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# Modelling energy dependencies : from raw materials to global health

Baptiste Andrieu

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THÈSE

Pour obtenir le grade de

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Spécialité : Sciences de la Terre et de l'Environnement

Unité de recherche : Institut des Sciences de la Terre

### Modelling energy dependencies: from raw materials to global health

### Modélisation des dépendances énergétiques : des matières premières à la santé mondiale

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# MODELLING ENERGY DEPENDENCIES: FROM RAW MATERIALS TO GLOBAL HEALTH



*«Le vrai pessimiste sait qu'il est déjà trop tard pour l'être.»*

Hervé Le Tellier, *L'Anomalie*

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## RÉSUMÉ

Atteindre un niveau de vie satisfaisant pour tous nécessiterait aujourd'hui une utilisation de ressources 2 à 6 fois supérieure à un niveau jugé durable. Il est donc nécessaire de découpler l'utilisation de ressources des besoins humains. La recherche sur ce sujet s'appuie sur le concept de systèmes d'approvisionnement, défini par Fanning et ses collègues comme "un ensemble d'éléments liés qui fonctionnent ensemble pour transformer des ressources pour satisfaire un besoin humain donné". Des transformations profondes de ces systèmes d'approvisionnement sont nécessaires, car suivre les tendances actuelles ne ferait qu'exacerber la crise écologique sans parvenir à éliminer les déficits sociaux. Pour renforcer notre compréhension de la chaîne allant de l'extraction des ressources de la biosphère jusqu'aux besoins humains, cette thèse vise à construire un modèle de stock et de flux des infrastructures mondiales.

Le chapitre 1 critique le manque de perspectives venant de l'écologie industrielle et de la recherche sur le métabolisme socio-économique dans les modèles d'évaluation intégrée (IAMs), établissant ainsi la nécessité de construire de nouveaux modèles. Le chapitre 2 présente le modèle MATER (Multi-regional Assessment of Technologies Energy and Resources). Ce modèle reproduit avec précision les tendances passées de consommation d'énergie et de ressources (de 1900 à aujourd'hui) et est un outil utile pour mener des analyses prospectives basées sur la demande de services, la demande d'énergie ou des trajectoires socio-économiques. Le chapitre 3 décrit comment l'utilisation de tableaux entrées-sorties a permis de régionaliser les flux dans MATER. Une application web interactive représentant divers périmètres potentiels pour les calculs d'empreinte carbone est également présentée. Le chapitre 4 commence par décrire comment MATER calcule les coûts et les prix à long terme des métaux, en intégrant des variables telles que la teneur en minerai, le progrès technologique, le prix de l'énergie et les limites thermodynamiques. Le modèle reproduit fidèlement l'évolution historique des prix des métaux depuis 1900 et prédit une inversion inévitable de la baisse des coûts à mesure que l'énergie de production s'approche des limites thermodynamiques. La deuxième partie du chapitre 4 compare les intensités énergétiques (une donnée importante dans MATER) en fonction de la richesse. Les régions à hauts revenus utilisent plus d'énergie par unité de consommation finale que les régions à faibles revenus. Ce résultat contredit la croyance selon laquelle un PIB plus élevé serait corrélé à une meilleure efficacité. Le chapitre 5 explore les interactions entre la santé et l'environnement. Une analyse de 49 systèmes de santé montre l'existence d'une relation exponentielle entre l'empreinte en ressources de ces systèmes et leur indice d'accès et de qualité des soins de santé (HAQ). Ensuite, les associations entre l'empreinte énergétique par habitant (représentative du mode de vie d'un individu) et l'incidence de maladies sont calculées. Une empreinte énergétique élevée par habitant est corrélée à des faibles taux de maladies transmissibles, mais aussi à des taux élevés de maladies liées au mode de vie ou de maladies chroniques. Étant donné le besoin de réduire la consommation d'énergie pour réussir la transition énergétique, il est vital d'optimiser l'utilisation de l'énergie, en l'affectant à ce qui améliore la santé plutôt qu'à ce qui risque d'aggraver les maladies chroniques. Bien que la santé ne soit pas encore un secteur

dans MATER, ce chapitre prépare son inclusion éventuelle. Le chapitre 6 conclut par une discussion sur les besoins futurs en matière de recherche, notamment la création de scénarios de post-croissance, l'inclusion d'exergie dans les modèles, l'étude de risques et la ludification des modèles afin de les rendre utiles à la prise de décision.

## SUMMARY

Based on current relationships, reaching universal high level of life satisfaction would require resource use at levels 2-6 times higher than the sustainable level. There is therefore a need to decouple resource use from human needs. Research on this topic is developed under the concept of provisioning systems, defined by Fanning and colleagues as “a set of related elements that work together in the transformation of resources to satisfy a foreseen human need”. Deep transformations of these provisioning systems are needed as current trends will only exacerbate the ecological crisis while failing to eliminate social shortfalls. To strengthen our understanding of the chain going from resource extraction from the biosphere all the way to human needs such as transportation or healthcare, this thesis aims to build a stock and flow model of the world’s infrastructures, with regionalized impacts.

Chapter 1 critiques the lack of insights from industrial ecology and socioeconomic metabolism research in Integrated Assessment Models (IAMs), thereby establishing the necessity for novel models. Chapter 2 introduces the MATER (Multi-regional Assessment of Technologies Energy and Resources) model. Proven to accurately replicate past trends in energy and resources consumption (from 1900 to the present), this model is a useful tool for prospective analyses rooted in service demand, energy demand, or socio-economic trajectories. Chapter 3 describes how input-output modelling was utilized for regionalizing impacts within MATER. We also present an interactive web application representing various potential perimeters for input-output footprint calculations. Chapter 4 begins by delineating how MATER calculates the long-term costs and prices of metals, incorporating variables such as ore grade, technological advancements, energy prices, and thermodynamic limits. The model accurately reproduces the historical evolution of metal prices since 1900 and predicts that the trend of declining costs will eventually reverse as production energy approaches thermodynamic limits. The latter part of Chapter 4 compares energy intensities (an important input in MATER) as a function of affluence. High-income regions use more energy per unit of final consumption than low-income ones. This result contradicts the common belief that a higher GDP is correlated with a better efficiency. In Chapter 5, we delve into the interplay of health and environment. First, we conduct an input-output analysis of 49 healthcare systems, establishing an exponential link between their resources footprint and their healthcare access and quality (HAQ) index. Then, we calculate the associations between energy footprint per capita (indicative of an individual’s lifestyle) and disease occurrence. High energy footprint per capita is correlated to low rate of communicable diseases but also to high rates of lifestyle-related/chronic diseases. In light of the need to consume less energy to achieve a successful energy transition and become more resilient to the risks of energy supply contraction, it is critical to make better use of energy, allocating it to what improves health and not to what may increase chronic disease risk. Though not yet a sector in MATER, this chapter lays the groundwork for its eventual inclusion. Chapter 6 concludes on future research needs, encompassing the creation of post-growth Shared Socioeconomic Pathways, the need to include exergy in models, risk incorporation, and model gamification.

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# ACRONYMS

## AEEI

Autonomous Energy-Efficiency Improvement. 100

ASF Atmospheric Stabilization Framework. 27

## B2DS

Beyond 2 Degree Scenario. 62

## BECCS

Bioenergy with Carbon Capture and Storage. 28, 29

CB Consumption-Based. 148

CBA Consumption-Based Account. 125

## CBA-IAM

Cost-Benefit Analysis IAM. 28

CBk CB approach with capital endogenized. 149

CCS Carbon Capture and Storage. 28

CFC Consumption of Fixed Capital. 150

## DICE

Dynamic Integrated Climate and Economy. 27

## DyMEMDS

Dynamic Modelling of Energy and Matter Demand and Supply. 55, 73

## EE-IOA

Environmentally Extended Input-Output Analysis. 24, 26

EFC Energy Footprint per Capita. 218

ESC Energy Service Cascade. 21

ETL Energy at Thermodynamic Limit. 105

## GBD

Global Burden of Disease. 219

**GCAM**

Global Change Assessment Model. 83

**GCF** Gross Capital Formation. 150

**GDP**

Gross Domestic Product. 32, 36

**HAQ**

Healthcare Access and Quality. 177

**IAM** Integrated Assessment Model. 26–30

**IEA** International Energy Agency. 62

**IIASA**

International Institute for Applied Systems Analysis. 27

**IMAGE**

Integrated Model to Assess the Global Environment. 27

**IPCC**

Intergovernmental Panel on Climate Change. 27

**LCA** Life Cycle Assessment. 73

**LED** Low Energy Demand. 36

**MATER**

Multiregional Assessment of Technologies, Energy and Resources. 38, 73

**MEFA**

Material and Energy Flow Analysis. 24–26

**MRIO**

Multi-Regional Input-Output. 125

**MuSIASEM**

Multiscale Integrated Analysis of Societal and Ecosystem Metabolism. 24, 25

**NCF** Net Capital Formation. 150

**NPISHS**

Non-Profit Institutions Serving Households. 150

**OG** Ore-Grade. 65, 66

**OT** Ore-Tonnage. 65

**PB** Production-Based. 148

**PBA**

Production-Based Account. 125

**PLDV**

Personnal Light Duty Vehicles. 77–79

- PME**  
Practical Minimum Energy. 105
- PPP** Purchasing Power Parity. 124
- RAINS**  
Regional Acidification Information and Simulation. 27
- RCP** Representative Concentration Pathway. 31, 83
- RECC**  
Resource Efficiency-Climate Change. 36, 77
- REE** Rare Earth Elements. 63
- RTS** Reference Technology Scenario. 62
- SDG**  
Sustainable Development Goals. 19, 22
- SSP** Shared Socioeconomic Pathways. 30, 31, 36
- SUV**  
Sports Utility Vehicles. 21
- UNFCCC**  
United Nations Framework Convention on Climate Change. 27
- URR**  
Ultimate Recoverable Resource. 65
- WMC**  
Model of Warming Commitment. 27
- YLDs**  
Years Lived with Disability. 218
- YLLs**  
Years of Life Lost. 218



# CHAPTER 1 | INTRODUCTION

For most of human history, the amount of energy used by humans was relatively small in comparison to the total energy input to the biosphere. With the advent of the industrial revolution, humans gained the ability to increase their energy consumption to a level comparable to that of the entire biosphere (Wagner et al., 1993; Lenton et al., 2016). Energy transformation allows changes to occur. Such high levels of energy use have thus allowed humans to radically transform the world we live in. It led to the introduction of the concept of Anthropocene, which considers the current geological epoch to be human-dominated (Crutzen, 2002).

The impacts of humans on the biosphere have increased together with this energy use (Steffen, Sanderson, et al., 2005). To avoid unacceptable environmental changes, Rockström and colleagues introduced the concept of planetary boundaries. These boundaries are critical processes regulating the Earth system's functioning and should not be transgressed (Rockström et al., 2009). In the most recent update of the work, the nine principal boundaries identified were: climate change, novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biochemical flows, freshwater use, land-system change and biosphere integrity (Steffen, Richardson, et al., 2015). Five of these boundaries have already been transgressed: novel entities, biogeochemical flows, land-system change, biosphere integrity and climate change (Persson et al., 2022).

Navigating back into a safe operating space for humanity requires a holistic approach (Q. Li et al., 2021). For example, Sustainable Development Goals (SDG) (Nations, 2015) are interrelated with resource use, in particular with water, energy, food, materials and land use (Bleischwitz et al., 2018). These interrelations can be tackled through a nexus approach in order to un-silo thinking and emphasize trade-offs. Bleischwitz and colleagues highlighted the resources needed to reach SDG 2 (zero hunger), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), SDG 13 (climate action), SDG 14 (life below water) and SDG 15 (life on land).

To reach both human needs and the preservation of the planet's life support systems, the concept of "safe and just space" was introduced for humanity to thrive in the middle of the doughnut economics (Raworth, 2017; Raworth, 2012). However, no country currently meets the social outcomes desired by citizens (such as food, education, health or transportation) with

a sustainable level of resource use (Daniel W. O’Neill et al., 2018). Based on current relationships, reaching universal high level of life satisfaction would require resource use at levels 2-6 times higher than the sustainable level (Daniel W. O’Neill et al., 2018). There is therefore a need to decouple resource use from human needs. Research on this topic is developed under the concept of provisioning systems, defined by Fanning and colleagues as “a set of related elements that work together in the transformation of resources to satisfy a foreseen human need” (Fanning, O’Neill, et al., 2020). Deep transformations of these provisioning systems are needed as current trends will only exacerbate the ecological crisis while failing to eliminate social shortfalls (Fanning, Daniel W. O’Neill, et al., 2022).

