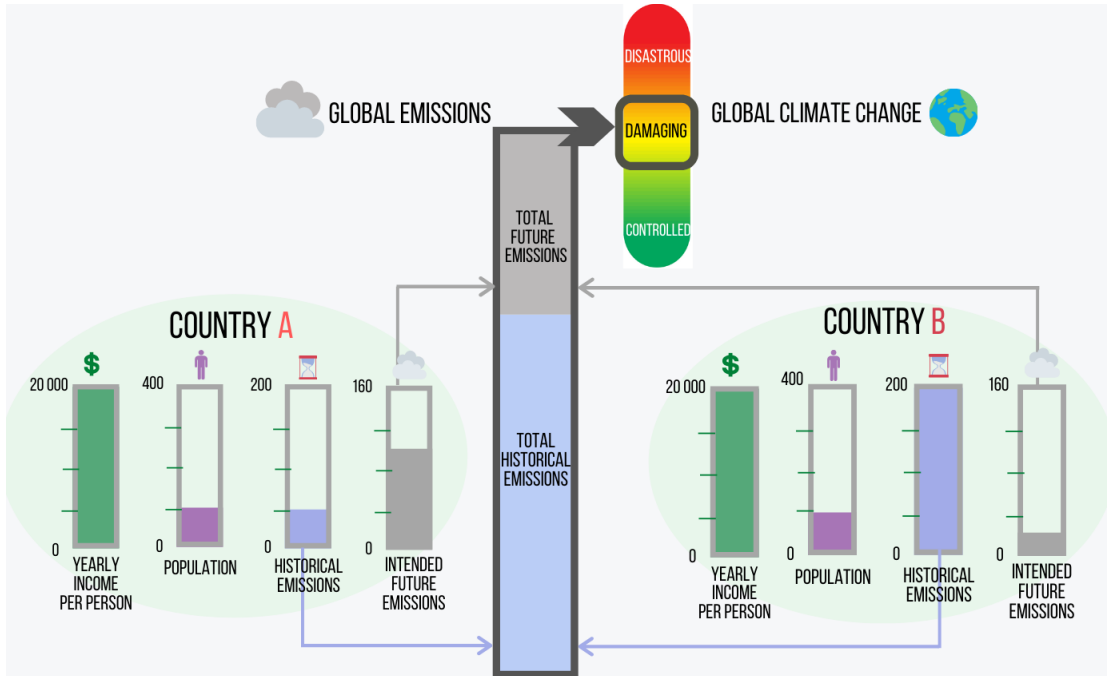


To what extent do you agree that each country is taking its fair share of the collective effort?

Please choose the appropriate response for each item:

	I strongly agree	I rather agree	I rather disagree	I strongly disagree
Country A				
Country B				

x In this new situation, countries are different from one another in terms of intended future emissions and historical emissions only. Their combined emissions lead to **damaging climate change**.

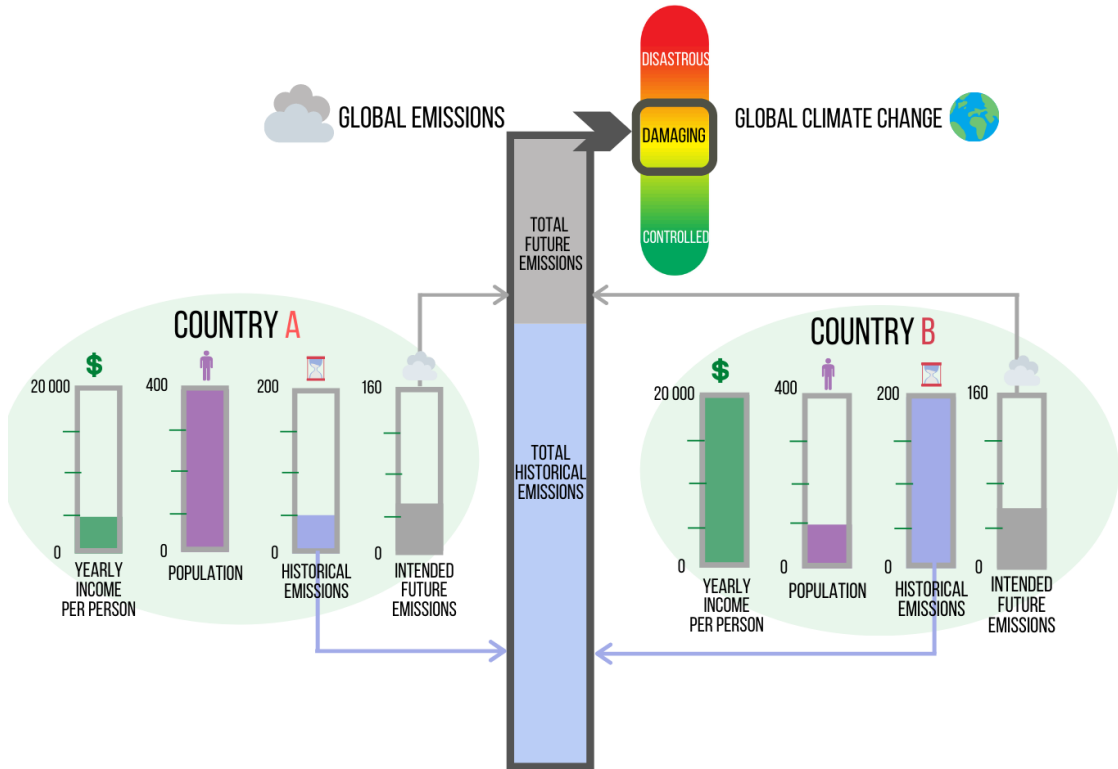


To what extent do you agree that each country is taking its fair share of the collective effort?

Please choose the appropriate response for each item:

	I strongly agree	I rather agree	I rather disagree	I strongly disagree
Country A				
Country B				

x In this new situation, countries are different from one another in terms of population, wealth and historical emissions. Their combined emissions lead to damaging climate change.

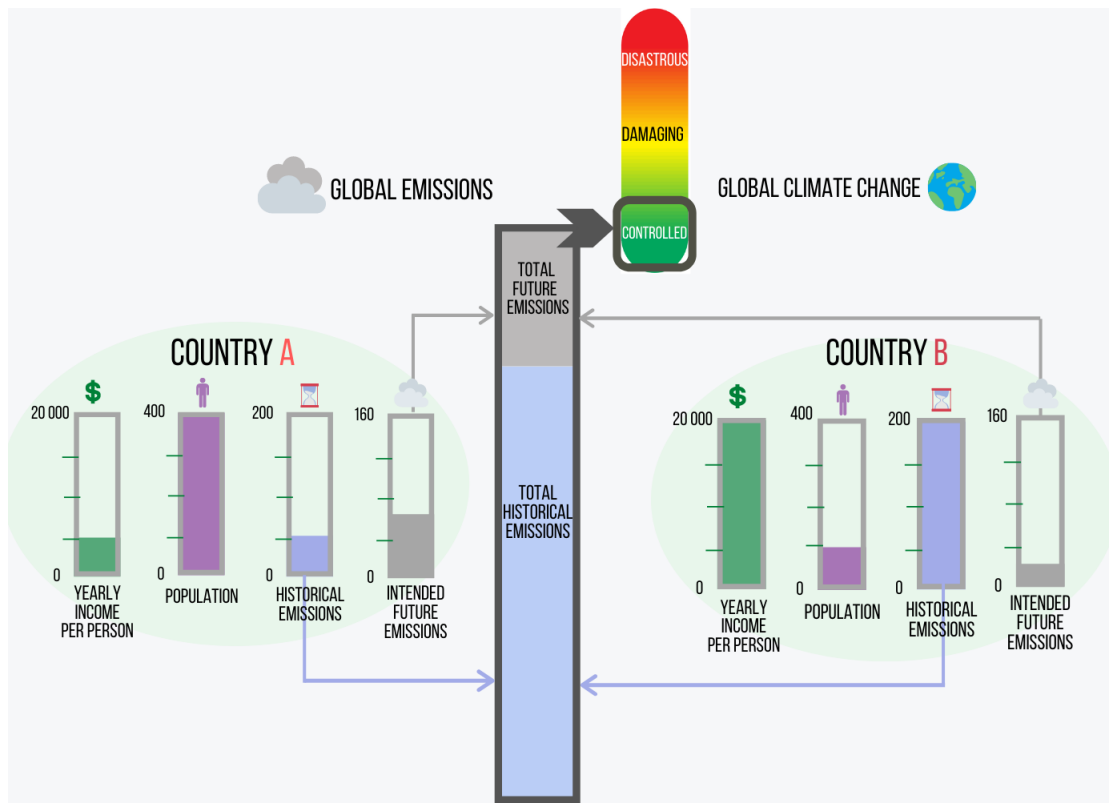


To what extent do you agree that each country is taking its fair share of the collective effort?

Please choose the appropriate response for each item:

	I strongly agree	I rather agree	I rather disagree	I strongly disagree
Country A				
Country B				

x In this new situation, countries are **different from one another on all aspects**. Their combined emissions lead to a **controlled climate change**.



To what extent do you agree that each country is taking its fair share of the collective effort?

Please choose the appropriate response for each item:

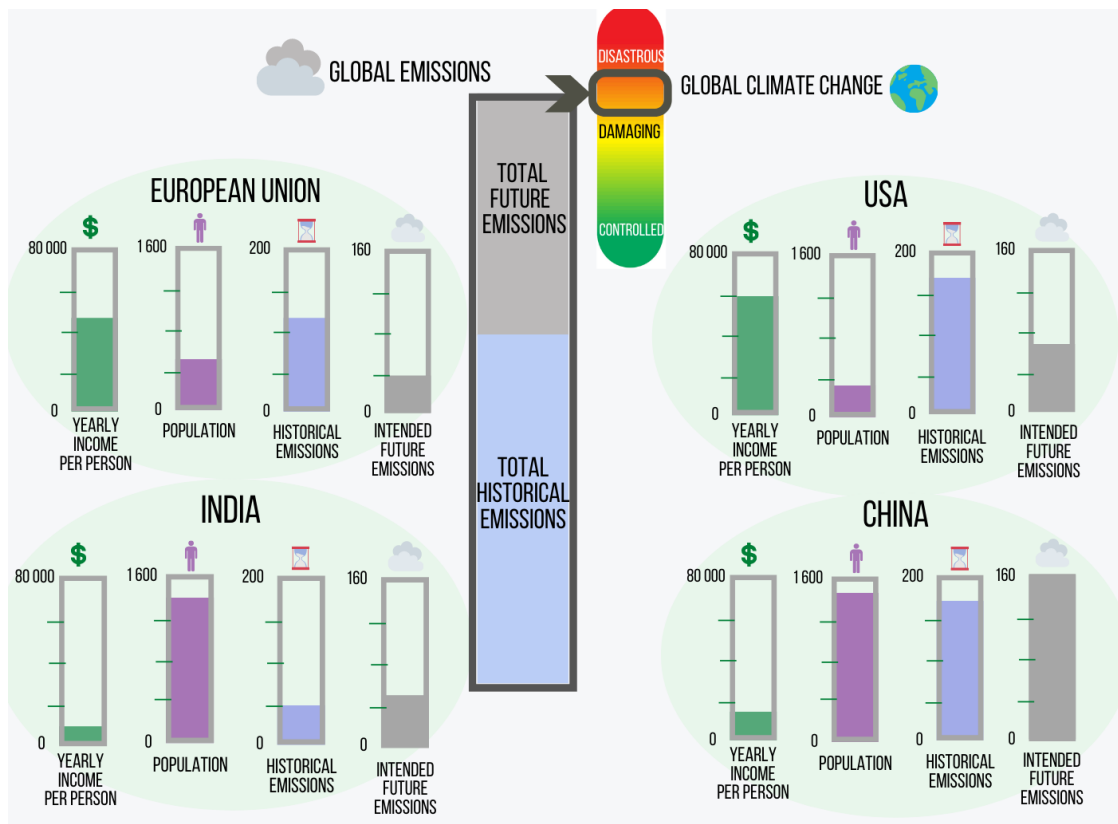
	I strongly agree	I rather agree	I rather disagree	I strongly disagree
Country A				
Country B				

x Let us consider the situation of a group of countries, including some of the World's largest emitters : **the USA, the EU, China, India**.

All these countries have signed the Paris Agreement (although the USA have given official notice of their intention to withdraw). Under the Agreement, the countries that have signed are required to submit **commitments for the future**.

However, the current commitments taken altogether fall short of achieving these objectives, and **will be insufficient to avoid damaging or disastrous climate change**.

The situation is represented here:

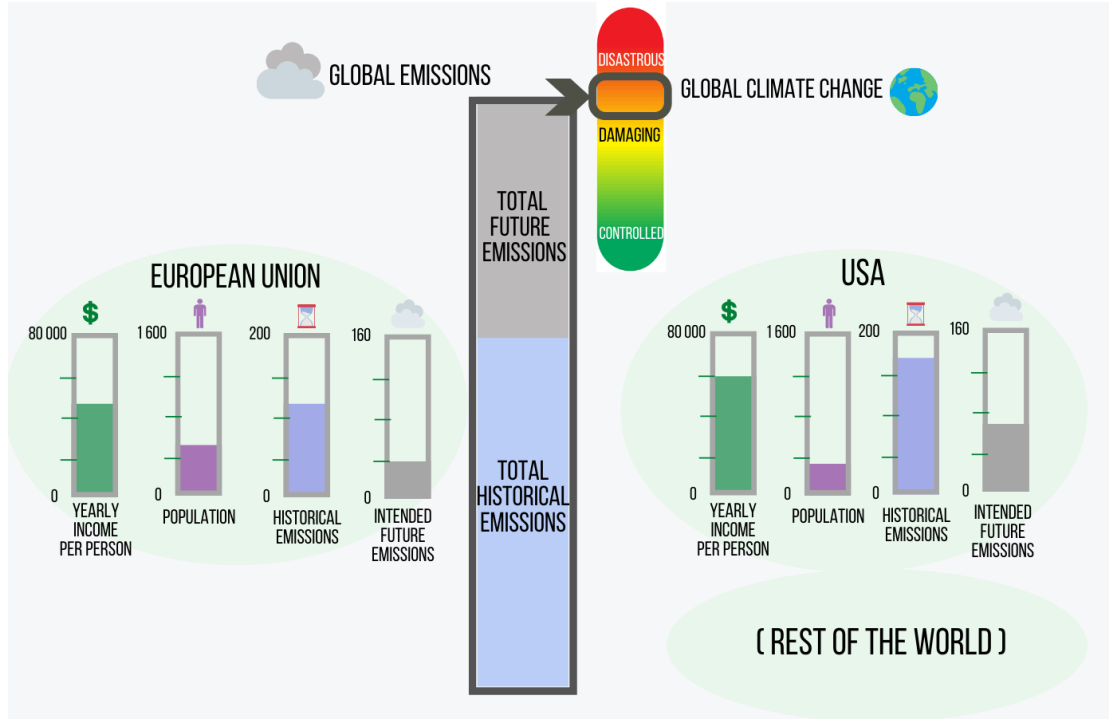


To what extent do you agree that each country is taking its fair share of the collective effort?

Please choose the appropriate response for each item:

	I strongly agree	I rather agree	I rather disagree	I strongly disagree
China				
India				
The European Union				
The USA				

x Imagine that you have to coordinate with someone living in Europe. This person also tries to answer the same as you do.



To what extent do you agree that each country is taking its fair share of the collective effort?*

At the end of the survey, your answer will be compared to that of a European respondent. Try to really imagine that the European respondent is also trying to answer the same as you do. Your common objective is to provide an identical answer. If your answers are the same, you will be successful and each receive a bonus reward of 25 LifePoints.

Please choose the appropriate response for each item:

	I strongly agree	I rather agree	I rather disagree	I strongly disagree
The European Union				
The USA				

x According to you, what are the chances that you successfully coordinated with the European respondent?

Please choose **only one** of the following:

- less than 1%
- 1 to 10%

- 11 to 49%
- 50 to 90%
- 90 to 99%
- more than 99%
- Other

x Did you feel you had all the necessary information to evaluate whether each country took their fair share?

Please choose **only one** of the following:

- Yes
- No
- I do not know

What useful information was lacking?

Please write your answer here:

x What is your highest degree?

Please choose **only one** of the following:

- High school completion or higher
- Associate degree or higher
- Bachelor degree or higher
- Master degree or higher
- Other/None of the above

x In which category does your occupation best fit?

Please choose **only one** of the following:

- Farmer
- Craftsman/merchant
- Large employer (10+ employees)
- Higher grade professional, administrative and managerial occupation (engineer, doctor, consultant, lawyer etc)
- Lower grade professional, administrative and managerial occupation, intermediate or teaching occupation
- Employee (office, service, sales and clerical occupation)
- Worker
- Retired
- Student
- Other (not employed)

If you have any comment about this survey and/or the fair share of countries in the global effort to tackle climate change, please mention it here.