Furthermore, some countries suffer from the double burden of not reaching social thresholds and facing the environmental and social costs of the extraction of resources used elsewhere. Global North alone is responsible for 74% of material use in excess of equitable and sustainable boundaries, China being responsible for 15% and the rest of Global South of only 8% (Hickel, Daniel W O’Neill, et al., 2022). Via trade, the impact of excess resource consumption in the Global North is offshored to the Global South (Hickel, Dorninger, et al., 2022). Similar results were found for climate change where the Global South was responsible for only 8% of excess emissions over the period 1850 to 2015 (Hickel, 2020).

To strengthen our understanding of the chain going from resource extraction from the biosphere all the way to human needs such as transportation or healthcare, this thesis aims to build a stock and flow model of the world’s infrastructures, with regionalized impacts.

Section 1.1 introduces the concept of energy and resources services cascades, provides an explanation of the role of stocks in society and concludes on the need to develop models to better understand the stock-flow-services nexus. Section 1.2 introduces socioeconomic metabolism and its associated research strands, which is the research paradigm in which this thesis takes place. Section 1.3 describes Integrated Assessment Models, their current limits from a socioeconomic metabolism perspective and the initiatives to overcome these limits. Section 1.4 presents the research gap, aim, objectives and questions of this thesis. Section 1.5 provides the structure of the thesis as well as the list of publications and contributions to these publications.

## **1.1. THE STOCK-FLOW-SERVICE NEXUS**

### **1.1.1. ENERGY AND RESOURCES SERVICE CASCADES**

Steering humanity towards the safe and just space requires to link planetary boundaries to human consumption, their main socio-economic driver (M. Li et al., 2021). Indeed, resource use does not occur ‘per se’ but to provide a service which can ultimately be linked to human needs. This idea has been abundantly discussed for the case of energy, through the lens of energy services (Fell, 2017). After a literature review of one hundred and eighty-five articles, Fell and colleagues defined energy services as “those functions performed using energy which are means to obtain or facilitate desired end services or states”.

However, while this focus on end states clearly defines the energy service of burning fuel in a car or in a heater, the energy service provided by industrial energy use is unclear (Kalt et al., 2019). For example, what is the energy service provided by high temperature heat in a factory? When assessing the service provided by energy it is important to consider the entire value chain. To reconcile different approaches, Kalt and colleagues introduced the Energy Service Cascade (ESC) conceptual framework. Inspired by the Ecosystem Services Cascade (Haines-Young et al., 2010), it comprises five elements: structures (the entire energy-conversion chain, including passive systems), functions (physical actions performed by the energy chain, such as a car acceleration), services (what humans want: they differ from functions because here a human beneficiary is identified), benefits (the contribution of services to aspects of well-being, for example the thermal comfort service contributes to being healthy) and values (individual and societal valuation of benefits) (Kalt et al., 2019).

These disaggregations enlighten the options available to decrease energy use. For example, Sports Utility Vehicles (SUV)s are seen by Vancouver citizens as a status symbol that communicates that the driver is “successful” (Axsen et al., 2022). If values change and riding an SUV in a city starts communicating a negative message of useless GHG emissions, some of these citizens could trade their SUV for a bike. The climate impact of values changes (last step of the ESC) could be even bigger than changes in the structures such as making SUVs more efficient (first step of the ESC).

Energy is not the only input factor to provide services, materials are also required (Carmona et al., 2017). Whiting and colleagues have thus proposed to bridge the gap between ecosystem, energy and material services via the overarching concept of ‘Resource Service Cascade’ (Whiting et al., 2022). Expanding the ESC to ecosystem and material services allows in particular to take better account of services that are mainly dependent on material stocks.

### 1.1.2. ROLE OF STOCKS

Stocks (or manufactured capital (Chen et al., 2015)) are made of buildings, infrastructures, machinery and equipment and provide services such as food, shelter or transport (Pauliuk and Müller, 2014). Currently, half of all extracted resources is used to expand or maintain existing material stocks and globally, material stocks increased 23-fold over the period 1900-2010 (Krausmann et al., 2017). Elhacham and colleagues showed that the mass of global stocks (which they define as ‘human-made mass’: the mass embedded in inanimate solid objects that have not yet been demolished or taken out of service) has outgrown the mass of all living biosphere in 2020 (Elhacham et al., 2020). During the last century, the mass of global stocks has doubled every 20 years and it currently increases by 30 billion tons each year (Elhacham et al., 2020).

An important share of stocks corresponds to infrastructure. Infrastructures are the networked systems providing services related to energy, water, waste management, transport and telecommunication (Thacker et al., 2019). A broader definition also includes the ‘social infrastructure’ required to provide services such as healthcare, education or justice. Infrastructure

influences the attainment of every SDG and of 72% of the SDG targets (Thacker et al., 2019). Considerable investments in infrastructure will therefore be required to meet the SDGs.

However, infrastructure also has negative impacts. During the production phase, they can consist of the social (ie. dangerous working conditions, displacements) and environmental (ie. artificialisation, greenhouse gas emissions to transform raw materials into the final stock) impacts of construction (Thacker et al., 2019). Infrastructure can also be harmful during and after the use-phase in the form of ‘lock-ins’.

The term ‘lock-in’ refers to a long-term commitment to certain patterns of resource consumption and waste generation that stem from the lifetime and inflexibility of existing infrastructure and technologies (Seto et al., 2016). Such a rigid system poses significant restrictions on the ability to transition towards more sustainable alternatives. For example, a city designed around car transportation creates a lock-in effect, where the built infrastructure—roads, parking lots, bridges—promotes continued car use and hinders the integration of alternative, more sustainable modes of transport. Similarly, an energy grid constructed for fossil fuel power generation may resist transition to renewable energy sources due to technical, economic, and institutional lock-ins. Therefore, understanding and mitigating lock-in effects becomes crucial for the transformation of existing provisioning systems towards sustainability, necessitating a rethinking and redesigning of infrastructures and technologies to be flexible, adaptable, and resilient.

Krausmann and colleagues showed that if stocks were to converge towards the level of industrial countries, global stocks would increase four-fold and would prevent climate targets from being met (Krausmann et al., 2017).

### 1.1.3. NEED STOCK-BASED MODELS

Modelling society’s physical stocks provides valuable insights for decision making today. For instance, in the context of energy systems, the stock of infrastructure such as power plants, transmission lines, and residential buildings determines the current capacity for energy generation, distribution, and use. Each piece of infrastructure added to this stock has a useful lifetime spanning several decades. Therefore, the decisions made today about building new power plants or retrofitting old buildings will have impacts far into the future, shaping the trajectory of energy use and emissions (Davis et al., 2010).

Similarly, in economic systems, the stock of capital—machinery, buildings, etc.—determines the economy’s production capacity. The accumulation of capital over time is a key factor allowing economic production, and the depreciation or obsolescence of capital is a central element of economic cycles. If not enough capital or the wrong type of capital is built today, this could limit what can be produced in the coming decades or create lock-ins.

A holistic model would also have to consider accumulated pollutants or depleted resources as stocks. For instance, the concentration of greenhouse gases in the atmosphere—a stock—determines the degree of global warming. This stock results from the balance between emissions (an inflow) and natural absorption processes (an outflow), both of which have been changing

over time due to human activities and natural processes.

Stock-based models are especially valuable for understanding the interactions and feedbacks within a system. A system's behaviour emerges not only from the individual elements it comprises but also from the network of interactions among these elements and the feedbacks that these interactions generate (Meadows, 2008). For example, in an energy system, the stock of renewable energy infrastructure (such as wind turbines or solar panels) can affect the electricity price, which in turn can influence the demand for renewable energy and the investment in new infrastructure. This forms a feedback loop: as more renewable energy infrastructure is built, electricity prices may drop, potentially increasing demand for renewable energy and incentivizing further investment in renewable infrastructure (J. D. Farmer et al., 2019). Similarly, in environmental systems, the stock of pollutants can affect the health of ecosystems, which in turn can influence the rate at which pollutants are absorbed or broken down. This forms another feedback loop, where increasing pollution can degrade ecosystems, potentially reducing their capacity to absorb pollutants and leading to further increases in pollution levels (Rockström et al., 2009). By capturing these kinds of interactions and feedbacks, stock-based models can provide a more holistic and dynamic understanding of system behaviour. This can be crucial for designing effective interventions and avoiding unintended consequences.

Stock-based models can be instrumental in evaluating long-term sustainability by providing a framework to assess the dynamics between the use and renewal of resources. For example, these models can be used to examine how the depletion of a resource stock (such as a mineral resource or a fossil fuel) may evolve over time given current extraction rates and known reserves. If extraction rates far exceed the rates of natural replenishment or the discovery of new reserves, this could signal that current usage patterns are not sustainable in the long term (Olivier Vidal, Rostom, et al., 2019). Importantly, stock-based models can also incorporate factors such as technological progress that may influence the sustainability of current trends. For instance, improvements in resource efficiency or the development of new, more sustainable technologies could potentially offset the depletion of resource stocks or reduce the generation of pollutants.

Research on the stock-flow-service nexus are part of a larger research paradigm: socio-economic metabolism.

## 1.2. A SOCIOECONOMIC METABOLISM PARADIGM

### 1.2.1. DEFINITION OF SOCIOECONOMIC METABOLISM

In biology, metabolism refers to “the chemical and physical processes by which a living thing uses food for energy and growth” (*Cambridge academic content dictionary* 2009). The concept of socioeconomic metabolism extends this principle to the interactions between society and nature, positing that these interactions follow laws analogous to those governing biological systems. This concept is rooted in an interdisciplinary research tradition dating back to the 18th century (Haberl et al., 2019; M. Fischer-Kowalski, 1998; Marina Fischer-Kowalski et al., 1998).

Pauliuk and Hertwich, 2015 offer a comprehensive definition of socioeconomic metabolism as follows:

“Socioeconomic metabolism constitutes the self-reproduction and evolution of the biophysical structures of human society. It comprises those biophysical transformation processes, distribution processes, and flows, which are controlled by humans for their purposes. The biophysical structures of society (‘in use stocks’) and socioeconomic metabolism together form the biophysical basis of society.”

They further propose that socioeconomic metabolism transcends metaphorical dimensions, positioning it as a potential scientific paradigm in the sense of Kuhn – a set of “universally recognized scientific achievements that, for a time, provide model problems and solutions for a community of practitioners” (Kuhn, 1970; Pauliuk and Hertwich, 2015).

The present PhD thesis is situated within this research paradigm, focusing on the investigation of the processes and flows responsible for constructing and maintaining the stocks comprising society’s biophysical foundation. As articulated by (Pauliuk and Hertwich, 2015), the tenets of this research approach recognize that:

- Society operates within the constraints of both physical laws (such as conservation of mass, energy, and monetary resources) and social mechanisms (including cultural and economic rationale).
- These physical laws and social mechanisms are intrinsically interrelated.
- The complexity of society-nature interconnections necessitates a detailed examination of supply chains.
- A delineation exists between human society and the natural world.
- The natural world, while finite, is subject to substantial human influence and control.

In a recent review, Haberl and colleagues identified five main traditions of sociometabolic research (Haberl et al., 2019): urban metabolism, Multiscale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), biophysical economics, Material and Energy Flow Analysis (MEFA) and Environmentally Extended Input-Output Analysis (EE-IOA).

### 1.2.2. URBAN METABOLISM

Urban metabolism refers to the study of material and energy flows within urban systems (Christopher Kennedy et al., 2007). It is an important framework for understanding and managing resources in urban areas, which are often hotspots of consumption and waste production. The concept of urban metabolism offers a way to analyse the sustainability of cities, from resource inputs to waste outputs (C. Kennedy et al., 2011).