Please write your answer here:

Thank you for your participation !

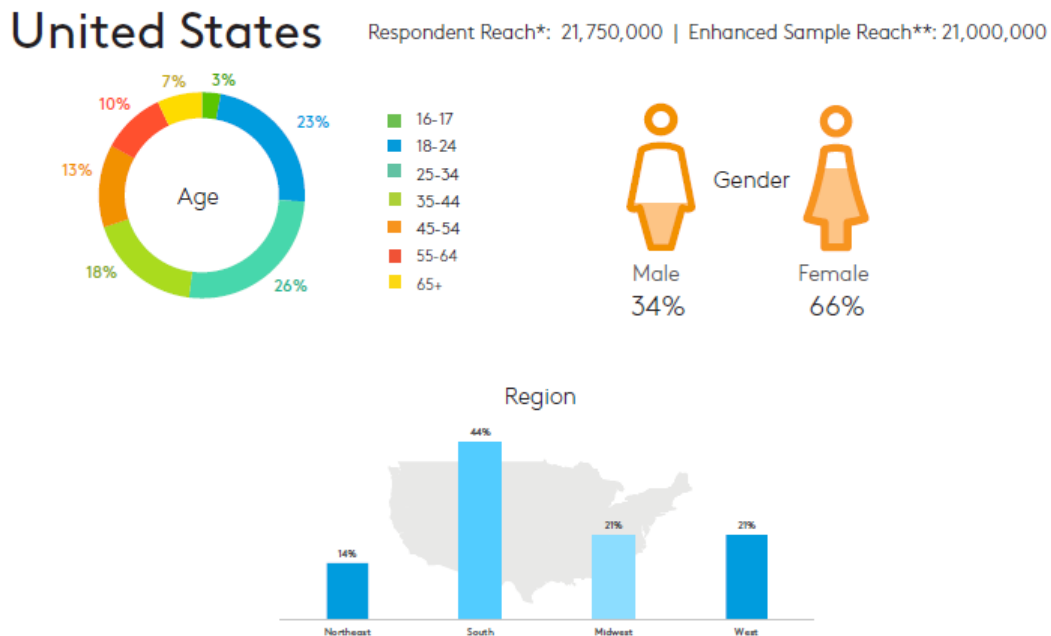
11 Samples and implementation

11.1 Lightspeed Research Panel characteristics

Lightspeed Research (Kantar) maintains representative panels in various countries, with respondents recruited by diverse methods and registered through a double opt-in process. Their identity is verified and duplicates are eliminated. The characteristics of the panels in France and in the United States are shown in Figures D.1 and D.2.

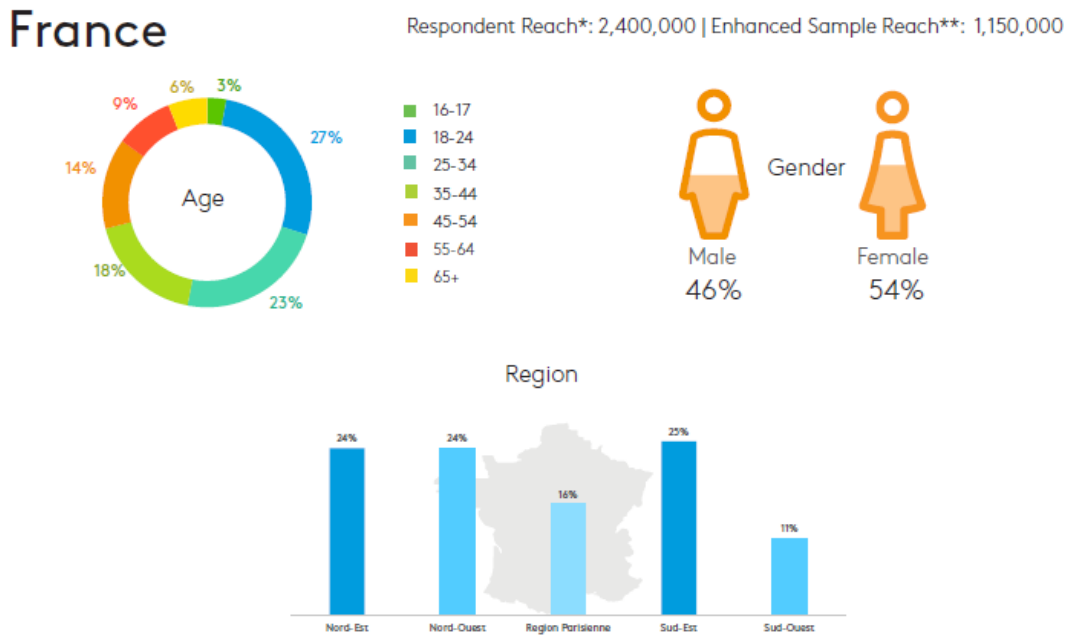
Invitations to answer the existing online survey are sent in an email with limited information on its subject. Respondents who choose to answer are paid in “LifePoints” depending on characteristics of the survey, such as its length, incidence rate or additional incentives. LifePoints can then be converted into gifts or cashed out (the value of LifePoints varies).

Figure D.1: Characteristics of Lightspeed Research’s US panel



11.2 Survey implementation

For our survey, for which the median time of completion was around 13m30 both in French and English, the reward was of around 2.2 euros for a complete answer. 127 French participants and 127 US participants, who successfully coordinated in the game, were listed and rewarded with an additional 25 LifePoints (around 0.4/0.5 euros) at the end of the study.

Figure D.2: Characteristics of Lightspeed Research’s French panel

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In order for the respondents who completed the survey to be representative of the French and US populations, screening questions were implemented in the survey code and quotas were monitored daily during the field work, for the following characteristics: gender, age (6 brackets), income (4 in the US, 5 in France), region (5 in France, 4 in the US) and agglomeration category (5 in France, 3 in the US). The reference quotas for representativity are displayed in Tables D.1 and D.2 with the proportions obtained in the study.

Although quotas were set loose at the end of the survey, the tables show that our final population is still very representative in both countries. Indeed, in the US survey, there are no significant differences between the distributions of any of the characteristics and the real proportions of the population. In France, the only significant difference is for the agglomeration category quota. This difference might be the result of mistakes of respondents when answering the question, more than a real difference in representativity. Indeed, many mistakes were noticed among people who lived in the “agglomeration of Paris” but rather chose the answer corresponding to the size of their city. Because of this, we chose not to correct the differences by weighting observations even on this criterion

Overall, respectively 2318 and 1838 respondents entered the French and US surveys, of which 1001 and 1004 provided a complete answer to the survey. The answers that were registered as incomplete represent people who abandoned the survey, people who

Table D.1: Representativity of the US respondents to the survey

	Quota	Number of respondents	Chi-test p-value
Income - Under \$ 20,000	140 (14%)	134	0.48
Income - \$ 20,000 to \$ 39,999	190 (19%)	204	
Income - \$ 40,000 to \$ 74,999	280 (28%)	303	
Income - over \$ 75,000	390 (39%)	363	
Gender - Men	500 (50%)	502	1
Gender - Women	500 (50%)	502	
Age - 18 to 24	120 (12%)	110	0.98
Age - 25 to 34	180 (18%)	187	
Age - 35 to 44	160 (16%)	167	
Age - 45 to 54	160 (16%)	163	
Age - 55 to 64	170 (17%)	175	
Age - over 65	200 (20%)	202	
Region - Midwest	220 (22%)	226	
Region - Northeast/Northwest	180 (18%)	182	
Region - South	370 (37%)	363	
Region - West	230 (23%)	233	
Agglo - rural/small	220 (22%)	225	0.97
Agglo - suburbs/medium	520 (52%)	521	
Agglo - urban/big	260 (26%)	258	

Differences between the respondents and official data for the US are tested using the Pearson chi-squared test. A P-value (against the null hypothesis of no difference) of $< 5\%$ is considered significant.

failed a speed quality check (we considered as incomplete the answers of respondents who went through the survey in under 6min) or people who belonged to an already-full quota category. In France, of the 1317 respondents who did not answer, 240 (18%) were eliminated because of their speed, 560 (43%) for quota reasons and 517 (39%) abandoned in the middle of the survey. In the US, of the 834 respondents who did not answer, 232 (28%) were eliminated because of their speed, 426 (51%) for quota reasons and 176 (21%) abandoned in the middle of the survey.

Table D.2: Representativity of the French respondents to the survey

	Quota	Number of respondents	Chi-test p-value
Income - Under 20,000 euros	240 (24%)	240	0.46
Income - 20,001 to 35,000 euros	280 (28%)	299	
Income - 35,001 to 50,000 euros	230 (23%)	233	
Income - 50,001 to 75,000 euros	150 (15%)	152	
Income - over 75,000	100 (10%)	77	
Gender - Men	500 (50%)	504	0.91
Gender - Women	500 (50%)	497	
Age - 18 to 24	110 (10%)	110	0.99
Age - 25 to 34	160 (16%)	164	
Age - 35 to 44	170 (17%)	169	
Age - 45 to 54	170 (17%)	175	
Age - 55 to 64	160 (16%)	162	
Age - over 65	220 (22%)	221	
Region - Ile-de-France	190 (19%)	197	
Region - Northeast	230 (23%)	230	
Region - Northwest	230 (23%)	233	
Region - Southeast	240 (24%)	237	
Region - Southwest	110 (11%)	104	
Agglo - Under 2 000	217 (21.7%)	223	2.10 - 16
Agglo - 2 000 to 19 999	309 (30.9%)	212	
Agglo - 000 to 99 999	172 (17.2%)	265	
Agglo - Over 100 000	139 (13.9%)	219	
Agglo - Aggl. Paris	157 (15.7%)	157	

Differences between the respondents and official data for France (INSEE) are tested using the Pearson chi-squared test. A P-value (against the null hypothesis of no difference) of < 5% is considered significant.

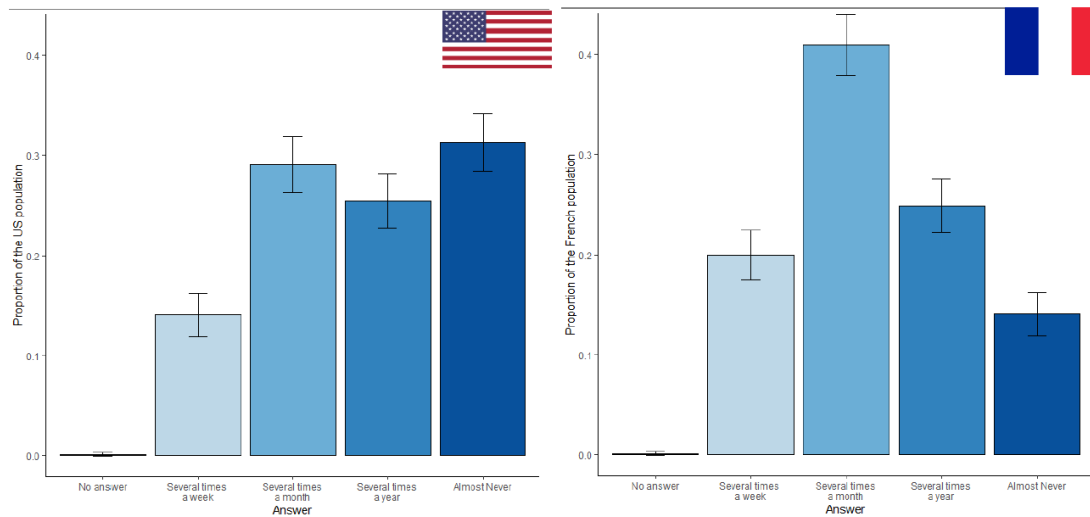
12 Descriptive results question by question

12.1 General beliefs and attitudes about climate change

Q.1 How often do you talk about climate change?

- Several times a week
- Several times a month
- Several times a year
- Almost never

Figure D.3: Distribution of answers to the question “How often do you talk about climate change ?” among the US (left) and French (right) populations



Error bars represent a confidence level over 95%.

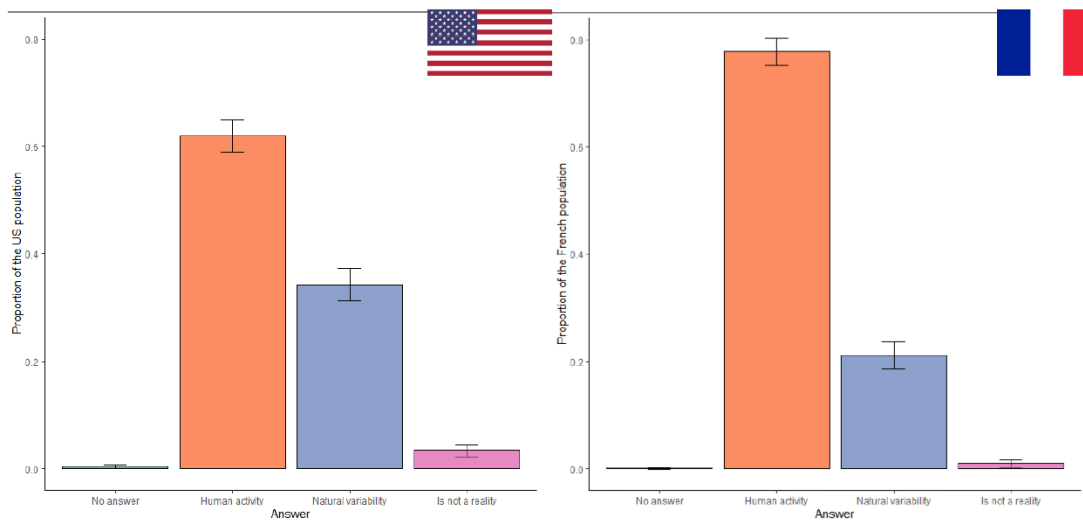
French respondents tend to talk about climate change more often than US respondents (more than 60% of French respondents declare talking about climate change several times a month or more, whereas only around 43% of the US respondents declare so)

In the US, around 31% of respondents declare that they almost never talk about climate change (only 14% of French respondents declare so).

Q.2 In your opinion, climate change...

- is not a reality
- is mainly due to natural climate variability [*label : Natural variability*]
- is mainly due to human activity [*label : Human activity*]

Figure D.4: Distribution of answers to question 2 among the US (left) and French (right) populations



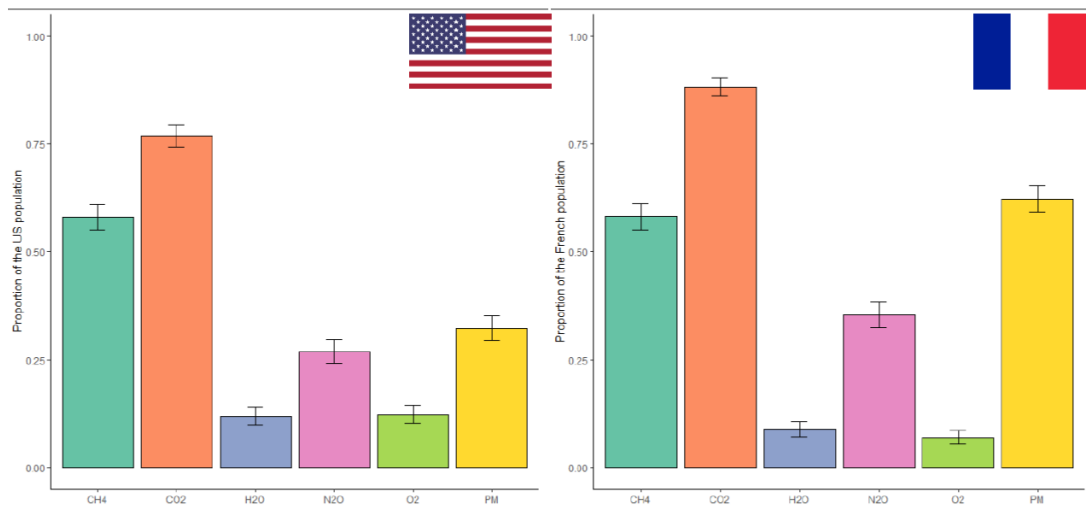
Error bars represent a confidence level over 95%.

Around 1% of French respondents and 3% of US respondents think that climate change is not a reality. In both countries, most respondents - respectively 62% and 78% of the US and French respondents - think that climate change is mainly caused by human activities (respectively 34% and 21% think its main causes are natural).

Q.3 in your opinion, which of the following contribute to global warming? (Several answers possible)

- Carbon dioxide (CO₂)
- Methane (CH₄)
- Oxygen (O₂)
- Water vapor (H₂O)
- Nitrous oxide (N₂O)
- Particulate matter [label : PM]

Figure D.5: Distribution of answers to question 3 among the US (left) and French (right) populations



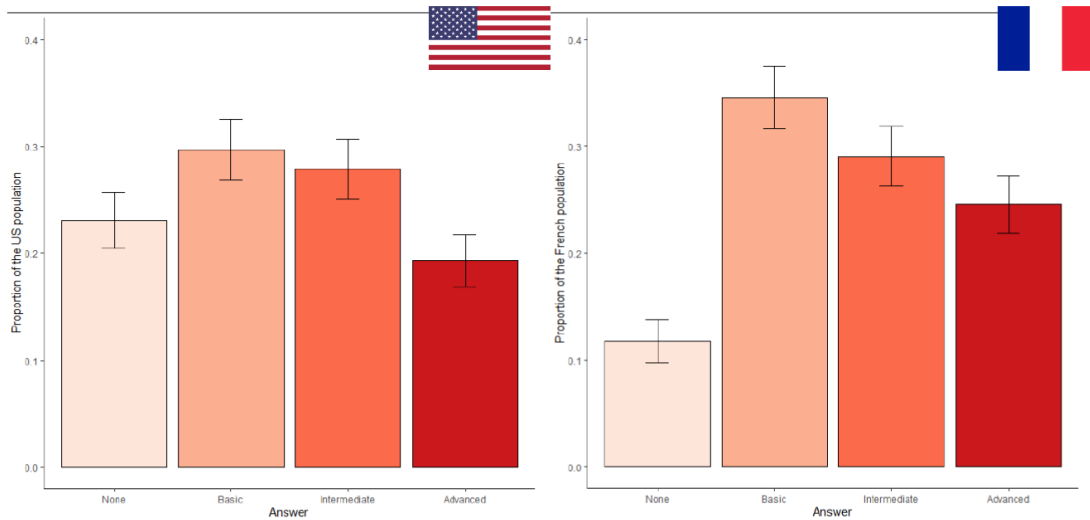
Error bars represent a confidence level over 95%.

Answers to Q.3 are recoded into a level of knowledge about climate change, as specified here :

- “Basic” knowledge : respondents who checked “Carbon Dioxide (CO₂)”
- “Intermediate” knowledge : respondents who checked “Carbon Dioxide (CO₂)” and “Methane (CH₄)”
- “Advanced” knowledge : respondents who checked “Carbon Dioxide (CO₂)”, “Methane (CH₄)” and “Nitrous oxide (N₂O)”
- “None” refers to respondents who did not mention any of these three greenhouse gases.

Whether “Water vapor (H₂O)”, “Oxygen (O₂)” or “Particulate matter” was checked by the respondents is not taken into account here.

Figure D.6: Distribution of the US (left) and French (right) respondents' knowledge about climate change, based on their answers to question 3



Error bars represent a confidence level over 95%.

Overall, most respondents know CO₂ to be a greenhouse gas (only around 23% of US respondents and 12% of French respondents do not have this “basic” knowledge). Around 47% of US respondents and more than 53% of French respondents can also cite CH₄; 19% of US respondents and 24% of French respondents add N₂O to the two previous gases.

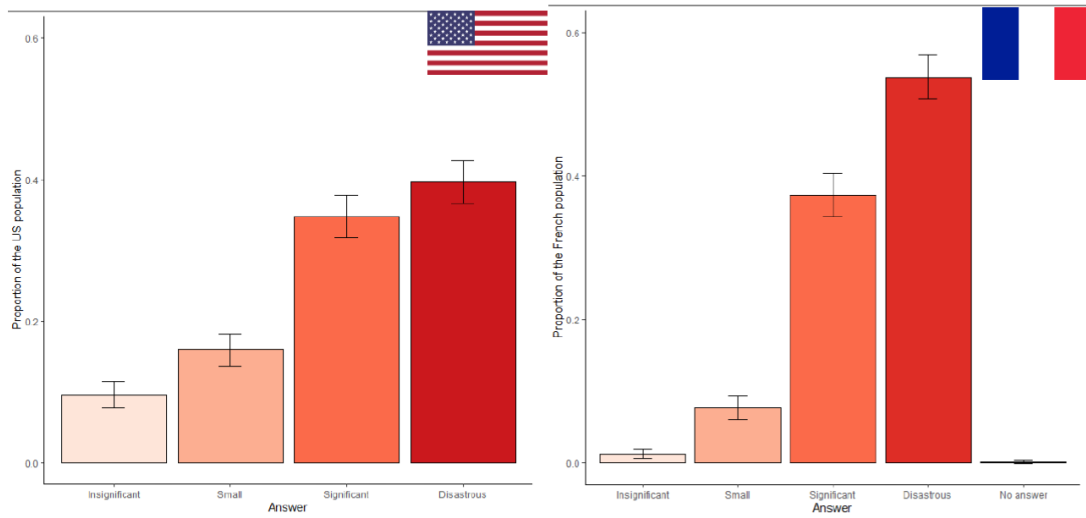
Most French respondents associate particulate matter with global warming (more than 60% of respondents, which is around the proportion of French respondents who cite CH₄ as a contributor). US respondents tend to not make this association as much (around 32% only).

Q.4 In your opinion, how would the effects of climate change be, if nothing was done to limit it?

- Insignificant
- Small
- Significant
- Disastrous

In both countries, most respondents think climate change will either have significant or disastrous effects - French respondents being more pessimistic than US respondents. Around 40% of US respondents (53% of French respondents) think the effects will be disastrous, and around 25% of US respondents (less than 10% of French respondents) think climate change will either have insignificant or small effects.

Figure D.7: Distribution of answers to question 4 among the US (left) and French (right) populations

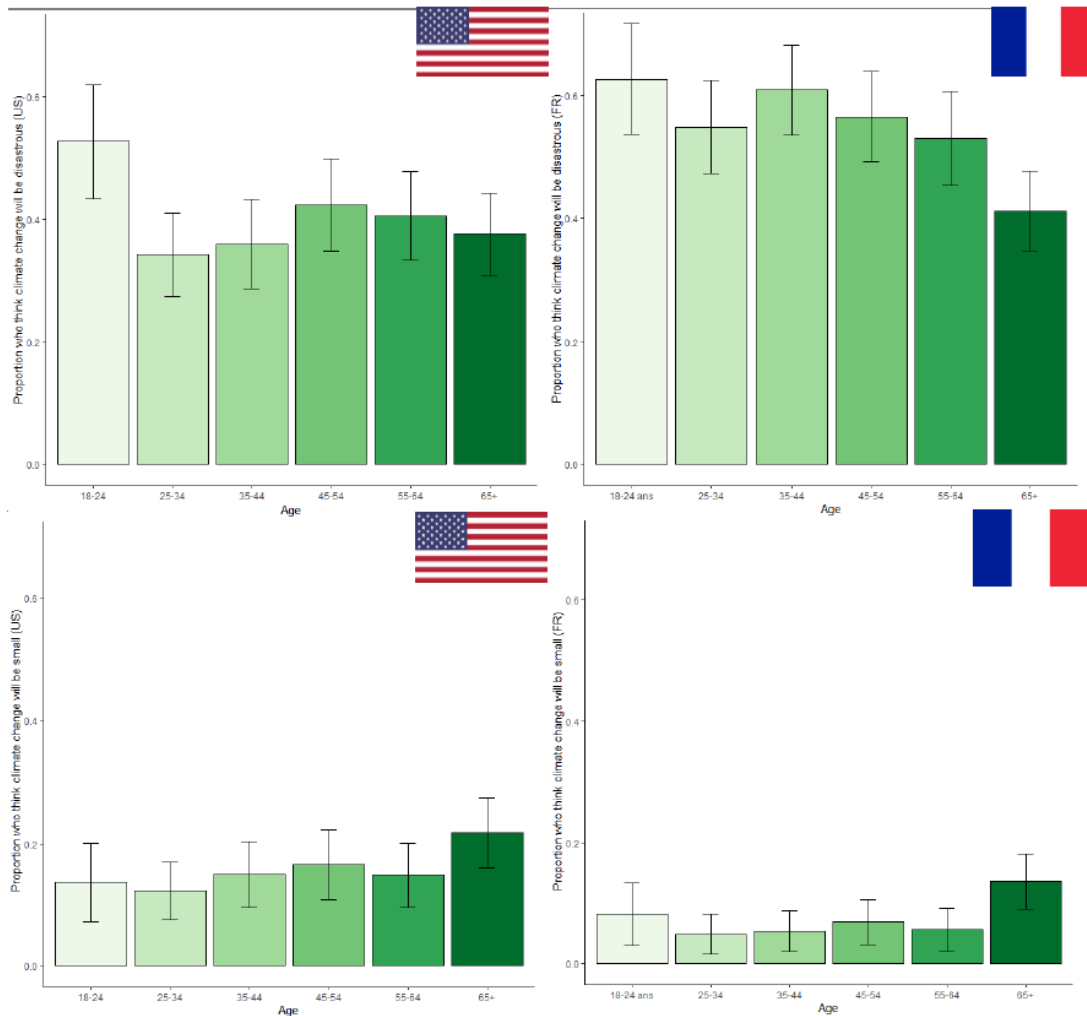


Error bars represent a confidence level over 95%.

In the US, the percentage of 18-24 year olds who think that climate change will have disastrous effects (around 53%) is higher than for some other age groups. In France, the percentage of respondents over 65 who think that climate change will have disastrous effects (around 41%) is lower than for some other age groups.

In both countries, the percentage of respondents over 65 who think that climate change will have small effects is higher than that for other age groups.

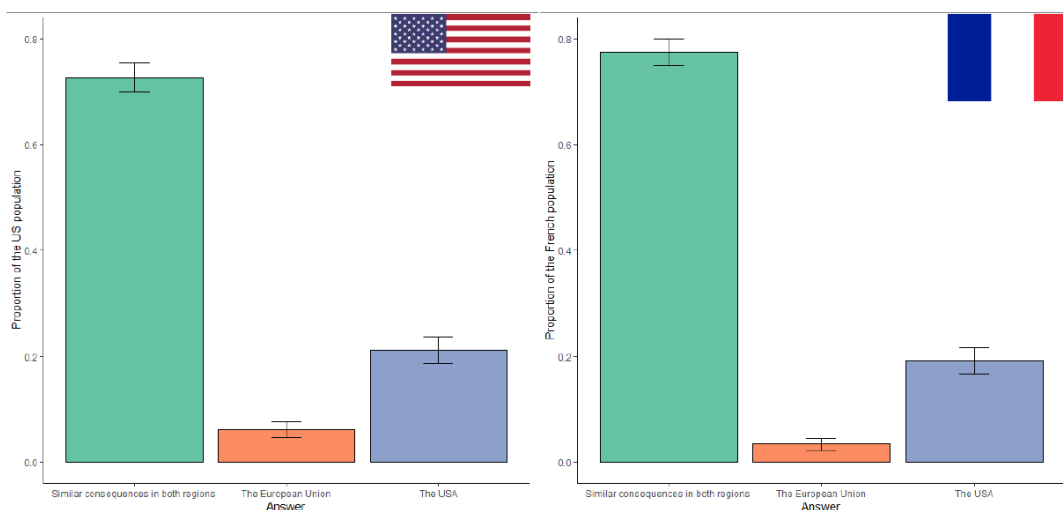
Figure D.8: proportion of US (left) and French (right) respondents who think climate change will have disastrous (top) or small (bottom) effects, by age category



Error bars represent a confidence level over 95%. Age and the answer to this question are correlated with a confidence level over 95% (the p-value for a chi-squared test is of respectively 0.012 and 0.045 for the US and France)

Q.5 In which of these regions do you think climate change will have the worst consequences?

- The European Union
- The USA
- Similar consequences in both regions

Figure D.9: Distribution of answers to question 5 among the US (left) and French (right) populations

Error bars represent a confidence level over 95%.

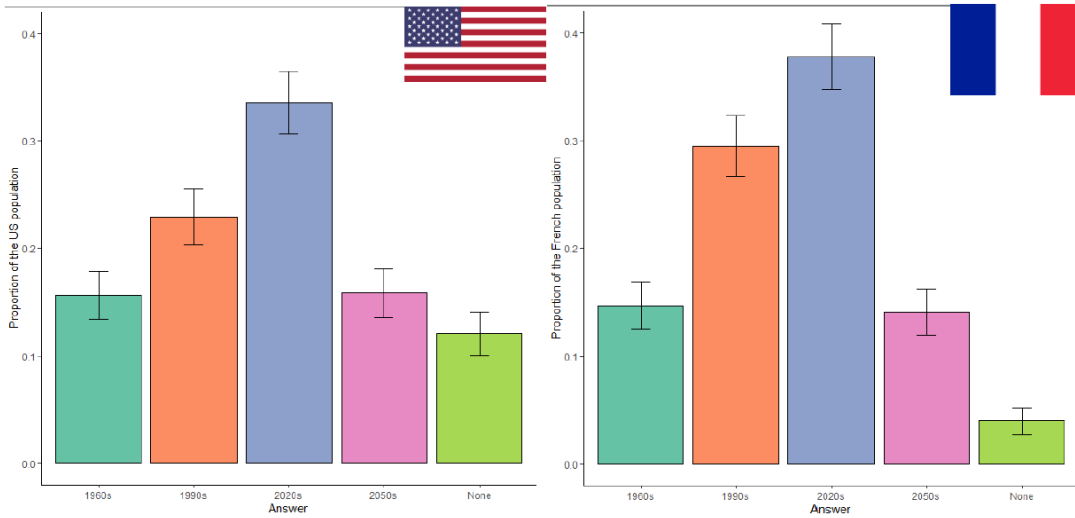
A major part of the respondents of both panels think that climate change will have similar consequences in the EU and in the USA (around 73% of US respondents and 77% of French respondents). The others tend to think the USA will be more affected (around 21% of US respondents and 19% of French respondents).

Q.6 In your opinion, in your country, which generations will be severely impacted by climate change? (Several answers possible)

- People born in the 1960s [*label: 1960s*]
- People born in the 1990s [*label: 1990s*]
- People born in the 2020s [*label: 2020s*]
- People born in the 2050s [*label: 2050s*]
- None of the above [*label: None*]

Although several answers are possible in this question, we will focus on the oldest generation affected according to each respondent (which corresponds to recoding the answers into the generation from which people will be affected).

To most respondents, the first generation affected by climate change will be that of people born in the 2020s (around 33% of US respondents, 38% of French respondents). More US respondents (around 12% for only 4% of French respondents) think that no generation will be affected - which is consistent with the fact that more US respondents (around 10%) think climate change will have insignificant or small effects.

Figure D.10: Distribution of answers to question 6 among the US (left) and French (right) populations

Error bars represent a confidence level over 95%.

Here, more than half of the respondents, in both countries, think that they will not be severely impacted by climate change themselves.

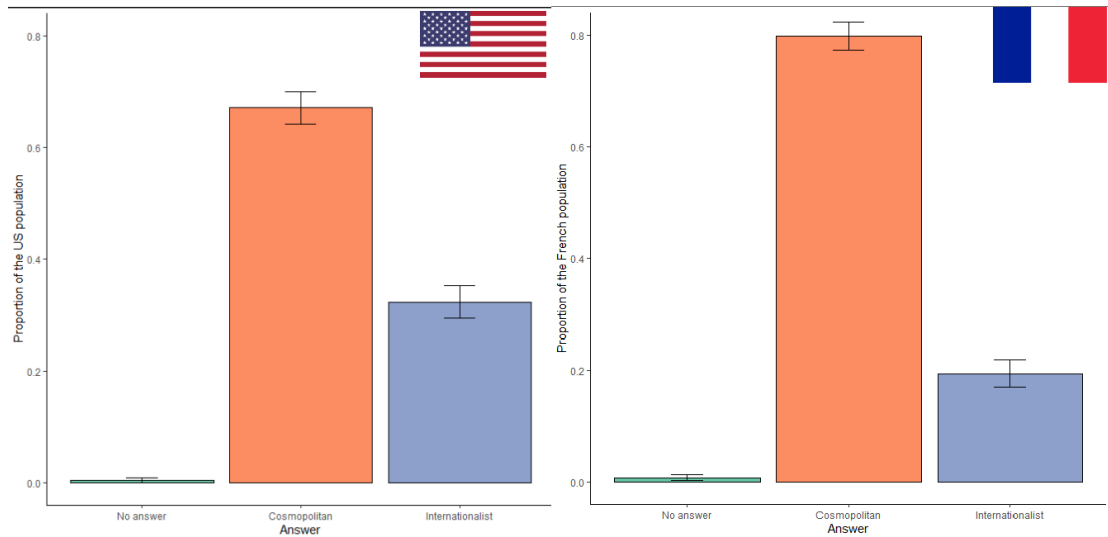
Q.7 Which of the following statements do you most agree with?

- Principles of climate justice should be settled at the international level, even if that may prevent countries from pursuing the interest of their own people [label: *Cosmopolitan*]
- Principles of climate justice should never prevail over countries' own national interests, even if it may impede the fight against climate change [label: *Internationalist*]
- Possibility not to answer

In both panels, most respondents think that principles of climate justice should be settled at the international level, even if that may prevent national States from pursuing the interest of their own people (around 67% of US respondents and 80% of French respondents).