### 1.2.3. MUsIASEM

MuSIASEM is a multi-scale, integrated approach to analysing societal and ecosystem metabolism. It provides a framework for understanding how societies use resources, including energy, materials, and time (Giampietro et al., 2009). MuSIASEM emphasizes the need to consider various scales of analysis, ranging from the individual to the global level, to capture the complexity and interconnectedness of socio-ecological systems (Gerber et al., 2018). By examining the flows of energy, materials, and information within and between these scales, MuSIASEM provides insights into the structure, functioning, and sustainability of these systems. MuSIASEM facilitates the identification of key drivers and feedbacks within socio-ecological systems, highlighting the trade-offs, synergies, and constraints associated with resource use. It helps uncover systemic issues contributing to unsustainability, such as unequal resource distribution, technological lock-ins, or governance failures. This systemic understanding enables the identification of leverage points for intervention and policy-making to promote sustainability and resilience. MuSIASEM has been applied in different contexts, including rural systems, mining, urban waste management and the nexus between resources such as food, water, and energy (Haberl et al., 2019).

### 1.2.4. BIOPHYSICAL ECONOMICS

Biophysical economics is an interdisciplinary approach that integrates the laws of physics, particularly the second law of thermodynamics, with economic principles. It recognizes that economic systems are embedded within the physical world and subject to its fundamental constraints. This perspective emphasizes the importance of energy and resources in economic activities and their relationship to sustainability. One key concept in biophysical economics is "energy return on investment" (EROI), which refers to the ratio of energy obtained from a particular energy source to the energy invested in its extraction and processing. High EROI sources are considered more economically viable and efficient, while low EROI sources may have significant economic and environmental implications (Cleveland et al., 1984). Biophysical economics also focuses on the links between exergy and the economy. Exergy refers to the maximum useful work that can be extracted from a system as it reaches equilibrium with its surroundings (Brockway, 2023). Unlike energy, which is a measure of quantity, exergy represents the quality or usefulness of energy (Romero et al., 2014). It takes into account factors such as temperature, pressure, and composition to evaluate the exergetic efficiency of processes and systems. In biophysical economics, exergy analysis is used to assess the role of energy as a factor of production (Santos et al., 2018).

### 1.2.5. MATERIAL AND ENERGY FLOW ANALYSIS

MEFA is a systematic approach used in industrial ecology to quantify and analyze the flows of materials and energy within a given system. MEFA provides valuable insights into resource use, waste generation, and the environmental impacts associated with industrial processes and

societal activities. MEFA involves tracking the flow of materials and energy from extraction through production, consumption, and waste management stages. It accounts for both direct and indirect flows, considering inputs from primary extraction, intermediate processes, and final consumption. By analyzing these flows, MEFA helps identify the sources, pathways, and destinations of materials and energy within a system.

### 1.2.6. ENVIRONMENTALLY EXTENDED INPUT-OUTPUT ANALYSIS

EE-IOA is a quantitative method used to assess the environmental impacts associated with the economic activities of a particular region or country. It's an extension of traditional input-output analysis, a technique that describes interdependencies between different sectors within an economy. EE-IOA adds an environmental dimension to these economic transactions, accounting for the direct and indirect environmental pressures, such as emissions or resource use, associated with the production, consumption, and trade of goods and services (Miller et al., 2009). EE-IOA is a powerful tool for understanding the full life-cycle environmental impacts of economic activities. It enables researchers to track environmental pressures along global supply chains and to allocate these pressures to the final consumption activities that ultimately drive production (Wiedmann, 2009). EE-IOA thus serves as the basis for “consumption-based” environmental accounting, which allocates environmental impacts to the place where goods are consumed, rather than where they are produced (“production-based” account).

Socioeconomic metabolism research sheds light on the patterns, driving factors, systemic feedbacks, and sustainability implications of resource use. It also uncovers non-linear society-nature interactions, such as saturation functions between social progress indicators and resource flows or material stocks. Additionally, it highlights the potential for lock-in effects and legacies tied to the build-up of material stocks, such as future greenhouse gas emissions resulting from existing infrastructures (Haberl et al., 2019). Most of these insights are missing from mainstream methodologies based on monetary or social data (Haberl et al., 2019).

## 1.3. INTEGRATED ASSESMENT MODELS (IAMs)

Section 1.1.3 identified the need to model society's stocks and flows to serve as a biophysical basis for a larger model of economy-environment interactions. Section 1.2 described socioeconomic metabolism, which provides plenty of methods to assess this biophysical basis. Section 1.3 will describe the limitations of existing models of economy-environment interactions and conclude that new models are needed.

### 1.3.1. DESCRIPTION AND HISTORY

Integrated Assessment Models (IAMs) refer to a computer simulation integrating multiple disciplines and dimensions to represent complex interactions and feedbacks between human

and natural systems, with the explicit objective of being useful for policy making (Capellán-Pérez, 2016; Beek et al., 2020). Two main IAMs types can be distinguished. The first is cost-benefit analysis IAMs that aim, for example, to determine an optimal degree of global warming by comparing the costs of mitigation with the costs of adaptation. A second type corresponds to technology-rich (process-based) IAMs which allow detailed assessments of the links between economy, energy end climate change via a high disaggregation of technologies.

Although IAMs are only supposed to inform policy makers, they often have the potential to shape the world by narrowing the possible futures explored (Beck et al., 2017; Beck et al., 2018; Keyßer et al., 2021; Koasidis et al., 2023). Based on this observation, van Beek and colleagues reviewed the IAM literature over the period 1970-2015 through the lens of the science-policy interface and identified five main phases (Beek et al., 2020).

The first phase (1970-1985) is the emergence of global modelling together with the development of computers, the most notorious models being the World2 and World3 models used for the “Limits to Growth” project (Meadows et al., 1972). World3 was not called an IAM but was the first attempt to use computer science to explore possible long-term futures (Beek et al., 2020). Following the 1974-74 oil crisis the first energy-economy models were created. The first climate models were versions built on these energy-economy models but were constrained by peak CO<sub>2</sub> concentrations (W. Nordhaus, 1975). This work by Nordhaus led to the creation of the first cost-benefit analysis type IAM, the Dynamic Integrated Climate and Economy (DICE) model (W. D. Nordhaus, 1993). In terms of policy, this first phase coincided with the first United Nations Conference on Human Environment in 1972 and on the creation of the International Institute for Applied Systems Analysis (IIASA) to promote scientific cooperation (Beek et al., 2020). DICE had a considerable early impact as the National Academy of Science advising to focus efforts on climate change adaptation rather than mitigation (Beek et al., 2020).

During the second phase (1985-1992), the links between IAMs and policy started tightening as the interest of the international community to environmental problems increased: First World Climate Conference (1979), Vienna Convention (1985), Montreal Protocol (1987), establishment of the Intergovernmental Panel on Climate Change (IPCC) (1988), Second World Climate Conference (1990) and the creation of the United Nations Framework Convention on Climate Change (UNFCCC) (Beek et al., 2020). The first model to be explicitly used to formulate policy is the Regional Acidification Information and Simulation (RAINS) model developed at IIASA to model the links between sulphur emissions and acid rains (Hordijk, 1995). RAINS inspired researchers to build climate IAMs, depicted by the creation in the 1980s of the Model of Warming Commitment (WMC), the Atmospheric Stabilization Framework (ASF), and the Integrated Model to Assess the Global Environment (IMAGE) (Beek et al., 2020). The ASF and IMAGE models were used to build scenarios for the IPCC as they could have a similar design as the climate models used by Working Group (WG) I (the group that examines the physical basis of climate change). The results from these runs were policy relevant as they depicted the future climate trajectory without policy interventions (Beek et al., 2020).

The third phase (1992-1997), between the Rio Earth Summit (1992) and the Kyoto Protocol

(1997) consisted in a shift towards quantified emission targets (Beek et al., 2020). From 1990 to 1997, the number of IAMs rose from three to 40, and became widely used by IPCC's WGIII (the group that focuses on climate change mitigation) (Sluijs et al., 1998). The objective was to be able to write reports on the socio-economical impacts of climate change with the same rigor as the physicists from WGI (Beek et al., 2020). IAMs provided windows of emissions with lower and higher bounds that would keep the world in a tolerable space of climate change and thereby contributed to the adoption of the 2°C target and the quantified engagements of Kyoto (Beek et al., 2020).

The fourth phase (1997-2009) was characterized by the growing influence of WGIII in the IPCC (Beek et al., 2020). To overcome critiques of a lack of inputs from social sciences in the reports, the IPCC started to use qualitative storylines involving a wide range of perspectives (Nakicenovic et al., 2000). The ambition to have a coherent vision with inputs from many disciplines made the use of IAM indispensable and led to the predominance of process-based IAMs in opposition to the historical Cost-Benefit Analysis IAMs (CBA-IAMs) (Beek et al., 2020). The IAM community, gathered around the IAM Consortium created in 2007, started having a central role of connecting the working groups and ensuring their coherency. During this phase, IAMs also started being used to evaluate mitigation scenarios (Beek et al., 2020).

The fifth phase (2009-2015), between the Copenhagen Conference (2009) and the Paris Agreement (2015), marked a shift from a top-down to a bottom-up approach in the national climate commitments. Over this period, the number of journal publications based on IAMs exploded and IAMs served as the “backbone” of the fifth assessment report, by showing the feasibility of the 2°C target (Beek et al., 2020). This coincided with the development of the idea of negative emissions, to keep feasible ambitious targets while emissions were still rising (Gasser et al., 2015).

Overall, an appetite of policy makers for quantified predictions contributed to the increasing influence of IAMs since the first models were created. Over the period studied, IAMs not only responded to the requests of policy makers but also actively contributed shaping policy changes (Beek et al., 2020). Despite numerous improvements since their creation, IAMs still face many criticisms, some of which are detailed in the next section.

### 1.3.2. GENERAL CRITICISMS

#### 1.3.2.1. TECHNOLOGICAL OPTIMISM BIAS

One of the main criticisms of technology-detailed IAMs is technological optimism bias. Technological optimism bias refers to the tendency of IAMs to assume that new or unproven technologies will be developed and adopted rapidly enough to achieve climate targets. This is often seen in IAMs' projections about the use of technologies such as Carbon Capture and Storage (CCS), advanced bioenergy, or even more speculative options such as direct air capture (Vaughan et al., 2016; Realmonte et al., 2019). For example, many IAMs that explore pathways to limit global warming to 1.5 or 2 degrees Celsius rely heavily on the widespread deployment of Bioenergy with Carbon Capture and Storage (BECCS) in the second half of the century (Fuss

et al., 2014). BECCS is attractive in these models because it is a form of negative emissions technology – it not only produces energy but also removes CO<sub>2</sub> from the atmosphere. However, while BECCS is technically feasible, it has not yet been deployed at scale, and there are significant challenges and uncertainties regarding its future scalability, cost, and environmental and social impacts (Smith et al., 2016). This technological optimism can create a misleading sense of security about our ability to mitigate climate change. It may lead to an overreliance on future technological solutions and underestimation of the importance of immediate emission reductions. Furthermore, it can divert attention and resources away from other important strategies such as energy efficiency, renewable energy deployment, and changes in consumption patterns (Anderson et al., 2016).

#### 1.3.2.2. UNCERTAINTIES IN PARAMETERS

Another critique is that of the uncertainties of assumptions. Technology-detailed IAMs rely heavily on future assumptions about a variety of technological parameters. These parameters can include the costs of technologies, their efficiencies, the rates at which they'll be adopted, and even their future development and improvement. These parameters can be difficult to predict and are subject to significant uncertainty (Pindyck, 2017). For instance, the cost projections of renewable technologies such as solar and wind energy, or of emerging technologies such as carbon capture and storage, are typically derived from a range of sources and methods. However, these projections often vary widely and depend on a host of uncertain factors, including future technological advancements, economies of scale, market conditions, policy support, and resource availability. Similarly, the rate at which new technologies are adopted can depend on a wide variety of factors, including not just the cost and performance of the technology itself, but also market conditions, policy support, social acceptance, and infrastructure availability, among others. Predicting these factors over the long term is inherently uncertain. Such uncertainties are inherent in modelling such complex and systemic issues.

Another aspect relates to structural uncertainty, which is the uncertainty about the correct mathematical representation of the systems being modelled. This is especially the case for cost-benefit assessment IAMs for which uncertainties surrounding these economic findings cast doubt on their accuracy, questioning whether policymakers and the public should rely on them (Rosen et al., 2015). A more reasonable strategy being to prioritize implementing climate change mitigation policies due to the urgent physical crisis at hand (Rosen et al., 2015). The problem is not so much uncertainties in itself but the fact that “IAM-based analyses of climate policy create a perception of knowledge and precision that is illusory and can fool policy-makers into thinking that the forecasts the models generate have some kind of scientific legitimacy” (Pindyck, 2017).