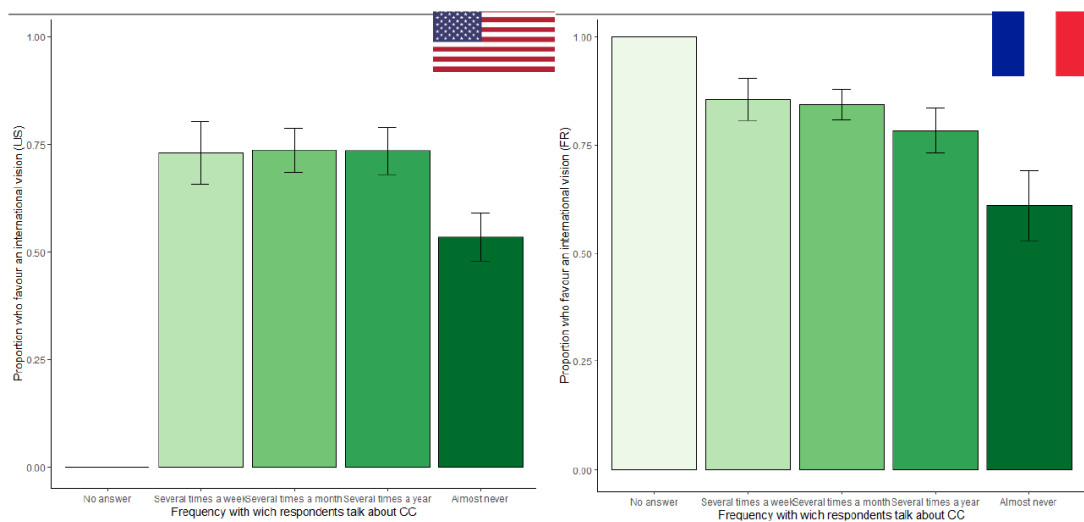
In both panels, respondents who almost never talk about climate change tend to less favour an international vision for climate equity. In both panels, respondents who think climate change will be disastrous or significant tend to also favour an international vision.

Figure D.11: Distribution of answers to question 7 among the US (left) and French (right) populations



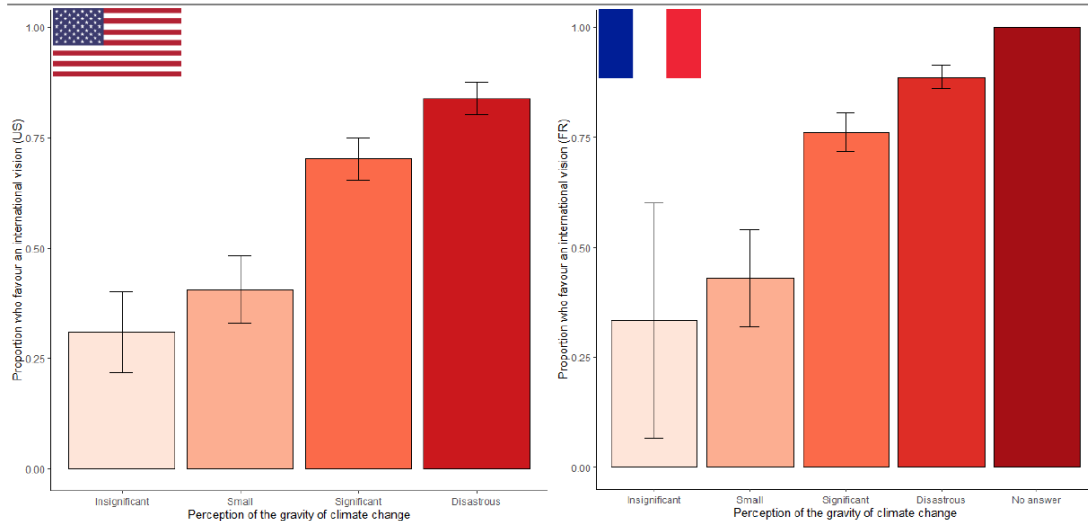
Error bars represent a confidence level over 95%.

Figure D.12: proportion of US (left) and French (right) respondents who think climate equity principles should be determined at the international level, by how frequently they talk about climate change



Error bars represent a confidence level over 95%. Frequency and the answer to this question are correlated with a confidence level over 95% (p-values of respectively 10^{-6} and 10^{-7} for the US and France)

Figure D.13: proportion of US (left) and French (right) respondents who favour an international vision for climate equity, by their perception of the gravity of climate change



Error bars represent a confidence level over 95%. Frequency and the answer to this question are correlated with a confidence level over 95% (p-values of respectively 10^{-33} and 10^{-22} for the US and France)

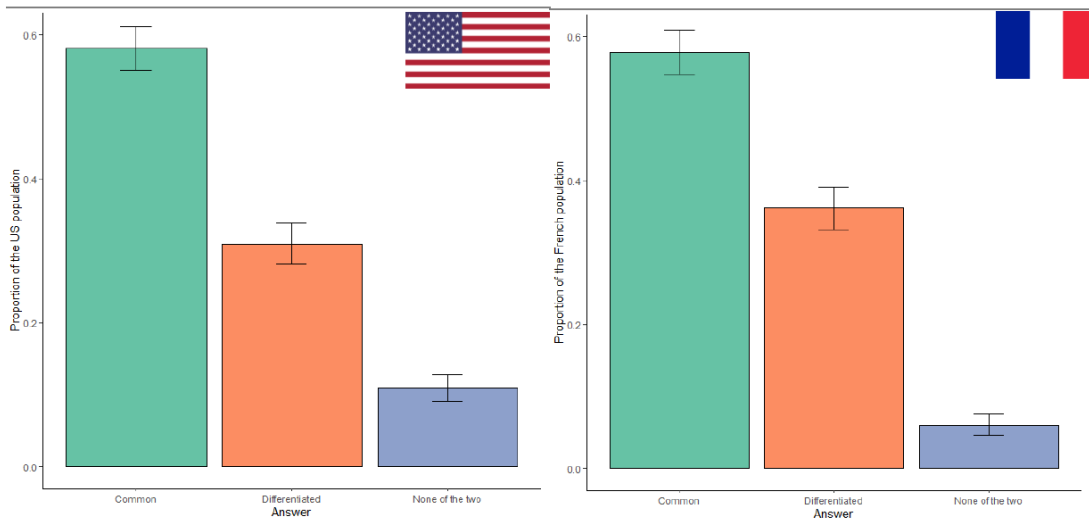
12.2 Adhesion to principles of climate justice

Q.8 Which of the following statements do you most agree with?

- Countries share common but differentiated responsibilities. However, if I had to choose, I would consider that countries mostly hold common responsibilities, which means that **all countries, without exception, should act to limit climate change.** [label: Common]
- Countries share common but differentiated responsibilities. However, if I had to choose, I would consider that countries mostly hold differentiated responsibilities, which means that **some should make more efforts than others to combat climate change.** [label: Differentiated]
- None of the above [label: None of the two]

In both countries, a clear preference is displayed for the common aspect of common but differentiated responsibilities, meaning that the respondents would insist on every country contributing to the fight against climate change rather than some countries doing more than others (around 58% of respondents for both countries).

Around 11% of US respondents and 6% of French respondents do not think countries share common but differentiated responsibilities.

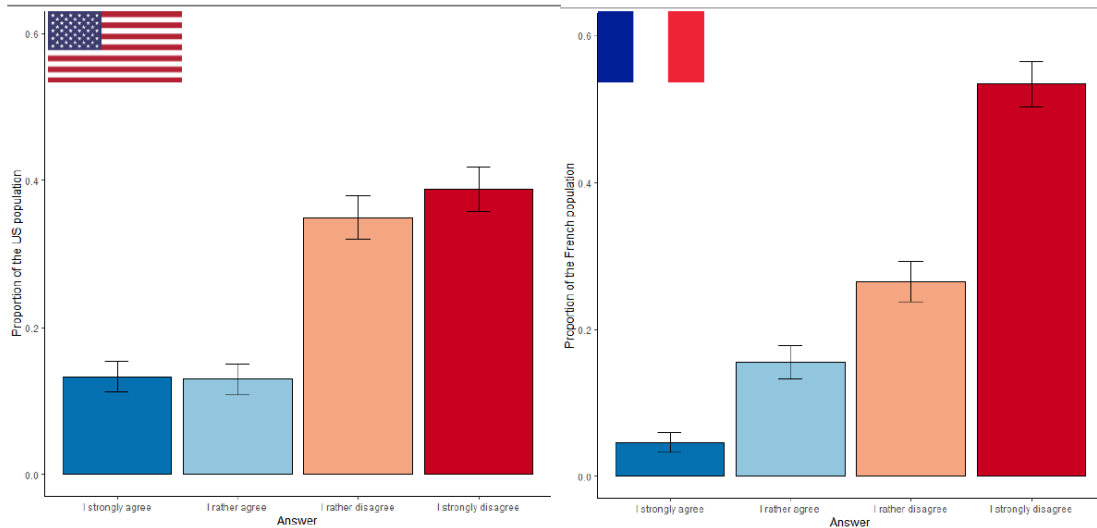
Figure D.14: Distribution of answers to question 8 among the US (left) and French (right) populations

Error bars represent a confidence level over 95%.

Q.9 To what extent do you agree with the statement that countries which emitted a lot of carbon in the past have a right to continue emitting more than others in the future?

- I strongly agree
- I rather agree
- I rather disagree
- I strongly disagree

In both countries, respondents show a disagreement with the underlying principle of grandfathering (which is the idea that countries that emitted a lot in the past have a right to continue emitting more in the future) with French respondents showing a stronger disagreement : around 73% of US respondents and 79% of French respondents rather disagree or strongly disagree with the statement, 39% of US respondents and 53% of French respondents strongly disagree.

Figure D.15: Distribution of answers to question 9 among the US (left) and French (right) populations

Error bars represent a confidence level over 95%.

Q.10 The countries' commitments are voluntary: countries are invited to submit targets for their own emission reduction plans. To what extent do you agree with each of the following statements?

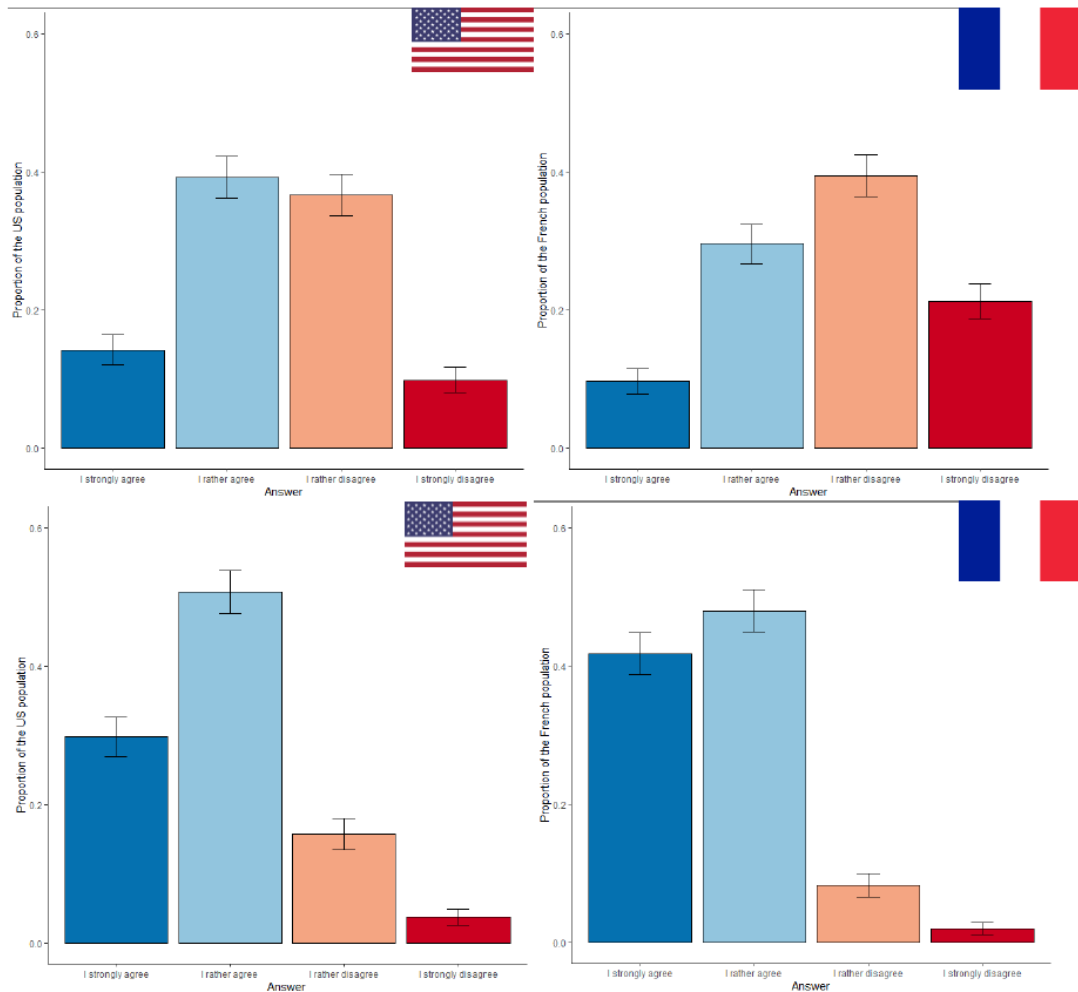
Answers in column:

- I strongly agree
- I rather agree
- I rather disagree
- I strongly disagree

Sub-questions in line:

- It would be fair that: countries which emitted less in the past commit to reduce their emissions less than other countries [*Q.10.a*]
- It would be fair that: all countries commit to converge to the same average of total emissions per inhabitant, compatible with a controlled climate change [*Q.10.b*]
- It would be fair that: all countries commit to reduce their emissions by a same proportion [*Q.10.c*]
- It would be fair that: poorer countries commit to reduce their emissions less than richer countries [*Q.10.d*]
- It would be fair that: countries where reducing emissions is more costly commit to reduce their emissions less than other countries [*Q.10.e*]

Figure D.16: Distribution of answers to questions 10.a (top) and 10.b (bottom) among the US (left) and French (right) populations

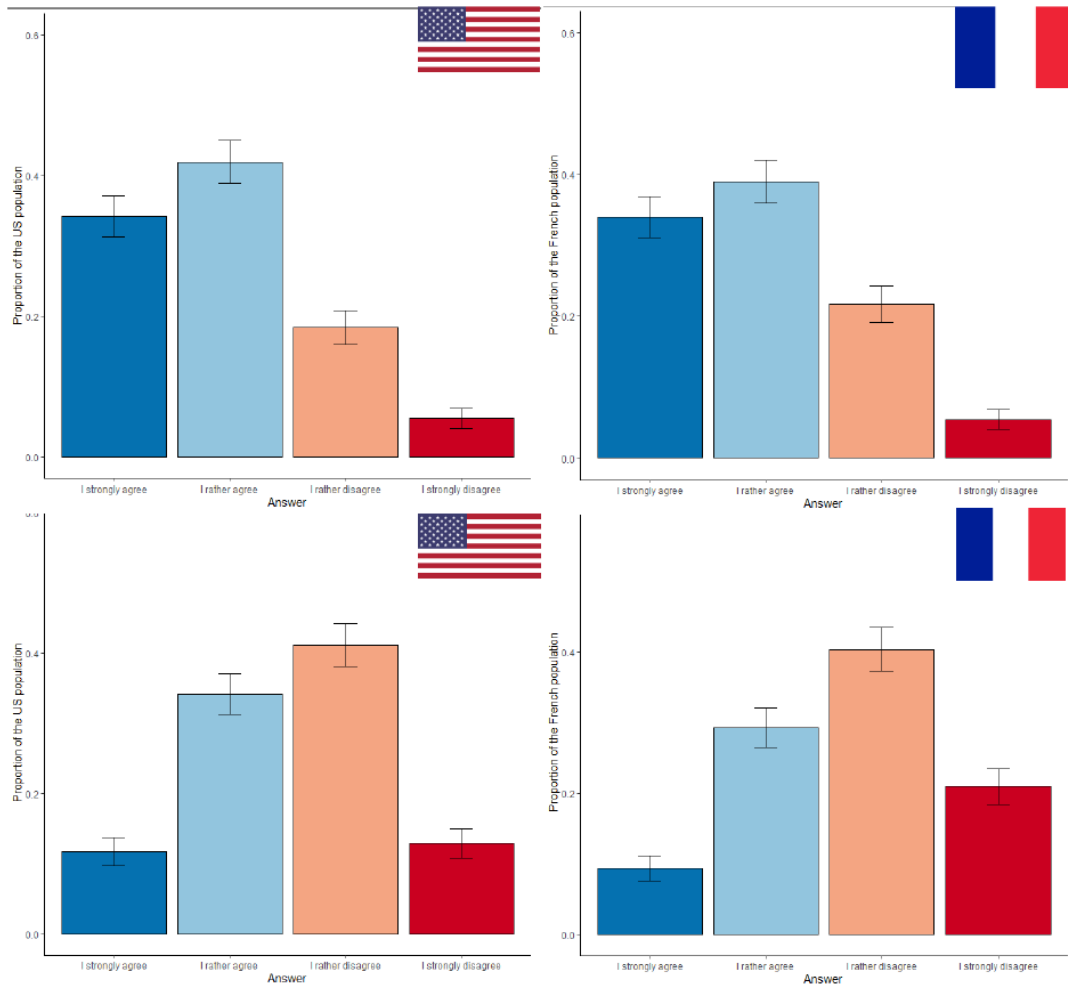


Error bars represent a confidence level over 95%.

Most of the US respondents (around 53%) rather or strongly agree that it would be fair that countries which emitted less in the past commit to reduce their emissions less than other countries. Most of the French respondents, however, disagree: only around 39% rather or strongly agree.

There is also strong adhesion to the fairness of a long-term convergence towards an equal per capita level of emissions: around 80% of US respondents and almost 90% of French respondents rather or strongly agree with the principle.

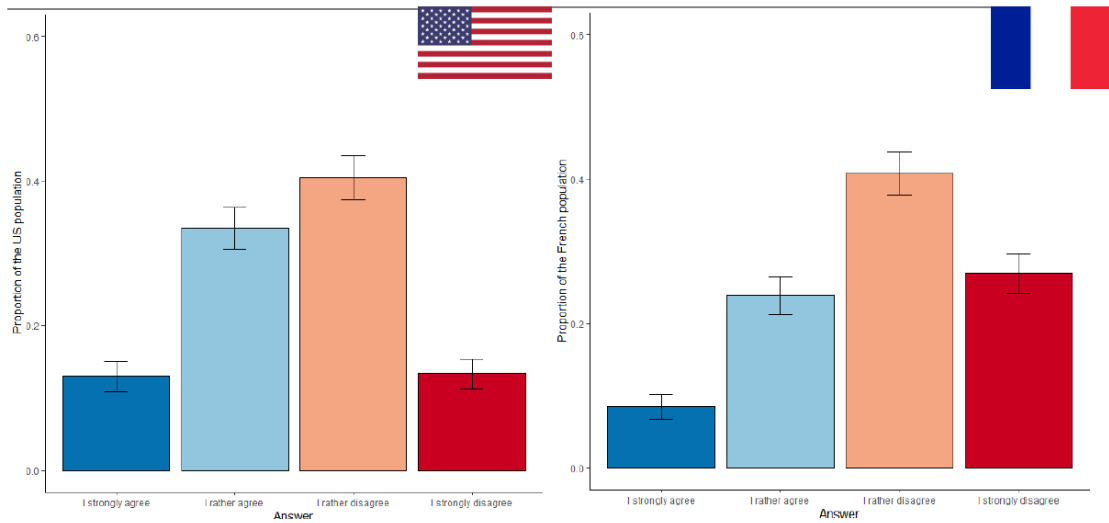
Figure D.17: Distribution of answers to questions 10.c (top) and 10.d (bottom) among the US (left) and French (right) populations



Error bars represent a confidence level over 95%.

In both countries, there is a strong agreement with the fairness of an operationalized grandfathering principle (in which all the countries would reduce their emissions by the same percentage): around 76% of US respondents and 73% of French respondents strongly agree or rather agree with the proposition.

In both countries, most of the respondents (around 54% for the US, 61% for France) rather or strongly disagree that it would be fair for poorer countries to less reduce their future emissions (with a stronger disagreement in the French panel as 21% of French respondents strongly disagree, for 13% of US respondents).

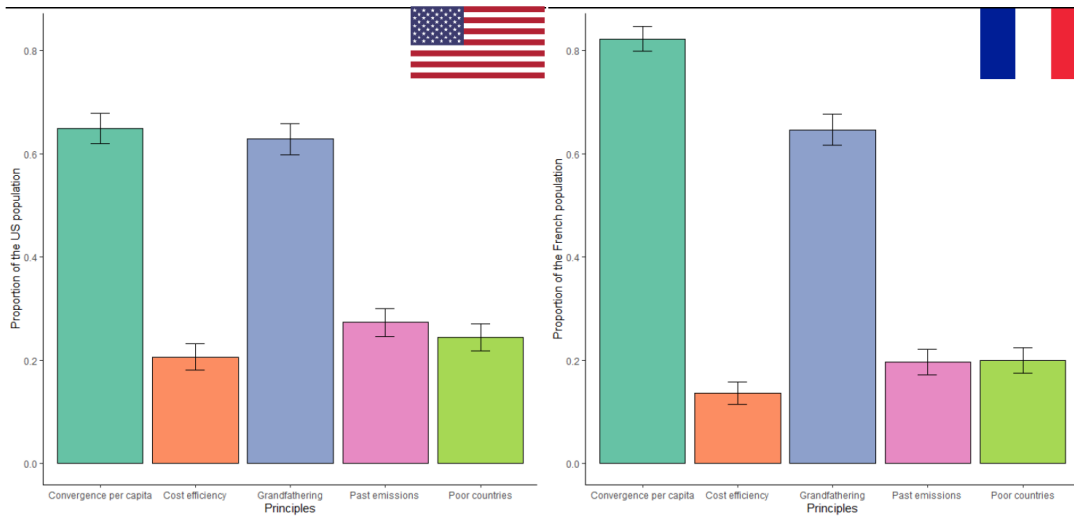
Figure D.18: Distribution of answers to question 10.d among the US (left) and French (right) populations

Error bars represent a confidence level over 95%.

In both countries, most of the respondents (around 53% for the US, 67% for France) rather or strongly disagree that it would be fair for countries where climate action is more costly to less reduce their future emissions (with a stronger disagreement in the French panel as around 27% of French respondents strongly disagree, for around 13% of US respondents)

Q.11 Among the statements of the previous question, select the two you agree with the most

When given a choice of two among the five proposed principles, both US and French respondents clearly tended to prioritize the operationalized version of grandfathering (63% of US respondents and 65% of French respondents) and a convergence towards equal per capita emissions (65% of US respondents and 82% of French respondents). Other principles did not get as much adhesion as no other principle was chosen by more than 30% of respondents.

Figure D.19: Distribution of answers to question 11 among the US (left) and French (right) populations

Error bars represent a confidence level over 95%.

Q.12 To what extent do you agree with the following statements?

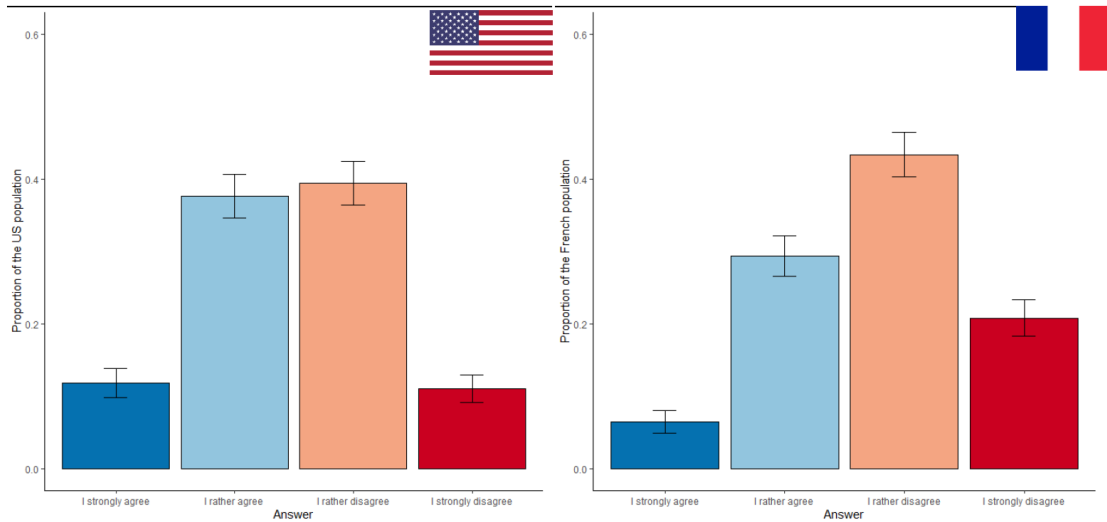
Answers in column:

- I strongly agree
- I rather agree
- I rather disagree
- I strongly disagree

Sub-questions in line:

- It would be fair that: countries with forests that sequester large quantities of carbon commit to reduce their emissions less than other countries [*Q.12.a*]
- It would be fair that: the poorest countries do not commit to reduce their emissions now [*Q.12.b*]
- It would be fair that: countries that fund low-carbon projects in other countries commit to reduce their emissions less than others [*Q.12.c*]
- It would be fair that: rich countries that share their low-carbon technologies with others commit to reduce their emissions less than others [*Q.12.d*]

Figure D.20: Distribution of answers to question 12.a among the US (left) and French (right) populations



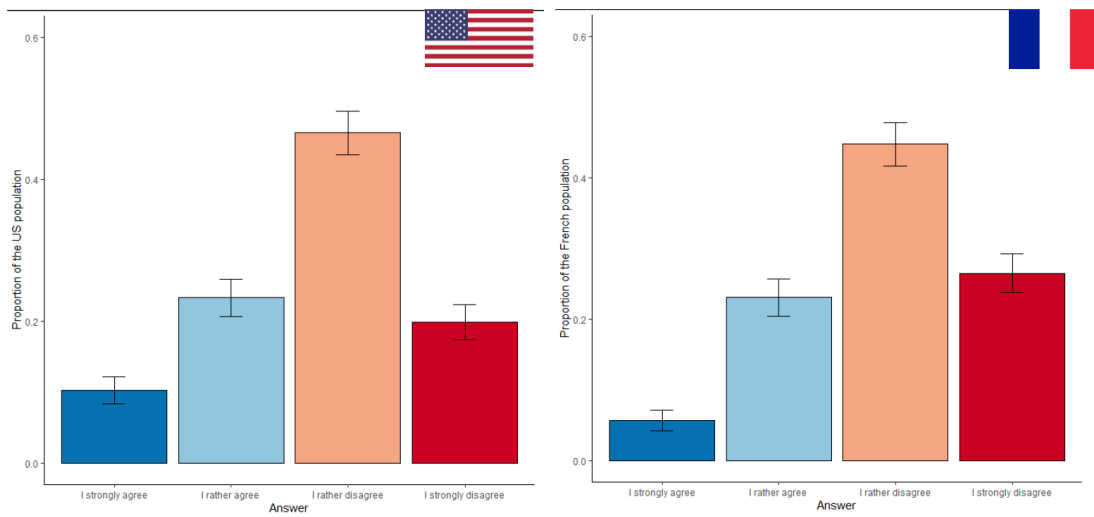
Error bars represent a confidence level over 95%.

While around 64% of French respondents rather or strongly agree that it would be fair for countries with forests sequestering carbon to less reduce their future emissions, there is roughly the same percentage of US respondents who agree and disagree with the principle.

In both countries, most of the respondents rather or strongly disagree with allowing the poorest countries to not immediately reduce their emissions (around 66% in the US and 71% in France), which seems consistent with the answer to question 10.c.

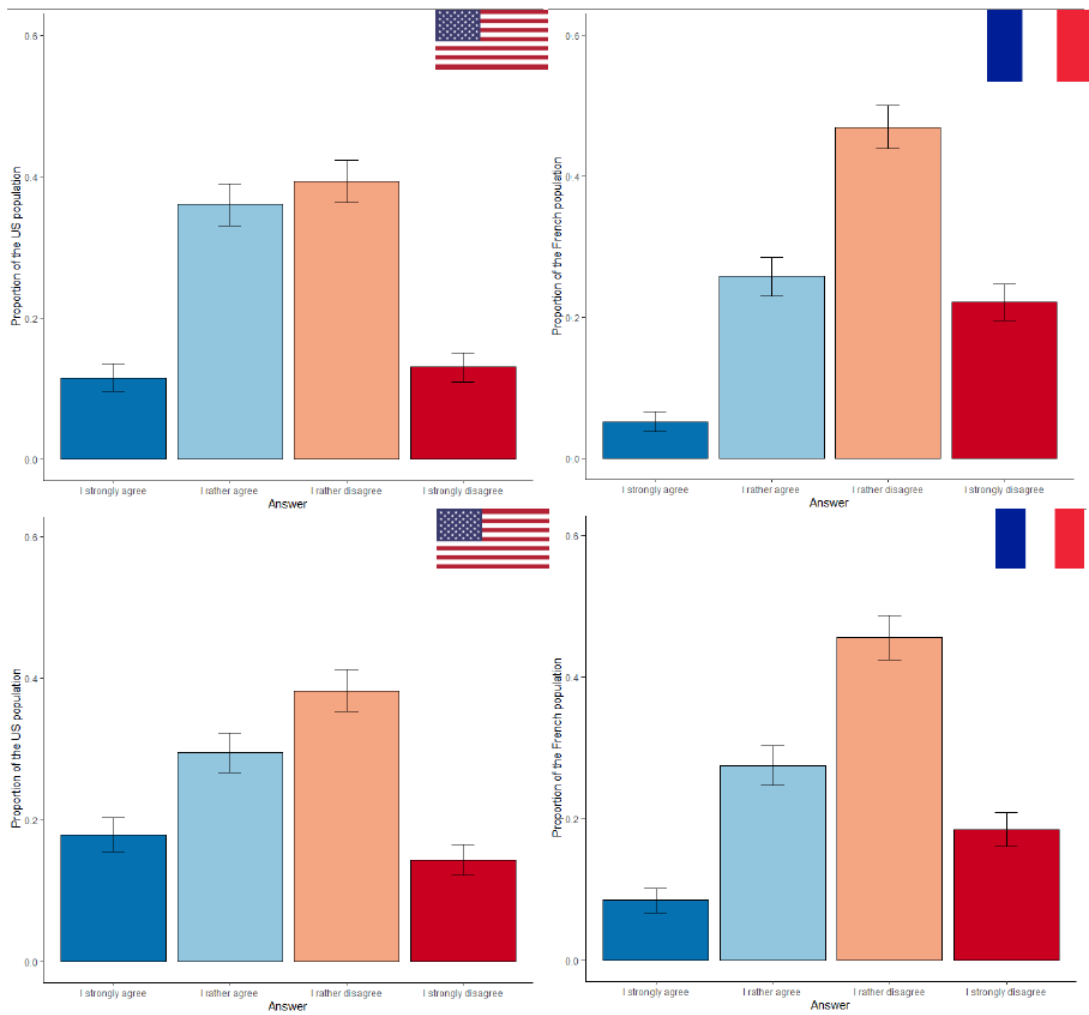
French respondents mostly disagree that it is fair if countries that fund low-carbon projects abroad or share their technologies reduce their future emissions less: for both principles, more than 64% of French respondents rather or strongly disagree. This result is less clear for US respondents with only around 52% of the respondents rather or strongly disagreeing with the principles.

Figure D.21: Distribution of answers to question 12.b among the US (left) and French (right) populations



Error bars represent a confidence level over 95%.

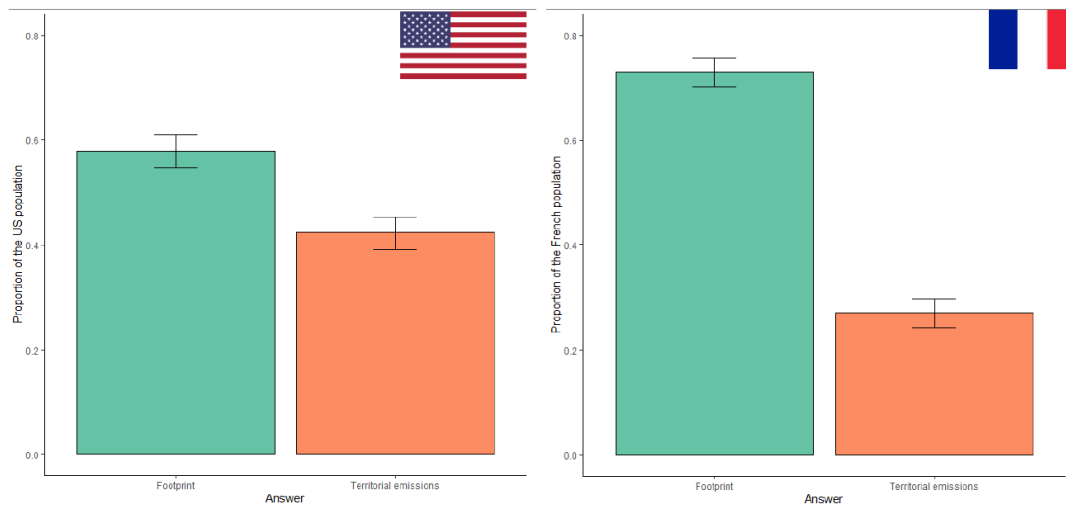
Figure D.22: Distribution of answers to questions 12.c (top) and 12.d (bottom) among the US (left) and French (right) populations



Error bars represent a confidence level over 95%.