#### 1.3.2.3. LACK OF BEHAVIOURAL AND INSTITUTIONAL FACTORS

While IAMs focus extensively on physical and economic dimensions, they are often critiqued for their oversimplification or lack of consideration for behavioural and institutional fac-

tors. These factors, which include individual and collective human behaviours, social norms, political systems, regulatory frameworks, and market failures, can significantly influence the adoption and effectiveness of different technologies and policies (McCollum et al., 2017). For example, IAMs may assume that energy consumers behave rationally and have perfect information, leading them to choose the most cost-effective technologies. However, in reality, consumer behaviour can be influenced by a variety of factors, such as habits, cultural preferences, lack of information, or aversion to risk, leading to less-than-optimal decisions (Frederiks et al., 2015). Similarly, IAMs often assume that policies can be implemented smoothly and that markets work efficiently. In practice, however, regulatory barriers, political opposition, or market failures, such as unpriced externalities or imperfect competition, can hinder the deployment of certain technologies or the effectiveness of policies (Jaffe et al., 2005). Addressing this criticism involves incorporating more realistic representations of behaviour and institutions in IAMs. This could involve, for example, using insights from behavioural economics, social sciences, or political science, or exploring a wider range of scenarios that reflect different behavioural or institutional assumptions.

#### 1.3.2.4. EQUILIBRIUM ASSUMPTIONS

IAMs, particularly those based on a neoclassical economic framework, often assume that economies operate in or near a state of equilibrium. This means that supply and demand in different markets balance each other, and the economy moves smoothly towards an optimal state over time (Böhringer et al., 2009). However, this assumption has been criticized for being overly simplistic and not accurately reflecting real-world dynamics. In reality, economies often operate far from equilibrium due to various frictions, shocks, and non-linearities. These can include, for example, market failures, technological disruptions, financial crises, or abrupt changes in policy or consumer behaviour (J. Doyne Farmer et al., 2009). IAMs may not adequately capture the potential for path dependencies, where early decisions and events significantly shape future trajectories and limit the range of feasible options. This could lead to overoptimistic projections of the speed and ease of energy transitions. Furthermore, the equilibrium assumption may limit the ability of IAMs to capture the potential for systemic risks and cascading failures, which could significantly disrupt energy systems and economies (Helbing, 2013).

Furthuremore, the driving force of IAMs is optimization through cost minimization. However, this approach hasn't been validated by historical data, which raises questions about its reliability for making future projections.

#### 1.3.2.5. POST-GROWTH CRITIQUE OF THE SHARED SOCIOECONOMIC PATHWAYS

In order to generate quantifiable projections and analyses, IAMs used the Shared Socioeconomic Pathways (SSPs) as input data (B. O'Neill et al., 2015). SSPs are global narratives or scenarios that depict potential pathways of societal development in the absence of climate change mitigation or adaptation. They were created to aid research on climate change impacts, adaptation, and mitigation. The SSPs comprise five pathways that describe alternative trends

in the evolution of society and ecosystems over the 21st century. Each pathway represents a different level of challenges to mitigation and adaptation to climate change. The five SSPs are (Riahi et al., 2017):

SSP1: Sustainability - Taking the Green Road (Low challenges to mitigation and adaptation): This scenario envisions a world making relatively good progress towards sustainability, with ongoing efforts to improve access to education and healthcare, reduce inequality, and protect the natural environment.

SSP2: Middle of the Road (Medium challenges to mitigation and adaptation): This pathway represents a world that continues much as it has in the recent past, with some progress towards achieving development goals, reductions in resource and energy intensity, and slowly decreasing fossil fuel dependency.

SSP3: Regional Rivalry - A Rocky Road (High challenges to mitigation and adaptation): This scenario depicts a world of increasing nationalism and regional self-reliance, characterized by a focus on national or regional security and economic development, leading to fragmented policies and slow progress on global environmental concerns.

SSP4: Inequality - A Road Divided (Low challenges to mitigation, high challenges to adaptation): This pathway envisions a highly unequal world where a well-educated global elite pushes for sustainability, but the benefits are largely confined to this group.

SSP5: Fossil-Fueled Development - Taking the Highway (High challenges to mitigation, low challenges to adaptation): This scenario represents a world pursuing rapid economic growth with little regard for the environment, leading to high greenhouse gas emissions and significant challenges for mitigation.

Each SSP provides a detailed narrative of potential global futures and is associated with quantifiable measures such as population, economic growth, urbanization, and rate of technology development. The SSPs are used in conjunction with Representative Concentration Pathways (RCPs) - which represent different greenhouse gas concentration trajectories - to produce a range of scenarios for climate impact, adaptation, and mitigation research (B. O'Neill et al., 2015; Riahi et al., 2017).

Several critiques can be made to SSPs and thus to the results of IAMs based on a post-growth perspective. All SSPs are based on a continuation of economic growth. This is problematic for two reasons. First, it is increasingly recognized that perpetual economic growth is ecologically unsustainable (Jackson, 2016). Second, there is a growing body of evidence suggesting that beyond a certain point, economic growth does not necessarily lead to increases in wellbeing (Daniel W. O'Neill et al., 2018). This failure to incorporate degrowth scenarios limits the range of futures considered by IAMs and may exclude potentially desirable and sustainable pathways. A pilot study has shown that degrowth scenarios minimize many key risks for feasibility and sustainability of 1.5°C scenarios (Keyßer et al., 2021).

The SSPs do not adequately model the convergence between the Global North and the Global South. Post-growth research emphasizes the need for wealthy nations to reduce their consumption to allow poorer nations room for necessary growth (Hickel and Kallis, 2020). This concept of "contraction and convergence" is not adequately represented in the SSPs, which

predominantly focus on how the Global South can "catch up" to the consumption levels of the Global North.

### 1.3.3. THE INDUSTRIAL ECOLOGY CRITIQUE

Industrial ecology takes its roots in the 19th century but the term started being widely used in the early 1990s (Erkman, 1997). In the introduction paper to the 1992 Industrial Ecology colloquium held at the National Academy of Science, Industrial Ecology was defined as "a concept in which an industrial system is viewed not in isolation from its surrounding systems but in concert with them" (Jelinski et al., 1992). Since then, industrial ecology has developed state of the art methods to better understand the interactions between society, technology, resources, and the environment (Weisz et al., 2015). The methods used in industrial ecology overlap with some of those used in sociometabolic research (described in section 2) and include life-cycle assessment, environmental input-output analysis, material flow analysis, analysis of industrial symbiosis and urban metabolism studies (Pauliuk, Arvesen, et al., 2017; Haberl et al., 2019).

In an in-depth review of five major technology rich and scenario-based IAMs, Pauliuk and colleagues identified six categories of IAM limitations from an industrial ecology perspective (Pauliuk, Arvesen, et al., 2017). First, supply chain impacts in physical or monetary units are not always considered when there are shifts from one technology to another. For instance, the production of low-carbon capital might be more resource-, capital-, or energy-intensive than that of fossil capital. If the entire value chains are not considered, inconsistencies in the model may arise. This lack of comprehensive supply chain modelling can result in underestimations or overestimations of the potential impacts and trade-offs associated with different technological pathways. Second, the annual raw material consumption, when it is considered, is not constrained by the demand of physical stocks. This is inconsistent with a socioeconomic metabolism paradigm, which posits that material flows (including raw material consumption) are intrinsically linked to the accumulation and depreciation of physical stocks in the economy. Third, among the models reviewed, only one model fully represented the entire life cycle of steel. However, the steel demand in this model was driven by Gross Domestic Product (GDP) and not stocks. For all other raw materials and models, the value chain was not modelled. This can hamper the assessment of crucial levers for emissions reduction, such as recycling and lightweighting. Fourth, IAMs typically do not explicitly incorporate waste generation, waste treatment, and recycling in their assessment of emission mitigation potential. Notable exceptions include a few models that consider cogeneration of heat and power or electricity from fuel use in industries. This omission overlooks the potential contribution of waste management and recycling strategies in reducing greenhouse gas emissions. Fifth, Most IAMs do not model physical capital stocks or do so without employing vintage tracking, which is the tracking of capital stocks according to their year of manufacture or installation. This can limit the realism and accuracy of the models, particularly in terms of capturing the inertia in technological systems due to existing capital stocks. Sixth, while IAMs often have a high level of detail for energy systems, a more comprehensive description of other sectors could enhance the robustness of mitigation

analyses. This could involve, for example, more detailed modelling of transportation, industry, or building sectors.

It is this industrial ecology critique of technology-rich IAMs which will be at the heart of this PhD thesis.

#### 1.3.4. RAW MATERIALS IN IAMS

IAM modelers are well aware of the limitations of their models and are constantly improving them.

Pauliuk and colleagues' review (section above) focused solely on technology-rich IAMs. The technology-rich aspect refers to the models' ability to represent various existing and potential future technologies in detail (such as power generation, transportation or buildings), including their costs, efficiencies, and lifetimes. This granularity allows for an explicit depiction of energy and emissions mitigation technologies, and can provide insight into the implications of different technological pathways and policy measures for energy use and emissions.

This subsection starts by giving the example of a non-technology-rich IAM that provides a precise description of raw material sectors (the WORLD models). It then gives examples of the use of industrial ecology to improve technology-rich IAM results.

##### 1.3.4.1. RAW MATERIALS IN WORLD7

Some non-technology-rich IAMs do include industrial ecology and raw materials in particular. This is for example the case of the WORLD7 model (Harald Ulrik Sverdrup, Olafsdottir, Ragnarsdottir, Stjernquist, et al., 2019). Rather than focusing primarily on energy systems and their related technologies, the WORLD7 model takes a broader perspective. It investigates the interactions among human population, economic growth, non-renewable and renewable resource availability, pollution, and land use. Its systems dynamics methodology allows it to account for feedback loops and time lags in these complex systems.

The development of the WORLD7 model builds on the systems dynamics methodology and traces its lineage from early global socioeconomic models developed by Forrester and Meadows. These models evolved from World1 to World3, each increasing in complexity but limited by computational constraints of their respective times. WORLD7, by Sverdrup and colleagues, introduces comprehensive adjustments that account for market dynamics, financial economics, governance, demographics, and social processes. WORLD7 is significantly more detailed, distinguishing between different types of natural resources, establishing more sophisticated economic models, addressing different types of pollution, and integrating social aspects, such as wage distribution, well-being metrics, and quality of governance (Harald Ulrik Sverdrup, Olafsdottir, Ragnarsdottir, Stjernquist, et al., 2019).

The WORLD7 model, by focusing on physical flow of resources, provides strategic long-term resource assessments that show the total energy production costs in relation to the energy use for different materials. It shows the rise in energy demand as ore quality declines, which could eventually exceed available energy. The model also examines metal availability and sug-

gests that energy and material extraction will increasingly consume a significant fraction of the GDP. It contains sub-modules for almost all raw materials, among which, sand, gravel, crushed stone and rock (Harald U. Sverdrup et al., 2017), molybdenum and rhenium (Harald Ulrik Sverdrup, Olafsdottir, Ragnarsdottir, and Koca, 2018), niobium and tantalum (Harald Ulrik Sverdrup and Olafsdottir, 2018), stainless steel (Harald Ulrik Sverdrup and Olafsdottir, 2019), helium (Olafsdottir et al., 2020), phosphorus (Frolova et al., 2021), cement (Harald Ulrik Sverdrup and Olafsdottir, 2023a), cobalt (Harald Ulrik Sverdrup, Ragnarsdottir, et al., 2017), steel (Pinto et al., 2019), nickel (Olafsdottir et al., 2021), vanadium (Harald Ulrik Sverdrup and Olafsdottir, 2023b), copper, zinc and lead (Harald Ulrik Sverdrup, Olafsdottir, and Ragnarsdottir, 2019), or mercury (Harald Ulrik Sverdrup and Olafsdottir, 2020).

The main strength of models like WORLD7 (or MEDEAS (Capellán-Pérez, I. d. Blas, et al., 2020)) is that unlike other IAMs, it is truly systemic, in the sense that it simultaneously assesses the dynamics of a wide range of resources, materials, population, and economy within a unified framework. However, this systemic perspective necessitates a certain level of abstraction from detailed subsystems, as excessive detail could compromise the overarching, holistic nature of the model. Therefore, other technology-rich IAMs could allow to study raw materials with more details, for example by describing precisely end-use sectors for various technologies, their raw material contents, lifetimes, etc. Such a model would be more precise for some variables but way less systemic. This is the case for MATER, the model that will be presented in chapter 2.