Q.13 Which of the following statements do you most agree with?

- Countries should only be held accountable for the carbon emissions that occur on their territories [*label: Territorial emissions*]
- Countries should be held accountable for the carbon emissions of all the products they consume, including the emissions of imported products that occur abroad [*label: Footprint*]

Figure D.23: Distribution of answers to question 13 among the US (left) and French (right) populations

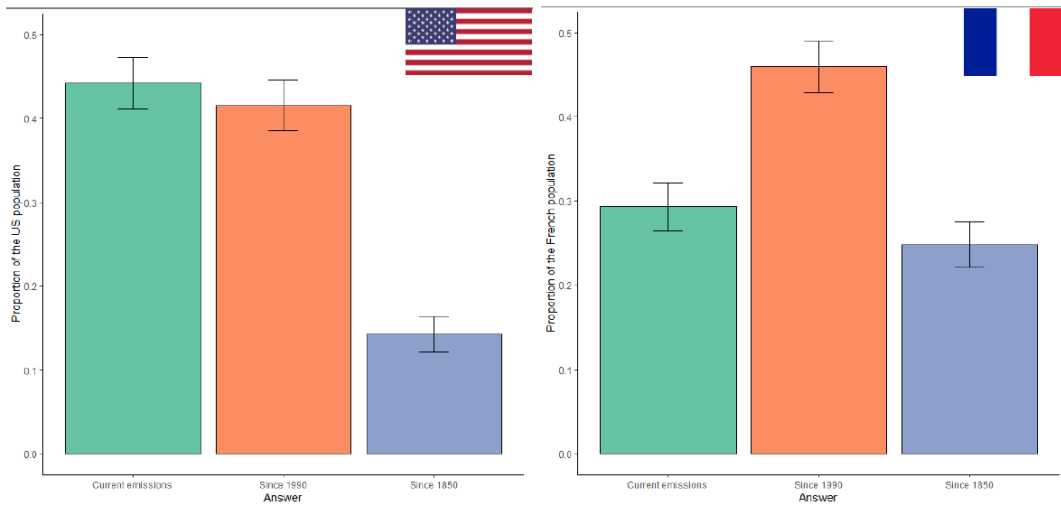
Error bars represent a confidence level over 95%.

In both countries, respondents tend to prefer insisting that countries should be held responsible for the emissions linked to all the products they consume, including the emissions of imported products that occur abroad. More French respondents (around 73%) choose the footprint over territorial emissions compared to the US (around 58%).

Q.14 Which of the following statements do you most agree with?

- Countries should only be held accountable for their current emissions [*label: Current emissions*]
- Countries should be held accountable for their historical emissions since 1990, when it was scientifically established that climate change was real and caused by human activities [*label: Since 1990*]
- Countries should be held for their historical emissions since 1850, when humans started emitting large quantities of carbon in the atmosphere [*label: Since 1850*]

Figure D.24: Distribution of answers to question 14 among the US (left) and French (right) populations



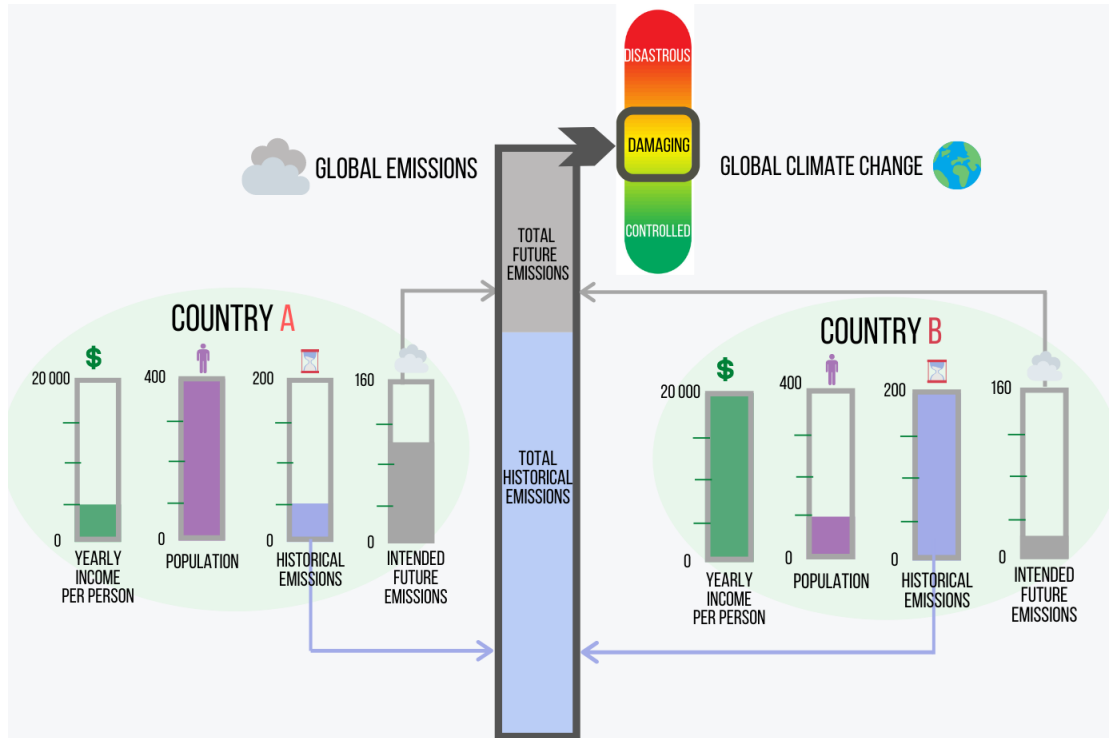
Error bars represent a confidence level over 95%.

French respondents tend to think countries should be held accountable for their historical emissions since 1990, when it was scientifically established that climate change was real and caused by human activities (around 46% of the answers). On the other hand, US respondents tend to mainly think that countries should only be held accountable for their current emissions (around 44% of the answers for current emissions, 42% of the answers for 1990). In both countries, respondents tend to disagree that countries should be held accountable for their historical emissions since 1850, when humans started emitting large quantities of carbon in the atmosphere (only around 24% of French respondents, 14% of US respondents chose this answer).

12.3 Judgements on particular cases

Q.15 This sketch will be used to present different situations in the next questions.
 True or false?

Figure D.25: Presentation of the test case



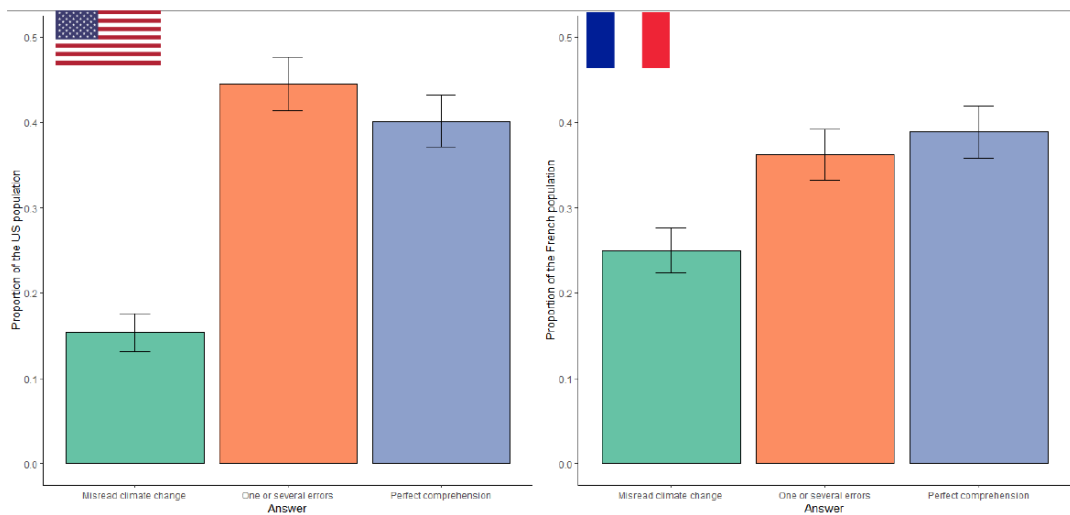
Sub-questions:

- Country A has emitted more in the past than country B [15.a]
- Country A will emit more in the future than country B [15.b]
- The intended future emissions of countries A and B will be sufficiently low to avoid damaging climate change [15.c]
- People in country A are poorer and more numerous than in country B [15.d]

As our interest here is in the level of comprehension respondents get of the test case, their answers to question 15 were recoded in the following way:

- “Misread climate change”: respondents who only got a wrong answer to question 15.c
- “Perfect comprehension”: respondents who got a right answer to all questions
- “One or several errors”: respondents who got a wrong answer among questions 15.a, 15.b or 15.d

Figure D.26: Respondents’ level of comprehension of the test case, based on their answers to question 15, among the US (left) and French (right) populations



Error bars represent a confidence level over 95%.

French respondents misread the level of climate change more than US respondents: only around 54% of French respondents got a right answer (around 62% of US respondents) to the related test question.

US respondents failed other comprehension questions more: around 39% of French respondents (around 40% of US respondents) did not make mistakes, around 25% (around 15%) only got a wrong answer for the climate change level, and around 36% (around 45%) made one or several errors at the other questions.

Q.16 to Q.22 feature a figure close to the test case, describing a different situation for each question. All cases are summarized in Table D.3.

Table D.3: Summary of the cases proposed in Block 2B of the survey

Case	Country List				Country List				Climate change
	Pop	GDP/cap/yr	Historical	Pledge	Pop	GDP/cap/yr	Historical	Pledge	
C0	100	20000	200	100	100	20000	200	20	Damaging
C1	400	20000	200	100	100	20000	200	20	Damaging
C2	100	5000	200	100	100	20000	200	20	Damaging
C3	100	20000	50	100	100	20000	200	20	Damaging
C4	400	5000	50	60	100	20000	200	60	Damaging
C5	400	5000	50	60	100	20000	200	20	Controlled

To what extent do you agree that each country is taking its fair share of the collective effort? For Country A and Country B:

- I strongly agree
- I rather agree
- I rather disagree
- I strongly disagree

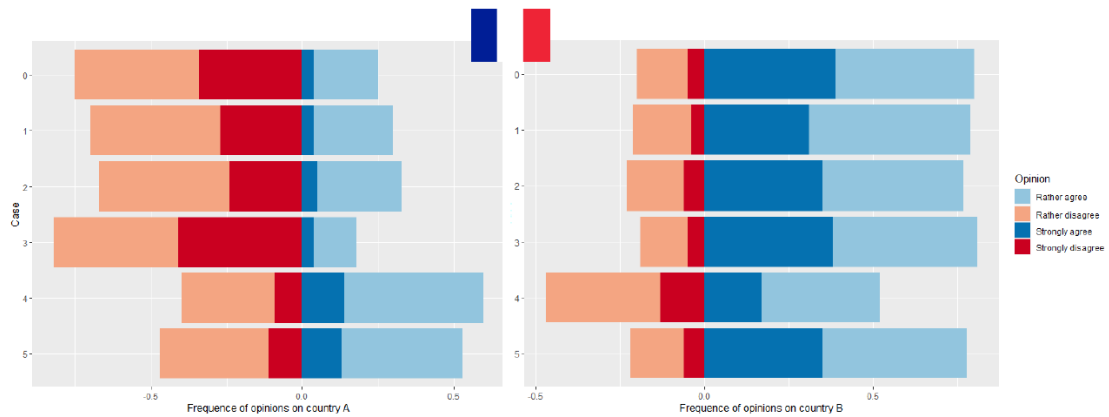
Reference case (C0): In both countries, most of the respondents rather or strongly disagree that country A is taking its fair share. A large majority of the respondents rather or strongly agree that country B is taking its fair share.

Table D.4: Judgement of French citizens on countries in illustrative cases presented in Block 2B

France	Strongly agree	Rather agree	Rather disagree	Strongly disagree
CO : Country A	0.04	0.21	0.41	0.34
CO : Country B	0.39	0.41	0.15	0.05
C1 : Country A	0.04	0.26	0.43	0.27
C1 : Country B	0.31	0.48	0.17	0.04
C2 : Country A	0.05	0.28	0.43	0.24**
C2 : Country B	0.35	0.42	0.17	0.06
C3 : Country A	0.04	0.14	0.41	0.41
C3 : Country B	0.38	0.43	0.14	0.05
C4 : Country A	0.14**	0.46**	0.31**	0.09**
C4 : Country B	0.17**	0.35	0.34**	0.13**
C5 : Country A	0.13**	0.40**	0.36**	0.11**
C5 : Country B	0.35	0.43	0.16	0.06

Two asterisks after a figure here show a significant difference with the equivalent value in Case1 with a confidence level of 95%. The distributions of answers to cases from this question are corrected to only account for the answers of respondents who succeeded the test. However, even though the proportions may change, the trends described are also valid among the global populations.

Figure D.27: Judgement of French citizens on countries in illustrative cases presented in Block 2B



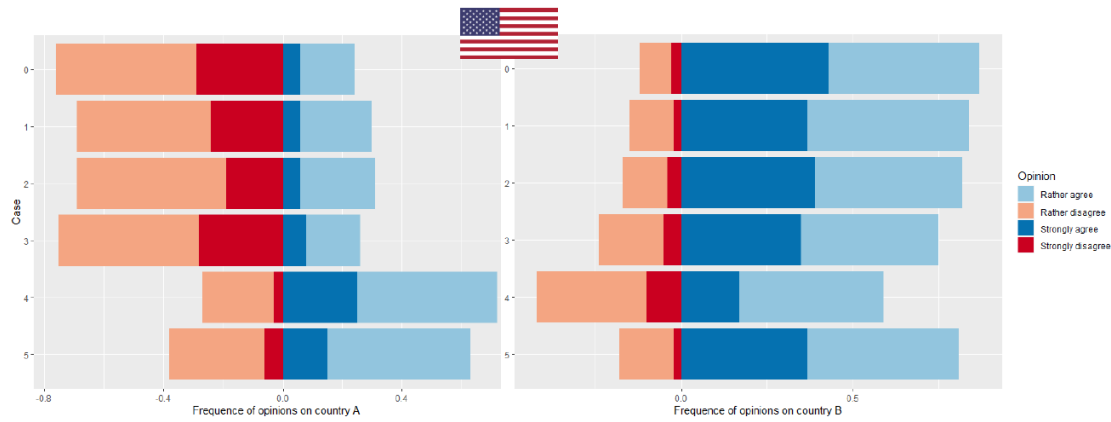
The respondents are presented with 6 simplified cases. They are then asked whether they think that the country A and the country B took their fair share or not, in cases 0 to 5. Case 0 is considered a reference case and is always presented first to the respondents. Case 1 to 3 deviate from the reference case by one characteristic of country A. In Case 4, countries differ by all their characteristics but implement the same pledge. Case 5 is similar to Case 4 except that country B adopts a more ambitious pledge, that leads to a global controlled climate change. Only Case 4 and country A in Case 5 show a significant difference with the equivalent value in Case 0 with a confidence level of 95%. The distributions of answers to cases are corrected to only account for the answers of respondents who succeeded the test. However, even though the proportions may change, the trends described are also valid among the global populations.

Table D.5: Judgement of US citizens on countries in illustrative cases presented in Block 2B

USA	Strongly agree	Rather agree	Rather disagree	Strongly disagree
CO : Country A	0.06	0.18	0.47	0.29
C0 : Country B	0.43	0.44	0.09	0.03
C1 : Country A	0.06	0.24	0.45	0.24
C1 : Country B	0.37	0.47	0.13	0.02
C2 : Country A	0.06	0.25	0.50	0.19**
C2 : Country B	0.39	0.43	0.13	0.04
C3 : Country A	0.08	0.18	0.47	0.28
C3 : Country B	0.35	0.40	0.19**	0.05
C4 : Country A	0.25**	0.47**	0.24**	0.03**
C4 : Country B	0.17**	0.42	0.32**	0.10**
C5 : Country A	0.15**	0.48**	0.32**	0.06**
C5 : Country B	0.37	0.44	0.16**	0.02

Two asterisks after a figure here show a significant difference with the equivalent value in Case1 with a confidence level of 95%. The distributions of answers to cases from this question are corrected to only account for the answers of respondents who succeeded the test. However, even though the proportions may change, the trends described are also valid among the global populations.

Figure D.28: Judgement of US citizens on countries in illustrative cases presented in Block 2B



The respondents are presented with 6 simplified cases. They are then asked whether they think that the country A and the country B took their fair share or not, in cases 0 to 5. Case 0 is considered a reference case and is always presented first to the respondents. Case 1 to 3 deviate from the reference case by one characteristic of country A. In Case 4, countries differ by all their characteristics but implement the same pledge. Case 5 is similar to Case 4 except that country B adopts a more ambitious pledge, that leads to a global controlled climate change. Only Case 4 and country A in Case 5 show a significant difference with the equivalent value in Case 0 with a confidence level of 95%. The distributions of answers to cases are corrected to only account for the answers of respondents who succeeded the test. However, even though the proportions may change, the trends described are also valid among the global populations.