#### 1.3.4.2. RAW MATERIALS IN MEDEAS-WILLIAM

The MEDEAS modeling framework (now developed as WILLIAM in the LOCOMOTION project) is an open-source integrated assessment model developed to guide decision-making towards sustainable energy systems. It encompasses several crucial aspects, such as biophysical constraints, economic, social, and technological limitations, and potential mineral scarcities and their impacts on net societal energy. The model also integrates a detailed sectoral economic structure using an input-output analysis within a system dynamics approach and offers a comprehensive set of socio-economic and environmental indicators. One of the main benefits of the MEDEAS model is its ability to capture dynamics and implications that are often overlooked in traditional models. The model's simulations suggest that if current trends continue, significant biophysical scarcities and impacts are likely to result, potentially leading to regionalization, conflict, and a severe global crisis that could threaten the stability of modern civilization. Despite these concerning projections, the model provides a realistic counterfactual scenario that can aid in designing more sustainable pathways for the future (Capellán-Pérez, I. d. Blas, et al., 2020).

The demand for materials in the MEDEAS model stems from two primary sources: bottom-up estimates from variable renewables and batteries, and regression over GDP for the rest of the economy. The model also incorporates the total primary demand for materials and estimates potential material shortages by comparing it with geological availability. A new submodule has been developed and integrated within the IAM MEDEAS-World model to address material requirements for transportation. The module features a combination of material intensities and

technical performance factors for each transport technology with new infrastructure to calculate total material demand, a recycling rate determining primary extraction coverage, modeling of material stocks in other sectors using a stylized approach with a 40-year average residence time, and consideration of EV battery sub-technology allocation based on material scarcities and Energy Stored On Investment (Pulido-Sánchez et al., 2022).

MEDEAS and WORLD7 are the two models that are the most consistent with industrial-ecology principles while being systemic.

#### 1.3.4.3. RAW MATERIALS IN IMAGE

Most technology-rich IAMS provide limited details of industrial energy use and are not constrained by the energy demand of raw material production (O. Y. Edelenbosch et al., 2017). To improve the description of industrial sub-sectors in IAMS, Kermeli and colleagues have investigated how to add bottom-up details in technology-rich IAMS. As a case study, they have reviewed how the cement sector was currently modelled in major IAMS and improved the cement sector description in the IMAGE model (Kermeli, Oreane Y. Edelenbosch, Crijns-Graus, Ruijven, Mima, et al., 2019). Out of the eight IAMS studied (AIM-CGE, DNE 21 +, GCAM, IMAGE, POLES, TIAM-UCL, Imaclim-R, MESSAGE), six provided a disaggregation of the industrial sector but only DNE 21+ and IMAGE explicitly considered the cement industry (Kermeli, Oreane Y. Edelenbosch, Crijns-Graus, Ruijven, Mima, et al., 2019). POLES also had a specific cement module which could be activated if needed. They suggest that long-term energy modelling of the cement industry could benefit from a bottom-up approach, focusing on modelling cement demand rather than energy demand directly, disaggregating the non-metallics sector, incorporating regional production technologies, considering material efficiency such as reduced clinker-to-cement ratio, and evaluating retrofit options (Kermeli, Oreane Y. Edelenbosch, Crijns-Graus, Ruijven, Mima, et al., 2019). By implementing these improvements in the IMAGE model, they show that the inclusion of retrofitting and the modelling of clinker content in cement have an important impact on the results (Kermeli, Oreane Y. Edelenbosch, Crijns-Graus, Ruijven, Mima, et al., 2019).

In a subsequent paper, Kermeli and colleagues focus on the differences between flow-based and stock-based approaches of steel-demand projections in IAMS and potential avenues for enhancement (Kermeli, Oreane Y. Edelenbosch, Crijns-Graus, Ruijven, Vuuren, et al., 2022). A stock-based approach would be better than a flow-based approach for two reasons. Firstly, it would allow for more realistic modelling of material demand through reduced demand for services, or through substitution of materials or function, thereby making IAMS more relevant for assessing circular economy policies and strategies. Secondly, by using the age distribution of the in-use steel stock, the amount of retired steel could be calculated, which could contribute to more accurate forecasting of steel production routes, each with distinct energy usage, thus improving the modelling of total energy use and GHG emissions. However, when steel demand is calculated, IAMS do so with a flow approach, where steel consumption is directly correlated with income levels. To overcome this limitation, Kermeli and colleagues develop a stock-based method for the calculation of the steel demand in the IMAGE IAM. Using different lifetimes

by sectors and recycling rates allows them to have a much more precise estimation of future demand. They show that with the stock-based approach, steel demand in 2100 is 38% lower than with the flow-based approach (1600 Mt vs. 2600 Mt) (Kermeli, Oreane Y. Edelenbosch, Crijns-Graus, Ruijven, Vuuren, et al., 2022).

The calculations by Kermeli and colleagues are based on GDP-based S-curves of stocks of raw materials in four aggregated categories: transportation, construction, machinery and others. Much more precision could be obtained by calculating stocks of infrastructures and equipment directly (cars, buses, surface of buildings, etc.), to better distinguish between raw materials and allow to study material efficiency levers.

#### 1.3.4.4. CALCULATING RAW MATERIALS FROM SSPs

In a recent paper, Fishman and colleagues argue that the use of aggregate GDP-driven or historical trend extrapolations of service and/or end-use sector energy demand often leads to unreasonable service levels in SSP modelling (Fishman et al., 2021). They highlight the need to quantify of service levels associated with SSP scenarios, as well as more regional specificity in depicting differences due to socioeconomic development, societal trends, technology adaptation rates, and climate. They therefore developed a comprehensive set of scenario parameters that focus on two major contributors to greenhouse gas emissions and environmental impacts: residential buildings and private vehicles. The scenarios cover 20 world regions up to 2060 for SSP1, SSP2 and the Low Energy Demand (LED) scenario. These technological parameters can be readily used for studying material and energy cycles within the field of industrial ecology, harmonizing with pre-existing scenario sets. While these scenarios have been linked to the Resource Efficiency-Climate Change (RECC) framework, they are model-agnostic and can be used in other contexts (Fishman et al., 2021).

In a subsequent paper, Pauliuk and colleagues build from that work to assess the potential of resource and emission savings from material efficiency in residential buildings and cars (Pauliuk, Heeren, et al., 2021). They show that material efficiency could save between 33 and 58 Gt for residential buildings and passenger vehicles (Pauliuk, Heeren, et al., 2021). This result confirms the need to better describe material value chains in IAMs.

#### 1.3.5. CONTRADICTIONARY INJUNCTIONS

The GDP projections of the SSPs are developed by using an iterative process of qualitative storyline development and quantitative modelling. The overall storyline of each SSP provides a qualitative description of the future world in terms of challenges to mitigation and adaptation. This storyline is then translated into GDP by neoclassical general equilibrium models.

For example, the OECD's SSP GDP projections are generated through the ENV-Growth model, a methodology based on an augmented Solow growth model. The six key drivers of economic growth in the model include: physical capital, employment (influenced by demographic trends, labor participation rates, and unemployment scenarios), human capital (driven by education), energy demand (determined by energy efficiency and future international oil prices),

extraction and processing patterns of fossil fuel resources (oil and gas), and total factor productivity (TFP) (Dellink et al., 2017). The results present a range of potential global GDP levels by the end of the century. The spectrum varies from approximately 280 trillion USD under SSP3 to over 1000 trillion USD in SSP5, which assumes a conventional economic growth narrative. In SSP5, global GDP is projected to increase more than 15 times the 2010 level by 2100. SSP3 and SSP4, scenarios associated with lower international cooperation and trade, predict significantly lower global growth rates (Dellink et al., 2017).

The GDP is not obtained at a disaggregated sector level and technology-rich IAMs do not have GDP feedback loops. GDP is an input and not an output. This necessarily leads to contradictory injunctions. For example, in SSP1, the world GDP increases 6-fold between 2020 and 2100. At the same time, the work by Fishman and colleagues showed that the “sustainable development” of SSP1 meant a limited development and a saturation of residential building surface per capita and passenger kilometres. The implementation of SSP1 would physically mean less GDP associated with these two sectors than other SSPs. This is not taken into account in the ENV-growth model. Furthermore, if the material efficiency levers suggested by Pauliuk and colleagues were implemented, such as car sharing or downsizing, it would also mean less GDP for these sectors (Pauliuk, Heeren, et al., 2021).

Less GDP growth is not a problem in itself, as discussed extensively in the post-growth literature. However, the issue here is the blindness to the fact that injunctions may be contradictory. If all models have economic growth as an input, policymakers may not realize that some of the levers needed to tackle environmental problems will translate in less GDP in these sectors and that this is the right choice to make.

Currently, GDP and RCPs are inputs of IAMs and technological pathways are outputs. A more logical method would be the opposite: choose either a GDP (respectively an RCP) pathway, provide realistic technological progress rates (accounting for thermodynamic limits), and obtain as an outcome an RCP (respectively a GDP) pathway.

## 1.4. RESEARCH GAP, AIM, OBJECTIVES, QUESTIONS

### 1.4.1. RESEARCH GAP

Based on the above-discussed literature, the following research gap is identified:

While recent improvements in IAMs have sought to better incorporate aspects of industrial ecology, most of them still lack a detailed representation of the material and energy stocks and flows that underpin economic activities. Furthermore, when these elements are studied, it is often based on post-processing and thus leads to inconsistencies between the models' exogenous GDP inputs and the stocks consistent with various SSPs and RCPs combinations.

This gap offers an opportunity for the creation of an innovative model of the energy-raw

materials-economy nexus. The proposed model should utilize transparent and physically realistic assumptions, advancing beyond the limitations of traditional IAMs. To avoid contradictory assumptions, the input could be one of the three following variables: GDP, energy, or services. A set of physically reasonable assumptions, including yearly technological progress rates and thermodynamic limits, would allow to calculate the two other variables from the input chosen. The specifications of such a model would be

- Multiregional consumption, production and impacts
- Stock and flow consistency of infrastructures
- Vintage tracking of stocks
- Attention to physical linkages (ie. co-productions)
- Representation of material life cycles
- Explicit description of processes
- Reproduction of long term past dynamics
- Explicit technological progress rates with thermodynamic limits
- Dynamic thermodynamic limits that depend on resource quality
- Endogenous energy requirements for the industrial energy use

Once developed and operational, the model could then be softly or hardly coupled to existing IAMs to have a truly holistic representation of socioeconomic metabolism.

#### 1.4.2. RESEARCH AIM

From this research gap, the following aim was set:

The aim of this PhD thesis is to better understand the energy-raw materials-GDP-service nexus, via the construction of a multi-regional stock-flow consistent model of infrastructures and services, with regionalized impacts.

#### 1.4.3. RESEARCH OBJECTIVES

Four researchers are working at ISTerre on the development of such a model, called Multiregional Assessment of Technologies, Energy and Resources (MATER): Olivier Vidal as a senior researcher, and Hugo Le Boulzec, François Verzier and Baptiste Andrieu as PhD students. This involves to collaborate a lot and to set different research objectives for the different thesis to be complementary.

The first objective of the present thesis is to

A) Contribute to the development of MATER in terms of stocks and flows of energy and raw materials to build and maintain infrastructures for major world regions over the period 1900-2100, with a particular focus on the transport sector

Studying a period of two hundred years requires to pay particular attention to the dynamics of technological progress, which can be partly or completely compensated by the decrease in quality of the remaining exploitable resources. The second objective is thus to

B) Study the contribution of technological progress and resource dilution on the energy intensity of production of metals in order to incorporate the dynamics into MATER

Trade takes place at every step of the value chain. To explicitly describe the responsibility of the human and environmental impacts of the industry in a given region, flows of resources, semi-transformed and transformed products must be incorporated into MATER. The third objective of the thesis is thus to:

C) Regionalize the impacts of production and consumption in MATER using input-output modelling

The energy-raw materials-service nexus of some sectors, such as transport, construction or energy production have been extensively documented, making them the easiest sectors to model. However, other sectors, such as healthcare, remain under-explored. Modelling healthcare is likely to be more difficult than in other sectors, as the service given by healthcare systems, being healthy, is much vaguer than that of sectors where services can be expressed in physical units: joules of final energy, passenger-kilometres of a vehicle or m<sup>2</sup> of residential building. The fourth objective of the thesis is thus to:

D) Explore the energy-resources-health nexus

#### 1.4.4. RESEARCH QUESTIONS

To guide the work, the following research questions (RQ) and sub-research questions were defined:

For objective A:

RQ1: What could be the future multiregional energy and raw materials demands?  
 RQ 1.1. How can society's biophysical basis be modelled?  
 RQ 1.2. How can future transport demand be modelled?

For objective B:

RQ2: Can technological progress be assessed?  
 RQ 2.1. Does technological progress compensate the decrease in quality of ore deposits?  
 RQ 2.2. Are richer countries more energy efficient than poorer ones?

For objective C:

RQ3: How can environmental impacts be regionalized in a global stock-flow consistent raw-materials-energy-economy model?  
 RQ 3.1. What are all the possible input-output scopes?  
 RQ 3.2. How can input-output be incorporated into MATER?

For Objective D:

RQ4: Is there an energy-health nexus?  
 RQ 4.1. What are the biophysical bases of healthcare systems around the world?  
 RQ 4.2. Are disease rates correlated to energy footprint per capita?

## 1.5. STRUCTURE OF THE THESIS, ARTICLES LIST AND CONTRIBUTIONS

### 1.5.1. STRUCTURE

Chapter 1 is the present introduction. Chapters 2 to 5 answer research questions 1 to 4 respectively, with a section for each secondary research question. Chapter 6 concludes.

### 1.5.2. ARTICLES LIST AND CONTRIBUTIONS

#### **Chapter 2.1. is based on the following publication:**

O. Vidal, H. Le Boulzec, B. Andrieu, and F. Verzier (2022). “Modelling the Demand and Access of Mineral Resources in a Changing World”. In: *Sustainability* 14.11. doi: 10.3390/su14010011

Author contributions: Conceptualization, O.V.; methodology, O.V.; software, O.V., H.L.B., B.A. and F.V.; validation, O.V., H.L.B., B.A. and F.V.; formal analysis, O.V., H.L.B., B.A. and F.V.; investigation, O.V., H.L.B., B.A. and F.V.; resources, O.V., H.L.B., B.A. and F.V.; data

curation, O.V., H.L.B., B.A. and F.V.; writing—original draft preparation, O.V., H.L.B., B.A. and F.V.; writing—review and editing, O.V., H.L.B., B.A. and F.V.; visualization, O.V., H.L.B., B.A. and F.V.; supervision, O.V.; project administration, O.V.; funding acquisition, O.V. All authors have read and agreed to the published version of the manuscript. Baptiste Andrieu was in charge of the transport sector, regionalization of impacts.

**Chapter 2.2. is based on the following publication draft:**

François Verzier, Hugo Le Boulzec, Baptiste Andrieu, and Olivier Vidal (2023). *Multi-regional Assesment of Technologies, Energy and Resources*

The research is led by François Verzier based on a formalism by Olivier Vidal. Baptiste Andrieu is in charge of the transport sector, regionalization of impacts.

**Chapter 2.3. is based on the following publication draft:**

Andrieu, B., Berthe, A., Verzier, F, Le Boulzec, H., Vidal, O., Dynamic modelling of past and future resource needs for the transport infrastructure

This research was led by Baptiste Andrieu.

**Chapter 3.1. is based on the following publication draft:**

Olivier Vidal, Baptiste Andrieu, Hugo Le Boulzec, François Verzier, Florian Fizaine, and Nicholas Arndt (2023). *Modeling production energy and thermodynamic prices of metals from 1900 to 2100*

Authorship statement: Olivier Vidal: Funding acquisition, Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision. Baptiste Andrieu: Writing – original draft, Formal analysis, Validation. Hugo Le Boulzec: Formal analysis, Validation – Francois Verzier: review & editing, Nicholas Arndt: Writing – review & editing

**Chapter 3.2. is based on the following publication:**

Baptiste Andrieu, Olivier Vidal, Hugo Le Boulzec, Louis Delannoy, and François Verzier (Oct. 2022). “Energy Intensity of Final Consumption: the Richer, the Poorer the Efficiency”. In: *Environmental Science & Technology* 56.19. Publisher: American Chemical Society, pp. 13909–13919. ISSN: 0013-936X. DOI: 10.1021/acs.est.2c03462. URL: <https://doi.org/10.1021/acs.est.2c03462> (visited on 11/08/2022)

This research was led by Baptiste Andrieu

**Chapter 4.1. is based on the following publication draft:**

Baptiste Andrieu, Hugo Le Boulzec, Louis Delannoy, François Verzier, Guillaume Winter, and Olivier Vidal (2023). “Mapping global greenhouse gases emissions: an interactive, open access web application”. In: *Submitted to Communications Earth & Environment*. DOI: 10.21203/rs.3.rs-2617637/v1

This research was led by Baptiste Andrieu

**Chapter 5.1. is based on the publication draft:**

Baptiste Andrieu, Laurie Marraud, Olivier Vidal, Mathis Egnell, Laurent Boyer, and Guillaume Fond (2022). “The Exponential Relationship between Healthcare Systems’ Resource Footprints and Their Access and Quality: A Study of 49 Regions between 1995 and 2015”. In: *SSRN Electronic Journal*. DOI: 10.2139/ssrn.4182423

Authorship statement: BA was responsible for conceptualisation. All authors contributed to literature search. BA and OV were responsible for data curation. All authors contributed to data analysis and interpretation of results. BA, GF and LM wrote the original draft. All authors were responsible for writing – review & editing. All authors had access to all data in the study and the corresponding author had final responsibility for the decision to submit for publication.

**Chapter 5.2. is based on the publication draft:**

Baptiste Andrieu, Laurie Marraud, Guillaume Chevance, Mathis Egnell, Olivier Vidal, Laurent Boyer, and Guillaume Fond (Dec. 2023). *Associations between Regional Energy Footprint and the Occurrence of Diseases*. en. SSRN Scholarly Paper. Rochester, NY. DOI: 10.2139/ssrn.4673537. URL: <https://papers.ssrn.com/abstract=4673537> (visited on 01/17/2024)

This research was led by Baptiste Andrieu

**Other publications not included in the thesis** Pierre Jacques, Louis Delannoy, Baptiste Andrieu, Devrim Yilmaz, Hervé Jeanmart, and Antoine Godin (2023). “Assessing the Economic Consequences of an Energy Transition Through a Biophysical Stock-Flow Consistent Model”. In: *Ecological Economics* 209, p. 107832. DOI: 10.1016/j.ecolecon.2023.107832

Hugo Le Boulzec, Louis Delannoy, Baptiste Andrieu, François Verzier, Olivier Vidal, and Sandrine Mathy (2022). “Dynamic modeling of global fossil fuel infrastructure and materials needs: Overcoming a lack of available data”. In: *Applied Energy* 326, p. 119871. DOI: 10.1016/j.apenergy.2022.119871

Hugo Le Boulzec, Sandrine Mathy, François Verzier, Baptiste Andrieu, Daniel Monfort-Climent, and Olivier Vidal (Nov. 2023). “Material requirements and impacts of the building sector in the Shared Socioeconomic Pathways”. In: *Journal of Cleaner Production* 428, p. 139117. ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2023.139117. URL: <https://www.sciencedirect.com/science/article/pii/S0959652623032754> (visited on 01/17/2024)

Louis Delannoy, Matthieu Auzanneau, Baptiste Andrieu, Olivier Vidal, Pierre-Yves Lon-

garetti, Emmanuel Prados, David J. Murphy, Roger W. Bentley, Michael Carbajales-Dale, Marco Rauegi, Mikael Höök, Victor Court, Carey W. King, Florian Fizaine, Pierre Jacques, Matthew Kuperus Heun, Andrew Jackson, Charles Guay-Boutet, Emmanuel Aramendia, Jianliang Wang, Hugo Le Boulzec, and Charles A.S. Hall (2024). “Emerging consensus on net energy paves the way for improved integrated assessment modeling”. en. In: *Energy & Environmental Science* 17.1. Publisher: Royal Society of Chemistry, pp. 11–26. DOI: 10.1039/D3EE00772C. URL: <https://pubs.rsc.org/en/content/articlelanding/2024/ee/d3ee00772c> (visited on 01/17/2024)

Guillaume Chevance, Baptiste Andrieu, Nicolas Koch, Cathryn Tonne, Mark Nieuwenhuijsen, and Paquito Bernard (Apr. 2023). *Gasoline Price and the Effectiveness of Interventions Targeting Healthier Transport Modes: A Meta-Analysis*. en. SSRN Scholarly Paper. Rochester, NY. DOI: 10.2139/ssrn.4429015. URL: <https://papers.ssrn.com/abstract=4429015> (visited on 07/20/2023)

Louis Delannoy, Angélique Palle, Noémie Rebière, and Baptiste Andrieu (2023). “‘Strong’ transdisciplinarity in the Anthropocene: lessons from a cross dialogue between social and modeling sciences”. In: *Hérodote* 188. DOI: 10.3917/her.188.0041

Baptiste Andrieu, Manon Roche, Pierre Simeone, Marc Leone, Benjamin De Sainte Marie, Baptiste Andre, Laurent Boyer, Laurent Zieleskiewicz, and Guillaume Fond (Dec. 2023). “Navigating Healthcare’s Dual Fronts — Balancing Quality and the Environment”. In: *Revue d’Épidémiologie et de Santé Publique* 71.6, p. 102182. ISSN: 0398-7620. DOI: 10.1016/j.respe.2023.102182. URL: <https://www.sciencedirect.com/science/article/pii/S039876202300785X> (visited on 01/17/2024) (commissioned editorial)

## 1.6. REFERENCES

- Anderson, Kevin and Glen Peters (Oct. 2016). “The trouble with negative emissions”. In: *Science* 354.6309. Publisher: American Association for the Advancement of Science, pp. 182–183. DOI: 10 . 1126 / science . aah4567. URL: <https://www.science.org/doi/10.1126/science.aah4567> (visited on 05/16/2023).
- Andrieu, Baptiste, Hugo Le Boulzec, Louis Delannoy, François Verzier, Guillaume Winter, and Olivier Vidal (2023). “Mapping global greenhouse gases emissions: an interactive, open access web application”. In: *Submitted to Communications Earth & Environment*. DOI: 10.21203/rs.3.rs-2617637/v1.
- Andrieu, Baptiste, Laurie Marraud, Guillaume Chevance, Mathis Egnell, Olivier Vidal, Laurent Boyer, and Guillaume Fond (Dec. 2023). *Associations between Regional Energy Footprint and the Occurrence of Diseases*. en. SSRN Scholarly Paper. Rochester, NY. DOI: 10.2139/ssrn.4673537. URL: <https://papers.ssrn.com/abstract=4673537> (visited on 01/17/2024).
- Andrieu, Baptiste, Laurie Marraud, Olivier Vidal, Mathis Egnell, Laurent Boyer, and Guillaume Fond (2022). “The Exponential Relationship between Healthcare Systems’ Resource Footprints and Their Access and Quality: A Study of 49 Regions between 1995 and 2015”. In: *SSRN Electronic Journal*. DOI: 10.2139/ssrn.4182423.
- Andrieu, Baptiste, Manon Roche, Pierre Simeone, Marc Leone, Benjamin De Sainte Marie, Baptiste Andre, Laurent Boyer, Laurent Zieleskiewicz, and Guillaume Fond (Dec. 2023). “Navigating Healthcare’s Dual Fronts — Balancing Quality and the Environment”. In: *Revue d’Épidémiologie et de Santé Publique* 71.6, p. 102182. ISSN: 0398-7620. DOI: 10.1016/j.respe.2023.102182. URL: <https://www.sciencedirect.com/science/article/pii/S039876202300785X> (visited on 01/17/2024).
- Andrieu, Baptiste, Olivier Vidal, Hugo Le Boulzec, Louis Delannoy, and François Verzier (Oct. 2022). “Energy Intensity of Final Consumption: the Richer, the Poorer the Efficiency”. In: *Environmental Science & Technology* 56.19. Publisher: American Chemical Society, pp. 13909–13919. ISSN: 0013-936X. DOI: 10.1021/acs.est.2c03462. URL: <https://doi.org/10.1021/acs.est.2c03462> (visited on 11/08/2022).
- Axsen, Jonn and Zoe Long (Oct. 2022). “Sport utility vehicles and willingness-to-downsize: A mixed-method exploration of functional, symbolic, and societal consumer perceptions in Canada”. en. In: *Energy Research & Social Science* 92, p. 102776. ISSN: 2214-6296. DOI: 10.1016/j.erss.2022.102776. URL: <https://www.sciencedirect.com/science/article/pii/S2214629622002791> (visited on 04/24/2023).
- Beck, Silke and Martin Mahony (May 2017). “The IPCC and the politics of anticipation”. en. In: *Nature Climate Change* 7.5. Number: 5 Publisher: Nature Publishing Group, pp. 311–313. ISSN: 1758-6798. DOI: 10.1038/nclimate3264. URL: <https://www.nature.com/articles/nclimate3264> (visited on 06/23/2023).
- (Nov. 2018). “The IPCC and the new map of science and politics”. en. In: *WIREs Climate Change* 9.6. ISSN: 1757-7780, 1757-7799. DOI: 10.1002/wcc.547. URL: <https://onlinelibrary.wiley.com/doi/10.1002/wcc.547> (visited on 06/24/2023).
- Beek, Lisette van, Maarten Hajer, Peter Pelzer, Detlef van Vuuren, and Christophe Cassen (Nov. 2020). “Anticipating futures through models: the rise of Integrated Assessment Modelling in the climate science-policy interface since 1970”. en. In: *Global Environmental Change* 65, p. 102191. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2020.102191. URL: <https://www.sciencedirect.com/science/article/pii/S0959378020307743> (visited on 04/05/2023).
- Bleischwitz, Raimund, Victor Nechifor, Matthew Winning, Beijia Huang, and Yong Geng (2018). “Extrapolation or saturation – Revisiting growth patterns, development stages and decoupling”. en. In: *Global Environmental Change* 48, pp. 86–96. ISSN: 09593780. DOI: 10.1016/j.gloenvcha.2017.11.008. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959378016306550> (visited on 09/05/2021).
- Böhringer, Christoph and Thomos F. Rutherford (Sept. 2009). “Integrated assessment of energy policies: Decomposing top-down and bottom-up”. en. In: *Journal of Economic Dynamics and Control* 33.9, pp. 1648–1661.