Main observations :

In the US, the distributions of answers for case 2 and case 4 are similar to case 1. In case 3, a few more respondents agree that country A is taking its fair share (but the opinions stay similar to the reference case).

The distributions of answers for cases 5 and 6 are different from the other cases. In case 5, more respondents strongly agree with the fact that country A is taking its fair share. Less people rather disagree with it. Less respondents strongly agree with the fact that country B is taking its fair share, and more respondents rather disagree. Overall, respondents in case 5 agree more with the fairness of country A's contribution than with that of country B. In case 6, the distribution of answers for country A is similar to that of case 5, and the distribution of answers for country B is similar to the ones of the first four cases. In this case, respondents still tend to agree more with the fairness of country B's contribution than that of country A, but the level of agreement with the fairness of country A's contribution is higher than in the first few cases.

In France, the results are roughly similar to the results for the US respondents, except that overall, less people tend to strongly agree than in the US survey.

This would tend to indicate that respondents did not take into account the population, wealth and historical emissions of the countries as answers for cases 2,3,4 are almost

identical to answers for the reference case, where countries differ only by their proposed future emissions.

However, in case 5 where countries differ by all parameters except for their proposed future emissions, the opinions about countries change and become similar to one another, which shows that people tend to think the same about two very different countries who propose similar contributions.

In case 6, the opinions about country A do not change compared to case 5 (the situation of country A is identical in both cases). Opinions about country B are much more close to the opinions about countries B of the first four cases than in case 5, where country B's proposed contribution is higher. This would tend to indicate that respondents pay more attention to the proposed contributions than to the resulting climate change, as case 6 results in a controlled climate change.

12.4 Coordinated question

Q.23 To what extent do you agree that each country is taking its fair share of the collective effort? In Q.23, a figure describing the case of India, China, the USA and the EU is presented to the respondents.

Answers in column, for each country:

- I strongly agree
- I rather agree
- I rather disagree
- I strongly disagree

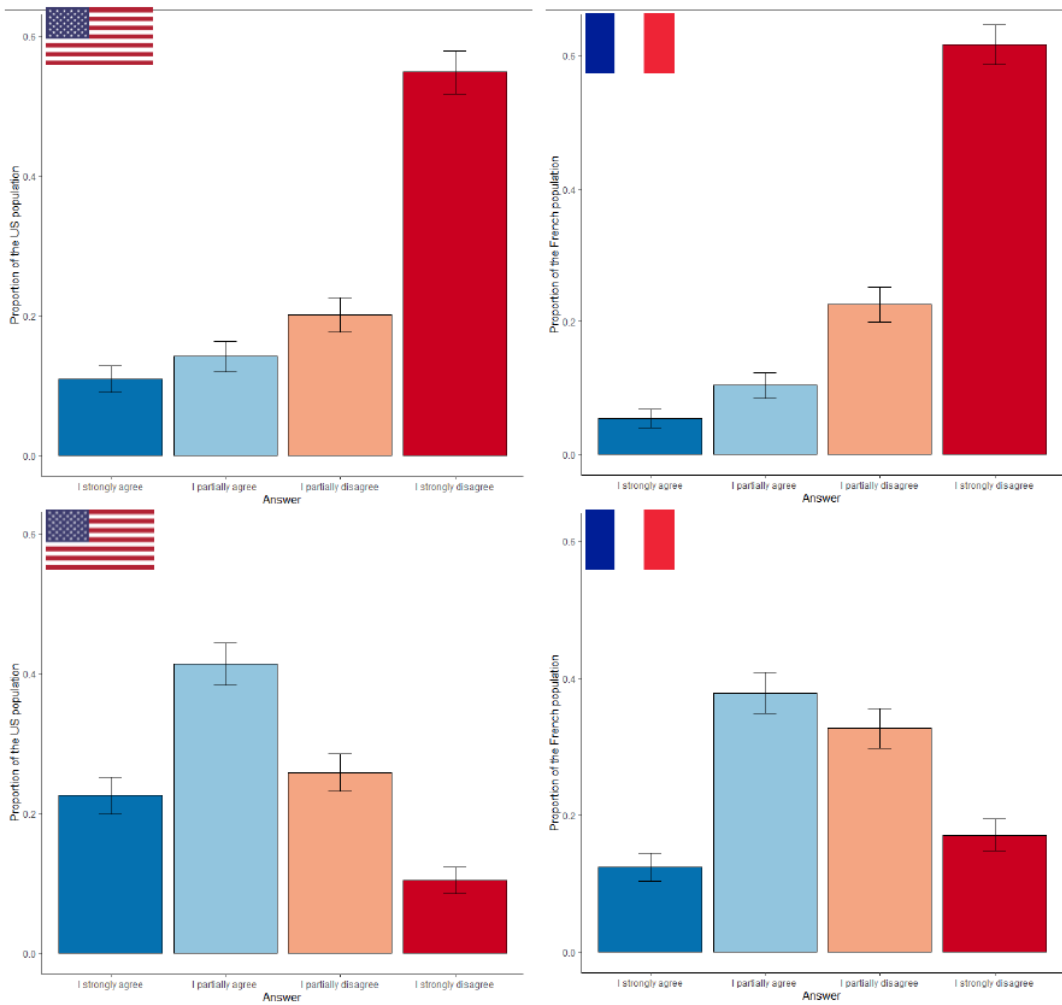
Overall, respondents strongly disagree that China is taking its fair share : the opinion is stronger in France where 62% of respondents strongly disagree, than in the US where 55% of respondents strongly disagree.

In the US, most of the respondents (around 63%) rather or strongly agree with the fairness of India's NDC. In France, there are as many respondents who rather or strongly agree as respondents who rather or strongly disagree with it.

For most of the US respondents, the EU is taking its fair share in climate change action (more than 80% of US respondents rather or strongly agree with it), and so are the USA (around 68% of US respondents rather or strongly agree with it).

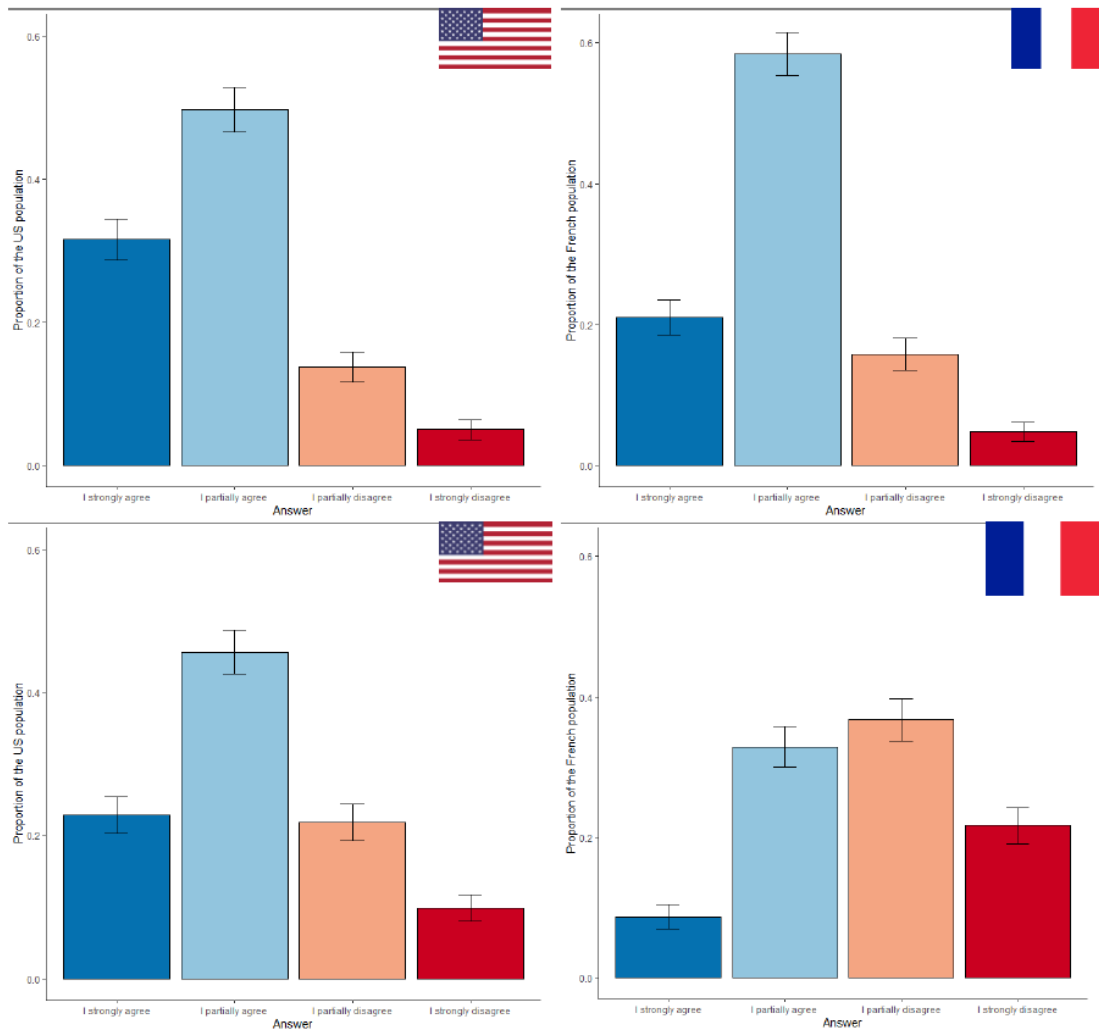
Around 79% of French respondents also rather or strongly agree that the EU is taking its fair share. However, around 58% of French respondents rather or strongly disagree that the US is taking its fair share.

Figure D.29: Respondents' judgment about China's (top) and India's (bottom) NDCs, among the US (left) and French (right) populations



Error bars represent a confidence level over 95%.

Figure D.30: Respondents' judgment about the EU's (top) and the USA's (bottom) NDCs, among the US (left) and French (right) populations



Error bars represent a confidence level over 95%.

In order to better look at judgements of individuals on the four countries' NDCs, 256 "**Judgement paths**" were built by combining each respondent's judgement on each of the NDCs.

In the US and in France, the median frequency of a path is around 0.2%. Among all possible paths, only 8 in the US and 9 in France gather significantly more than 2% of respondents each, and more than 30% all together. They are represented on figure 28.

The most represented judgement path among the US population is H (strong disagreement with China, partial agreement with India, the EU, the US), representing around 6.9% of respondents.

The most represented judgement path among the French population is I (strong disagreement with China, partial agreement with India, the EU, partial disagreement with the US), representing around 8.0% of respondents.

We classify all possible paths in 5 categories, depending on how many country they tend to deem ambitious enough. The repartition of answers is presented in Table D.9.

Table D.6: Proportion of the different categories of judgement paths

	Number of paths	Proportion in France	Proportion in the US
Agree with all	16	17%	10%
Agree with three	64	32%	15%
Agree with two	96	33%	40%
Agree with one	64	10%	21%
Agree with none	16	8%	14%
Total	256	100%	100%

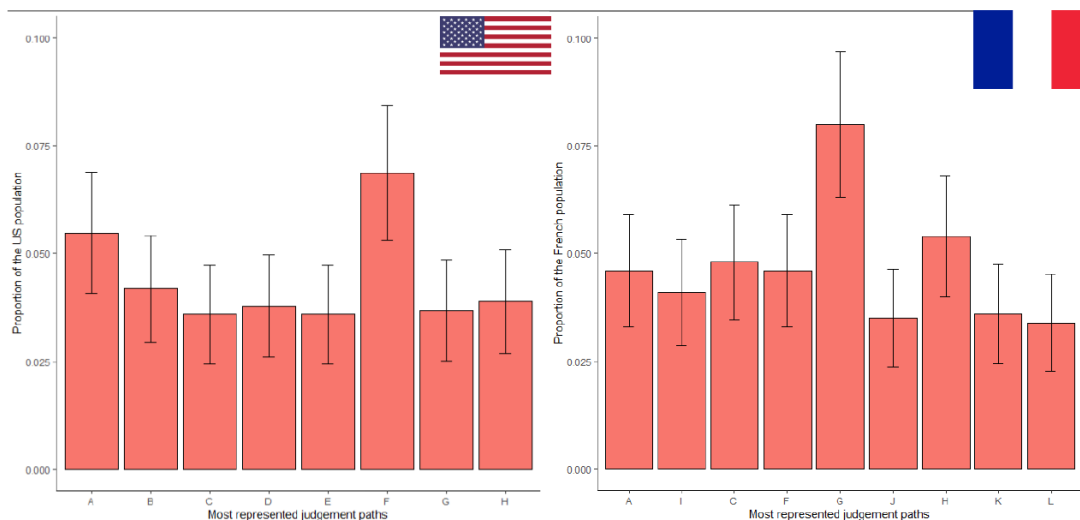
In France, most respondents only agree that two of the four countries take their fair share: their proportion (40%) is significantly higher than for other judgement paths. In the US, most respondents tend to agree with two or three of the four countries.

Q.24 Imagine that you have to coordinate with someone living in Europe. This person also tries to answer the same as you do. To what extent do you agree that each country is taking its fair share of the collective effort?

Answers are identical to the previous questions, sub-questions target the EU and the USA.

When asked to coordinate with a respondent from another country, the respondents show a distribution of answers that is similar to when they are asked for their opinion. A look into the respondent's behavior shows that a majority of respondents (around 54% for both countries) changed their minds when asked to coordinate with a respondent of the other country. In order to get a better understanding of how opinions changed when they did, flowcharts of the evolution of the respondents' answers were drawn.

Figure D.31: Respondents' most represented "judgement paths" among the US (left) and French (right) populations

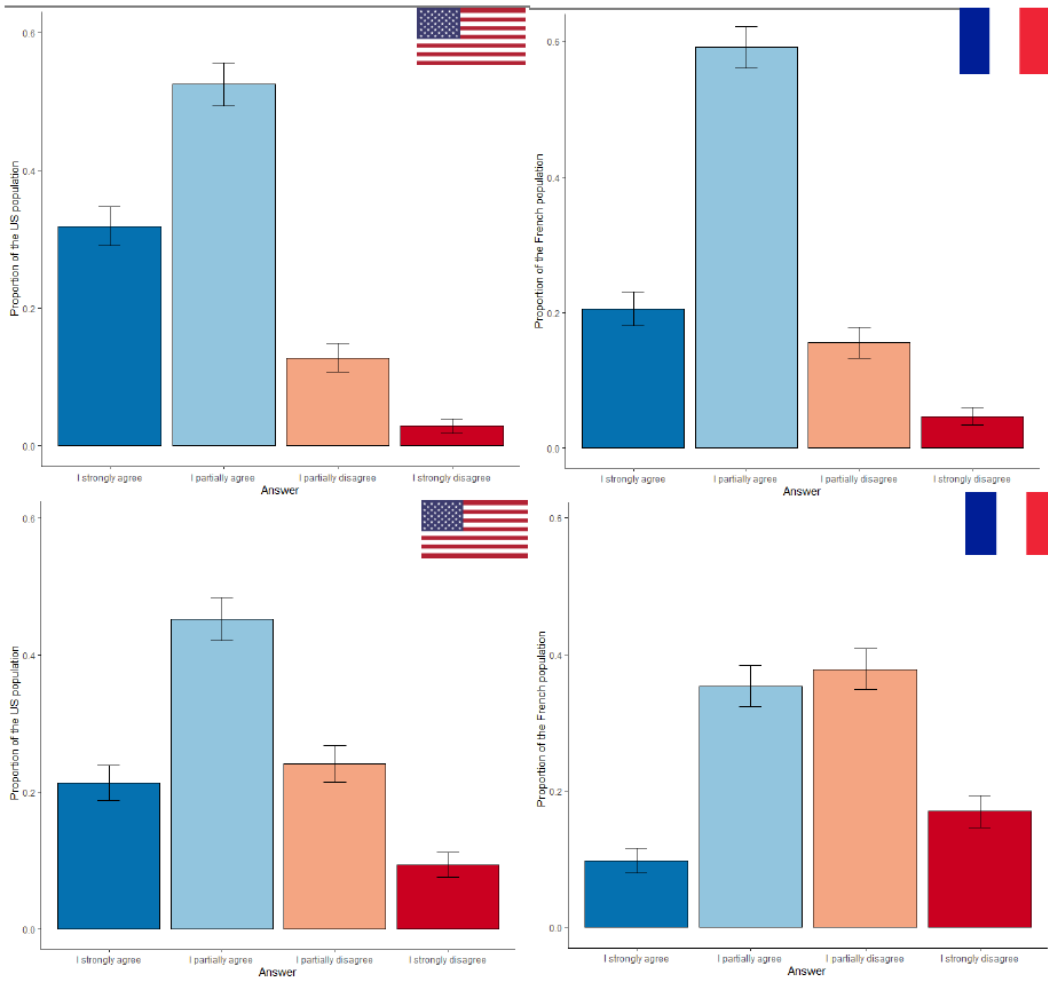


Error bars represent a confidence level over 95%.