- ISSN: 0165-1889. DOI: 10.1016/j.jedc.2008.12.007. URL: <https://www.sciencedirect.com/science/article/pii/S0165188909000529> (visited on 05/16/2023).
- Brockway, Paul E. (Feb. 2023). “Exergy”. eng. In: *Dictionary of Ecological Economics*. Section: Dictionary of Ecological Economics. Edward Elgar Publishing, pp. 216–216. ISBN: 978-1-78897-491-2. URL: [https://www.elgaronline.com/display/book/9781788974912/E\\_157.xml](https://www.elgaronline.com/display/book/9781788974912/E_157.xml) (visited on 05/16/2023).
- Cambridge academic content dictionary* (2009). eng. 1st ed. OCLC: 183392531. New York: Cambridge University Press. ISBN: 978-0-521-87143-3. URL: <http://catdir.loc.gov/catdir/toc/ecip086/2007049860.html> (visited on 04/10/2023).
- Capellán-Pérez, Iñigo (June 2016). “Development and Application of Environmental Integrated Assessment Modelling towards Sustainability”. PhD thesis.
- Capellán-Pérez, Iñigo, Ignacio de Blas, Jaime Nieto, Carlos de Castro, Luis Javier Miguel, Óscar Carpintero, Margarita Mediavilla, Luis Fernando Lobejón, Noelia Ferreras-Alonso, Paula Rodrigo, Fernando Frechoso, and David Álvarez-Antelo (2020). “MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints”. In: *Energy & Environmental Science* 13.3, pp. 986–1017. DOI: 10.1039/c9ee02627d.
- Capellán-Pérez, Iñigo, Ignacio de Blas, Jaime Nieto, Carlos de Castro, Luis Javier Miguel, Oscar Carpintero, Margarita Mediavilla, Luis Fernando Lobejón, Noelia Ferreras-Alonso, Paula Rodrigo, Fernando Frechoso, and David Álvarez-Antelo (2020). “MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints”. In: *Energy & Environmental Science* 13.3. Publisher: Royal Society of Chemistry (RSC), pp. 986–1017. DOI: 10.1039/c9ee02627d.
- Carmona, Luis Gabriel, Kai Whiting, Angeles Carrasco, Tânia Sousa, and Tiago Domingos (Sept. 2017). “Material Services with Both Eyes Wide Open”. en. In: *Sustainability* 9.9. Number: 9 Publisher: Multidisciplinary Digital Publishing Institute, p. 1508. ISSN: 2071-1050. DOI: 10.3390/su9091508. URL: <https://www.mdpi.com/2071-1050/9/9/1508> (visited on 04/07/2023).
- Chen, Wei-Qiang and T. E. Graedel (May 2015). “In-use product stocks link manufactured capital to natural capital”. In: *Proceedings of the National Academy of Sciences* 112.20. Publisher: Proceedings of the National Academy of Sciences, pp. 6265–6270. DOI: 10.1073/pnas.1406866112. URL: <https://www.pnas.org/doi/10.1073/pnas.1406866112> (visited on 04/24/2023).
- Chevance, Guillaume, Baptiste Andrieu, Nicolas Koch, Cathryn Tonne, Mark Nieuwenhuijsen, and Paquito Bernard (Apr. 2023). *Gasoline Price and the Effectiveness of Interventions Targeting Healthier Transport Modes: A Meta-Analysis*. en. SSRN Scholarly Paper. Rochester, NY. DOI: 10.2139/ssrn.4429015. URL: <https://papers.ssrn.com/abstract=4429015> (visited on 07/20/2023).
- Cleveland, Cutler J., Robert Costanza, Charles A. S. Hall, and Robert Kaufmann (Aug. 1984). “Energy and the U.S. Economy: A Biophysical Perspective”. In: *Science* 225.4665. Publisher: American Association for the Advancement of Science, pp. 890–897. DOI: 10.1126/science.225.4665.890. URL: <https://www.science.org/doi/10.1126/science.225.4665.890> (visited on 05/16/2023).
- Crutzen, Paul J. (Jan. 2002). “Geology of mankind”. en. In: *Nature* 415.6867. Number: 6867 Publisher: Nature Publishing Group, pp. 23–23. ISSN: 1476-4687. DOI: 10.1038/415023a. URL: <https://www.nature.com/articles/415023a> (visited on 04/10/2023).
- Davis, Steven J., Ken Caldeira, and H. Damon Matthews (Sept. 2010). “Future CO2 Emissions and Climate Change from Existing Energy Infrastructure”. In: *Science* 329.5997. Publisher: American Association for the Advancement of Science, pp. 1330–1333. DOI: 10.1126/science.1188566. URL: <https://www.science.org/doi/10.1126/science.1188566> (visited on 05/16/2023).
- Delannoy, Louis, Matthieu Auzanneau, Baptiste Andrieu, Olivier Vidal, Pierre-Yves Longaretti, Emmanuel Prados, David J. Murphy, Roger W. Bentley, Michael Carbajales-Dale, Marco Raugei, Mikael Höök, Victor Court, Carey W. King, Florian Fizaine, Pierre Jacques, Matthew Kuperus Heun, Andrew Jackson, Charles Guay-Boutet, Emmanuel Aramendia, Jianliang Wang, Hugo Le Boulzec, and Charles A.S. Hall (2024). “Emerging consensus on net energy paves the way for improved integrated assessment modeling”. en. In: *Energy & Environmental Science* 17.1. Publisher: Royal Society of Chemistry, pp. 11–26. DOI: 10.1039/D3EE00772C.

- URL: <https://pubs.rsc.org/en/content/articlelanding/2024/ee/d3ee00772c> (visited on 01/17/2024).
- Delannoy, Louis, Angélique Palle, Noémie Rebière, and Baptiste Andrieu (2023). “‘Strong’ transdisciplinarity in the Anthropocene: lessons from a cross dialogue between social and modeling sciences”. In: *Hérodote* 188. DOI: 10.3917/her.188.0041.
- Dellink, Rob, Jean Chateau, Elisa Lanzi, and Bertrand Magné (Jan. 2017). “Long-term economic growth projections in the Shared Socioeconomic Pathways”. en. In: *Global Environmental Change* 42, pp. 200–214. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2015.06.004. URL: <https://www.sciencedirect.com/science/article/pii/S0959378015000837> (visited on 05/10/2023).
- Edelensbosch, O. Y., K. Kermeli, W. Crijns-Graus, E. Worrell, R. Bibas, B. Fais, S. Fujimori, P. Kyle, F. Sano, and D. P. van Vuuren (Mar. 2017). “Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models”. en. In: *Energy* 122, pp. 701–710. ISSN: 0360-5442. DOI: 10.1016/j.energy.2017.01.017. URL: <https://www.sciencedirect.com/science/article/pii/S0360544217300178> (visited on 05/19/2023).
- Elhacham, Emily, Liad Ben-Uri, Jonathan Grozovski, Yinon M. Bar-On, and Ron Milo (Dec. 2020). “Global human-made mass exceeds all living biomass”. en. In: *Nature* 588.7838. Number: 7838 Publisher: Nature Publishing Group, pp. 442–444. ISSN: 1476-4687. DOI: 10.1038/s41586-020-3010-5. URL: <https://www.nature.com/articles/s41586-020-3010-5> (visited on 04/06/2023).
- Erkman, S. (Jan. 1997). “Industrial ecology: An historical view”. en. In: *Journal of Cleaner Production* 5.1-2, pp. 1–10. ISSN: 09596526. DOI: 10.1016/S0959-6526(97)00003-6. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959652697000036> (visited on 04/25/2023).
- Fanning, Andrew L., Daniel W. O’Neill, and Milena Büchs (Sept. 2020). “Provisioning systems for a good life within planetary boundaries”. en. In: *Global Environmental Change* 64, p. 102135. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2020.102135. URL: <https://www.sciencedirect.com/science/article/pii/S0959378020307184> (visited on 04/06/2023).
- Fanning, Andrew L., Daniel W. O’Neill, Jason Hickel, and Nicolas Roux (Jan. 2022). “The social shortfall and ecological overshoot of nations”. en. In: *Nature Sustainability* 5.1. Number: 1 Publisher: Nature Publishing Group, pp. 26–36. ISSN: 2398-9629. DOI: 10.1038/s41893-021-00799-z. URL: <https://www.nature.com/articles/s41893-021-00799-z> (visited on 04/10/2023).
- Farmer, J. D., C. Hepburn, M. C. Ives, T. Hale, T. Wetzler, P. Mealy, R. Rafaty, S. Srivastav, and R. Way (Apr. 2019). “Sensitive intervention points in the post-carbon transition”. In: *Science* 364.6436. Publisher: American Association for the Advancement of Science, pp. 132–134. DOI: 10.1126/science.aaw7287. URL: <https://www.science.org/doi/10.1126/science.aaw7287> (visited on 05/16/2023).
- Farmer, J. Doyne and Duncan Foley (Aug. 2009). “The economy needs agent-based modelling”. en. In: *Nature* 460.7256. Number: 7256 Publisher: Nature Publishing Group, pp. 685–686. ISSN: 1476-4687. DOI: 10.1038/460685a. URL: <https://www.nature.com/articles/460685a> (visited on 05/16/2023).
- Fell, Michael James (May 2017). “Energy services: A conceptual review”. en. In: *Energy Research & Social Science* 27, pp. 129–140. ISSN: 2214-6296. DOI: 10.1016/j.erss.2017.02.010. URL: <https://www.sciencedirect.com/science/article/pii/S2214629617300518> (visited on 04/21/2022).
- Fischer-Kowalski, M. (1998). “The Intellectual History of Materials Flow Analysis, Part I, 1860-1970”. In: URL: <https://www.semanticscholar.org/paper/The-Intellectual-History-of-Materials-Flow-Part-I-%2C-Fischer-Kowalski/c4a74407e44271e387dc621f9b04eee4fed6d39f> (visited on 04/07/2023).
- Fischer-Kowalski, Marina and Walter Hüttler (Jan. 1998). “Society’s Metabolism.: The Intellectual History of Materials Flow Analysis, Part II, 1970-1998”. In: *Journal of Industrial Ecology - JIND ECOL* 2, pp. 107–136.
- Fishman, Tomer, Niko Heeren, Stefan Pauliuk, Peter Berrill, Qingshi Tu, Paul Wolfram, and Edgar G. Hertwich (2021). “A comprehensive set of global scenarios of housing, mobility, and material efficiency for material cycles and energy systems modeling”. en. In: *Journal of Industrial Ecology* 25.2. \_eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111>