Reading key:

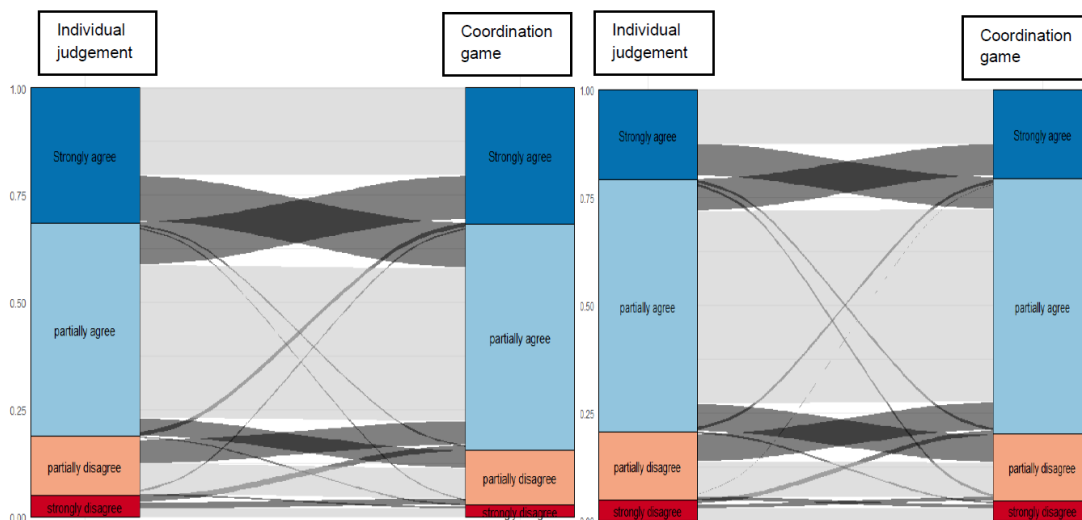
- A: partial agreement with all NDCs
- B: partial disagreement with China, partial agreement with India, the EU, the US
- C: partial disagreement with all NDCs
- D: strong disagreement with China, strong agreement with India, the EU, partial agreement with the US
- E: strong disagreement with China, strong agreement with the EU, partial agreement with India, the US
- F: strong disagreement with China, partial agreement with India, the EU, the US
- G: strong disagreement with China, partial agreement with India, the EU, partial disagreement with the US
- H: strong disagreement with China, partial disagreement with India, partial agreement with the EU, the US
- I: partial agreement with the EU, partial disagreement with China, India, the US
- J: strong disagreement with China, the US, partial agreement with India, the EU
- K: strong disagreement with China, partial disagreement with India, the US, partial agreement with the EU
- L: strong disagreement with all NDCs

Figure D.32: Respondents' judgment about the EU's (top) and the USA's (bottom) NDCs when asked to coordinate, among the US (left) and French (right) populations



Error bars represent a confidence level over 95%.

Figure D.33: Evolution of the answers of US (left) and French (right) respondents about the EU’s NDC, when asked for their opinion in isolation and in the tacit coordination game



In the coordination game, respondents are given the following question: “Imagine that you have to coordinate with someone living in Europe. This person also tries to answer the same as you do. To what extent do you agree that each country is taking its fair share of the collective effort?”

Among French respondents who rather or strongly agreed that the EU took its fair share (795 people), only 78 respondents changed their mind and rather or strongly disagreed when asked to coordinate with a US respondent (of which only 10 switched to “strongly disagree”). Among French respondents who rather or strongly disagreed that the EU took its fair share (206 respondents), 81 changed their mind and rather or strongly agreed (of which 8 switched to “strongly agree”).

Among US respondents who rather or strongly agreed that the EU took its fair share (816 people), only 50 respondents changed their mind and rather or strongly disagreed when asked to coordinate with a US respondent (of which only 6 switched to “strongly disagree”). Among US respondents who rather or strongly disagreed that the EU took its fair share (188 respondents), 81 changed their mind and rather or strongly agreed (of which 14 switched to “strongly agree”).

For this analysis, we take the example of the judgement on the EU’s NDC. We classify all possible evolutions of judgement towards this NDC in 8 categories :

- 1: Strongly agreed in both cases
- 2: Partially agreed in both cases
- 3: Strongly agreed then partially agreed in the coordination

- 4: Partially agreed then strongly agreed in the coordination
- 5: Partially disagreed in both cases
- 6: Partially disagreed then partially agreed in the coordination
- 7: Partially agreed then partially disagreed in the coordination
- Other cases

The repartition of French and US respondents into these categories is presented in the following tables.

Table D.7: Determinants of the evolution the opinion of US respondents on the fairness of the EU's NDC

Change	Global%	Male	Wealth (+\$75,000)	Concerned by CC**	Common resp.**	Optimistic coord**
1	20%	57%	37%	51%	64%	58%
2	35%	46%	34%	35%	55%	45%
3	10%	55%	42%	40%	71%	47%
4	10%	51%	40%	37%	56%	52%
5	8%	40%	25%	46%	66%	23%
6	5%	41%	37%	26%	65%	28%
7	4%	57%	35%	35%	45%	35%
Other	8%	52%	33%	39%	35%	27%
All sample		50%	36%	40%	58%	44%

Here, two asterisks in the column title mean that the independence of both variables is rejected with an associated confidence level of 95% using a chi-square test, three asterisks show a confidence level of 99%. Green colors refer to people who agreed or strongly agreed in both situations, red to people who disagreed.

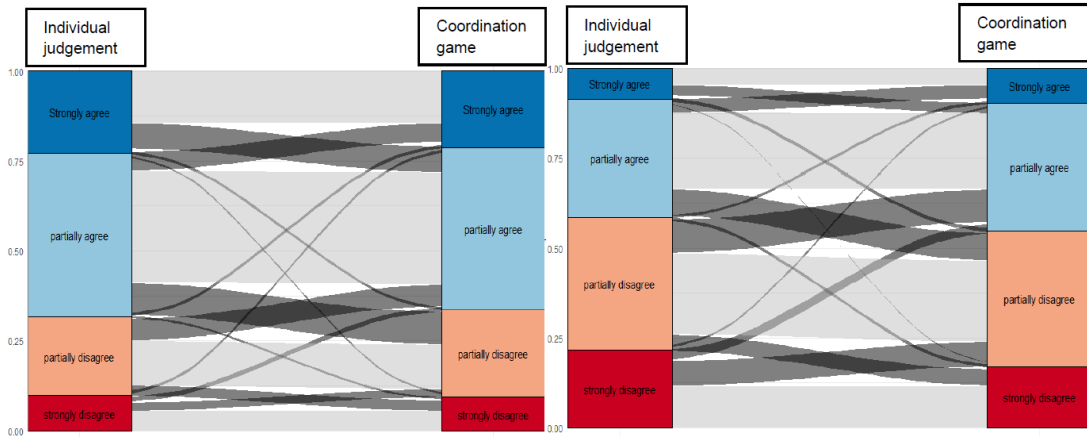
Table D.8: Determinants of the evolution of the opinion of French respondents on the fairness of the EU's NDC

Change	Global %	Male	Wealth (+ 50 000 euros)	Concerned by CC	Common resp.**	Optimistic coord**
1	12%	53%	16%	52%	64%	29%
2	45%	48%	24%	51%	59%	19%
3	7%	62%	20%	55%	64%	25%
4	7%	53%	23%	57%	64%	18%
5	8%	59%	25%	59%	51%	10%
6	6%	49%	21%	41%	54%	11%
7	6%	48%	21%	63%	52%	16%
Other	8%	40%	17%	65%	42%	17%
All sample		50%	23%	54%	58%	19%

Here, two asterisks in the column title mean that the independence of both variables is rejected with an associated confidence level of 95% using a chi-square test, three asterisks show a confidence level of 99%. Changes are categorized in the same way as for the US panel.

Even though significant differences exist among the populations of individuals with different characteristics, there is no clear trend that appears and reveals the existence of a shared comprehension of what a fair contribution of a country would be.

Figure D.34: Evolution of the answers of US (left) and French (right) respondents about the US’s NDC, when asked for their opinion in isolation and in the tacit coordination game



In the coordination game, respondents are given the following question: “Imagine that you have to coordinate with someone living in Europe. This person also tries to answer the same as you do. To what extent do you agree that each country is taking its fair share of the collective effort?”

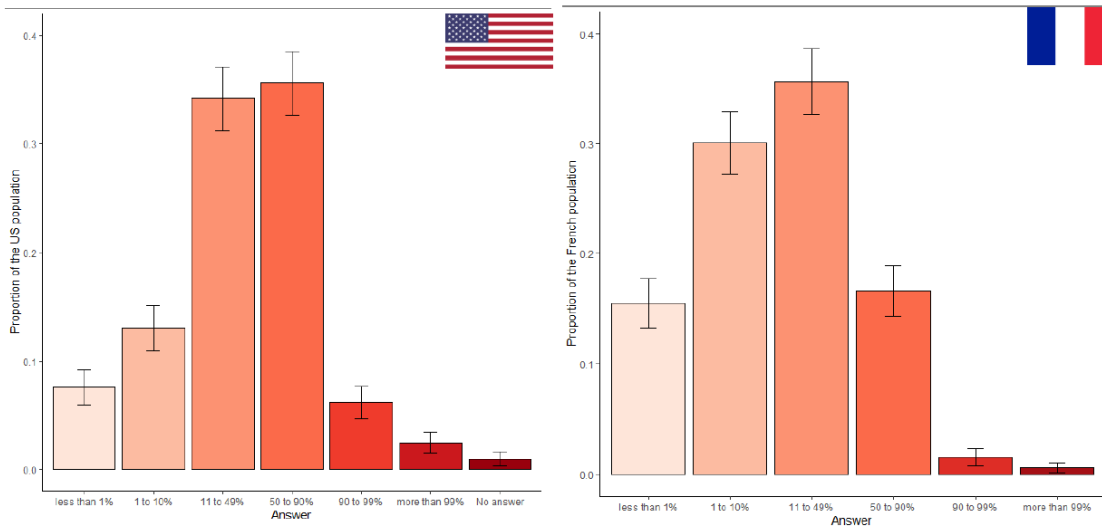
Among French respondents who rather or strongly agreed that the USA took their fair share (416 people), 95 respondents changed their mind and rather or strongly disagreed when asked to coordinate with a US respondent (of which only 11 switched to “strongly disagree”). Among French respondents who rather or strongly disagreed that the USA took their fair share (585 respondents), 131 changed their mind and rather or strongly agreed (of which 14 switched to “strongly agree”).

Among US respondents who rather or strongly agreed that the USA took their fair share (687 people), 109 respondents changed their mind and rather or strongly disagreed when asked to coordinate with a US respondent (of which only 11 switched to “strongly disagree”). Among US respondents who rather or strongly disagreed that the USA took their fair share (317 respondents), 90 changed their mind and rather or strongly agreed (of which 14 switched to “strongly agree”).

Q.25 According to you, what are the chances that you successfully coordinated with the European respondent?

- less than 1%
- 1 to 10%
- 11 to 49%
- 50 to 90%
- 90 to 99%

Figure D.35: Distribution of answers to question 25 among the US (left) and French (right) populations



Error bars represent a confidence level over 95%.

- more than 99%
- Other

Around 80% of French respondents estimate their chances to have successfully coordinated to be less than 50%, whereas it is only the case for around 54% of US respondents.

The questionnaire also featured open-text questions, for which the responses are not analyzed in this document but are available online with the survey data.

13 Additional analyses

13.1 Consistency analyses

We formulate the following consistency hypotheses.

- *Citizens show a preference for a convergence towards equal per capita emissions. If the judgements on which this result is based are consistent, then people's opinion about the fairness of this theoretical principle should match their opinion on study case 1, where future emissions per capita of A and B are close (H1.1). Moreover, we also assume that people in favour of common responsibilities should agree with a convergence towards equal per capita emissions, as all the countries are included in this principle (H1.2).*

- *Citizens adhere to an operational version of the grandfathering principle. If the judgements on which this result is based are consistent, then opinions both formulations of the grandfathering principle as stated in questions 9 and 10 should match (H2.1). We also assume that people should tend to have opposite positions on this operational grandfathering principle and the principle in which countries that emitted less in the past are allowed to reduce less their emissions in the future (H2.2). Finally, opinions about the fairness of the operational principle should be the opposite of their opinion on study case 3 where country A emitted less in the past (H2.3).*
- *As a corollary to the other consistency results, there seems to be less support for principles in which poor countries or countries that emitted less in the past get to reduce their emissions less in the future. If the judgements on which these results are based are consistent, then people's opinions about the fairness of allowing poorer countries to less reduce their emissions or not reduce them immediately, and study case 2 where country A is poorer should match (H3.1). This would also be the case between the principle proposing different efforts for countries that emitted less in the past and study case 3 where country A emitted less in the past (H3.2). Finally, we then assume that people in favour of differentiated responsibilities would be more in favour of these two principles (H3.3).*

Some of the judgements are consistent and others display inconsistencies. In the following paragraphs, the results that are described show a confidence level over 99% using a chi-squared test.

On our first set of hypotheses, we show that people prioritising common responsibilities tend to agree more with a convergence towards equal per capita emissions (which tends to validate hypothesis H1.2). However, the inconsistency lies between the citizens' judgement about this principle and their opinion about country A's contribution in case 1 (where A is more populated). Although both opinions are dependent, people who strongly agree with the principle tend to either strongly agree or strongly disagree more with the fact that country A's contribution is fair (which invalidates hypothesis H1.1). Although this last result could be explained by lack of attention, we also show that careful respondents (those who can read the situations without mistake) almost only take into account future pledges when judging countries' pledges.

On our second set of hypotheses, the judgements about an operational grandfathering principle are completely inconsistent, in both panels. Although people's opinions about both formulations of grandfathering are dependent, respondents who strongly agree with one tend to either strongly agree or strongly disagree more than others with the other (which invalidates hypothesis H2.1). Moreover, respondents tend to have the same opinion about one of the formulations of grandfathering and the principle which proposes that countries that emitted less in the past could reduce their emissions less in the future (which invalidates hypothesis H2.2). This last result is a marker of inconsistency, as the principles are not compatible, but some people could very well think

that two incompatible principles are both fair in absolute terms. This phenomenon exists in both panels, as around 13% of French respondents and 19% of US respondents never disagree with one of the five proposed principles (respectively 2% and 4% of people always disagree). It could be behind the invalidation of H2.2 but not H2.1, where we observe that opinions towards two compatible situations are opposite. The invalidation of H2.1 could signal the existence of heuristics - respondents might have had two very different interpretations of the same principle, depending on its formulation – or the inconsistency of responses related to the grandfathering principle.

Judgements about poorer countries and countries that emitted less prove to be rather consistent throughout the survey, and for both panels. Most people have an identical opinion about the principles which propose for poor countries to respectively less reduce their emissions and not start reducing their emissions immediately. Similarly, the same opinion is often observed about these principles and the fairness of country A's contribution in case 2 (which tends to validate H3.1). The same goes for opinions about the principle which proposes for countries that emitted less in the past to reduce less their future emissions, and the fairness of country A's contribution in case 3 (which validates 3.2). However, in the USA, while there is a link between the opinions on CBDR and on most principles (regarding countries that are poor, emitted less in the past, have forests or fund low-carbon projects abroad), people in favour of common responsibilities tend to strongly agree or strongly disagree more on the principles (thus partly invalidating hypothesis H3.3). The presence of people who strongly agree among people in favour of differentiated responsibilities could here also be explained by the existence of tolerant people.

13.2 Complements on moral reasoning

The following table summarizes the significant results obtained when testing for learning effects.

Table D.9: Learning effects on the respondents' judgements on principles

French respondents	US respondents
Weaker disagreement with the underlying principle of grandfathering (more people « rather disagree »)	Stronger preference for accounting for the carbon footprint of countries rather than territorial emissions
Weaker disagreement with the principle about past emissions higher representation among people who rather agree with it	Stronger preference for accounting for historical emissions since 1990 (decreased preference for current emissions)
Increase in agreement with the convergence towards equal per capita (less « rather disagree »)	
Weaker opinion – increase in « rather agree » and « rather disagree » - with the principle about costly climate action	
Weaker opinion – increase in « rather agree » and « rather disagree » - with an operational grandfathering	

Here, we list the opinions of respondents who answered to Block 2B first, that are significantly different from the general case

In France, it is interesting to note that most of the observed variations concern the principles themselves, and are in the direction of a less righteous judgement: on four out of the six principles, the proportion of respondents who learned with the cases first is higher for moderate opinions (« rather agree », « rather disagree »). As for a convergence towards equal per capita emissions, the evolution of judgments with learning seems to be towards an increase in the proportion of the existing major opinion.