- pp. 305–320. ISSN: 1530-9290. DOI: 10.1111/jiec.13122. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.13122> (visited on 04/05/2023).
- Frederiks, Elisha R., Karen Stenner, and Elizabeth V. Hobman (Jan. 2015). “Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour”. en. In: *Renewable and Sustainable Energy Reviews* 41, pp. 1385–1394. ISSN: 1364-0321. DOI: 10.1016/j.rser.2014.09.026. URL: <https://www.sciencedirect.com/science/article/pii/S1364032114007990> (visited on 05/16/2023).
- Frolova, Liudmila L., Antoniy Elias Sverdrup, and Harald Ulrik Sverdrup (Oct. 2021). “Developing a System Dynamics Model for the Nizhny Kaban and Sredny Kaban Lakes, Kazan, Russia, Assessing the Impacts of Phosphorus and Nitrogen Inputs on Lake Ecology”. en. In: *Water, Air, & Soil Pollution* 232.11, p. 454. ISSN: 1573-2932. DOI: 10.1007/s11270-021-05371-1. URL: <https://doi.org/10.1007/s11270-021-05371-1> (visited on 07/23/2023).
- Fuss, Sabine, Josep G. Canadell, Glen P. Peters, Massimo Tavoni, Robbie M. Andrew, Philippe Ciais, Robert B. Jackson, Chris D. Jones, Florian Kraxner, Nebosja Nakicenovic, Corinne Le Quéré, Michael R. Raupach, Ayyoob Sharifi, Pete Smith, and Yoshiki Yamagata (Oct. 2014). “Betting on negative emissions”. en. In: *Nature Climate Change* 4.10. Number: 10 Publisher: Nature Publishing Group, pp. 850–853. ISSN: 1758-6798. DOI: 10.1038/nclimate2392. URL: <https://www.nature.com/articles/nclimate2392> (visited on 05/16/2023).
- Gasser, T., Céline Guivarch, K. Tachiiri, C. Jones, and P. Ciais (Aug. 2015). “Negative emissions physically needed to keep global warming below 2 °C”. In: *Nature communications* 6. DOI: 10.1038/ncomms8958.
- Gerber, Julien-François and Arnim Scheidel (Feb. 2018). “In Search of Substantive Economics: Comparing Today’s Two Major Socio-metabolic Approaches to the Economy – MEFA and MuSIASEM”. en. In: *Ecological Economics* 144, pp. 186–194. ISSN: 0921-8009. DOI: 10.1016/j.ecolecon.2017.08.012. URL: <https://www.sciencedirect.com/science/article/pii/S0921800917304822> (visited on 04/07/2023).
- Giampietro, Mario, Kozo Mayumi, and Jesus Ramos-Martin (Mar. 2009). “Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Theoretical concepts and basic rationale”. en. In: *Energy*. WESC 2006 34.3, pp. 313–322. ISSN: 0360-5442. DOI: 10.1016/j.energy.2008.07.020. URL: <https://www.sciencedirect.com/science/article/pii/S0360544208001965> (visited on 04/05/2023).
- Haberl, Helmut, Dominik Wiedenhofer, Stefan Pauliuk, Fridolin Krausmann, Daniel B. Müller, and Marina Fischer-Kowalski (Mar. 2019). “Contributions of sociometabolic research to sustainability science”. en. In: *Nature Sustainability* 2.3. Number: 3 Publisher: Nature Publishing Group, pp. 173–184. ISSN: 2398-9629. DOI: 10.1038/s41893-019-0225-2. URL: <https://www.nature.com/articles/s41893-019-0225-2> (visited on 04/05/2023).
- Haines-Young, Roy and Marion Potschin-Young (Mar. 2010). “The links between biodiversity, ecosystem service and human well-being”. In: *Ecosystem Ecology: A New Synthesis*. Journal Abbreviation: Ecosystem Ecology: A New Synthesis, pp. 110–139. ISBN: 978-0-521-51349-4. DOI: 10.1017/CB09780511750458.007.
- Helbing, Dirk (May 2013). “Globally networked risks and how to respond”. In: *Nature* 497, pp. 51–9. DOI: 10.1038/nature12047.
- Hickel, Jason (Sept. 2020). “Quantifying national responsibility for climate breakdown: an equality-based attribution approach for carbon dioxide emissions in excess of the planetary boundary”. en. In: *The Lancet Planetary Health* 4.9, e399–e404. ISSN: 2542-5196. DOI: 10.1016/S2542-5196(20)30196-0. URL: <https://www.sciencedirect.com/science/article/pii/S2542519620301960> (visited on 04/10/2023).
- Hickel, Jason, Christian Dorninger, Hanspeter Wieland, and Intan Suwandi (Mar. 2022). “Imperialist appropriation in the world economy: Drain from the global South through unequal exchange, 1990–2015”. en. In: *Global Environmental Change* 73, p. 102467. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2022.

102467. URL: <https://www.sciencedirect.com/science/article/pii/S095937802200005X> (visited on 04/21/2022).
- Hickel, Jason and Giorgos Kallis (June 2020). “Is Green Growth Possible?” en. In: *New Political Economy* 25.4, pp. 469–486. ISSN: 1356-3467, 1469-9923. DOI: 10.1080/13563467.2019.1598964. URL: <https://www.tandfonline.com/doi/full/10.1080/13563467.2019.1598964> (visited on 05/17/2023).
- Hickel, Jason, Daniel W O’Neill, Andrew L Fanning, and Huzaifa Zoomkawala (Apr. 2022). “National responsibility for ecological breakdown: a fair-shares assessment of resource use, 1970–2017”. en. In: *The Lancet Planetary Health* 6.4, e342–e349. ISSN: 25425196. DOI: 10.1016/S2542-5196(22)00044-4. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2542519622000444> (visited on 04/09/2022).
- Hordijk, L. (1995). *Integrated assessment models as a basis for air pollution negotiations*. English. Tech. rep. URL: [https://scholar.google.com/scholar\\_lookup?title=Integrated+assessment+models+as+a+basis+for+air+pollution+negotiations.&author=Hordijk%2C+L.&publication\\_year=1995](https://scholar.google.com/scholar_lookup?title=Integrated+assessment+models+as+a+basis+for+air+pollution+negotiations.&author=Hordijk%2C+L.&publication_year=1995) (visited on 04/11/2023).
- Jackson, Tim (Dec. 2016). *Prosperity without Growth: Foundations for the Economy of Tomorrow*. 2nd ed. London: Routledge. ISBN: 978-1-315-67745-3. DOI: 10.4324/9781315677453.
- Jacques, Pierre, Louis Delannoy, Baptiste Andrieu, Devrim Yilmaz, Hervé Jeanmart, and Antoine Godin (2023). “Assessing the Economic Consequences of an Energy Transition Through a Biophysical Stock-Flow Consistent Model”. In: *Ecological Economics* 209, p. 107832. DOI: 10.1016/j.ecolecon.2023.107832.
- Jaffe, Adam B., Richard G. Newell, and Robert N. Stavins (Aug. 2005). “A tale of two market failures: Technology and environmental policy”. en. In: *Ecological Economics*. Technological Change and the Environment 54.2, pp. 164–174. ISSN: 0921-8009. DOI: 10.1016/j.ecolecon.2004.12.027. URL: <https://www.sciencedirect.com/science/article/pii/S0921800905000303> (visited on 05/16/2023).
- Jelinski, L W, T E Graedel, R A Laudise, D W McCall, and C K Patel (Feb. 1992). “Industrial ecology: concepts and approaches.” en. In: *Proceedings of the National Academy of Sciences* 89.3, pp. 793–797. ISSN: 0027-8424, 1091-6490. DOI: 10.1073/pnas.89.3.793. URL: <https://pnas.org/doi/full/10.1073/pnas.89.3.793> (visited on 04/25/2023).
- Kalt, Gerald, Dominik Wiedenhofer, Christoph Görg, and Helmut Haberl (July 2019). “Conceptualizing energy services: A review of energy and well-being along the Energy Service Cascade”. en. In: *Energy Research & Social Science* 53, pp. 47–58. ISSN: 2214-6296. DOI: 10.1016/j.erss.2019.02.026. URL: <https://www.sciencedirect.com/science/article/pii/S2214629618311757> (visited on 04/06/2023).
- Kennedy, C., S. Pincetl, and P. Bunje (Aug. 2011). “The study of urban metabolism and its applications to urban planning and design”. en. In: *Environmental Pollution*. Selected papers from the conference Urban Environmental Pollution: Overcoming Obstacles to Sustainability and Quality of Life (UEP2010), 20-23 June 2010, Boston, USA 159.8, pp. 1965–1973. ISSN: 0269-7491. DOI: 10.1016/j.envpol.2010.10.022. URL: <https://www.sciencedirect.com/science/article/pii/S0269749110004781> (visited on 04/10/2023).
- Kennedy, Christopher, John Cuddihy, and Joshua Engel-Yan (2007). “The Changing Metabolism of Cities”. en. In.
- Kermeli, Katerina, Oreane Y. Edelenbosch, Wina Crijns-Graus, Bas J. van Ruijven, Silvana Mima, Detlef P. van Vuuren, and Ernst Worrell (Apr. 2019). “The scope for better industry representation in long-term energy models: Modeling the cement industry”. en. In: *Applied Energy* 240, pp. 964–985. ISSN: 03062619. DOI: 10.1016/j.apenergy.2019.01.252. URL: <https://linkinghub.elsevier.com/retrieve/pii/S030626191930279X> (visited on 04/05/2023).
- Kermeli, Katerina, Oreane Y. Edelenbosch, Wina Crijns-Graus, Bas J. van Ruijven, Detlef P. van Vuuren, and Ernst Worrell (Jan. 2022). “Improving material projections in Integrated Assessment Models: The use of a stock-based versus a flow-based approach for the iron and steel industry”. en. In: *Energy* 239, p. 122434. ISSN: 0360-5442. DOI: 10.1016/j.energy.2021.122434. URL: <https://www.sciencedirect.com/science/article/pii/S0360544221026839> (visited on 04/05/2023).

- Keyßer, Lorenz T. and Manfred Lenzen (May 2021). “1.5 °C degrowth scenarios suggest the need for new mitigation pathways”. en. In: *Nature Communications* 12.1. Number: 1 Publisher: Nature Publishing Group, p. 2676. ISSN: 2041-1723. DOI: 10.1038/s41467-021-22884-9. URL: <https://www.nature.com/articles/s41467-021-22884-9> (visited on 04/05/2023).
- Koasidis, Konstantinos, Alexandros Nikas, and Haris Doukas (Mar. 2023). “Why integrated assessment models alone are insufficient to navigate us through the polycrisis”. English. In: *One Earth* 6.3. Publisher: Elsevier, pp. 205–209. ISSN: 2590-3330, 2590-3322. DOI: 10.1016/j.oneear.2023.02.009. URL: [https://www.cell.com/one-earth/abstract/S2590-3322\(23\)00089-1](https://www.cell.com/one-earth/abstract/S2590-3322(23)00089-1) (visited on 04/06/2023).
- Krausmann, Fridolin, Dominik Wiedenhofer, Christian Lauk, Willi Haas, Hiroki Tanikawa, Tomer Fishman, Alessio Miatto, Heinz Schandl, and Helmut Haberl (Feb. 2017). “Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use”. In: *Proceedings of the National Academy of Sciences* 114.8. Publisher: Proceedings of the National Academy of Sciences, pp. 1880–1885. DOI: 10.1073/pnas.1613773114. URL: <https://www.pnas.org/doi/full/10.1073/pnas.1613773114> (visited on 04/06/2023).
- Kuhn, Thomas S. (1970). *The structure of scientific revolutions*. en. [2d ed., enl. International encyclopedia of unified science. Foundations of the unity of science, v. 2, no. 2. Chicago: University of Chicago Press. ISBN: 978-0-226-45803-8.
- Le Boulzec, Hugo, Louis Delannoy, Baptiste Andrieu, François Verzier, Olivier Vidal, and Sandrine Mathy (2022). “Dynamic modeling of global fossil fuel infrastructure and materials needs: Overcoming a lack of available data”. In: *Applied Energy* 326, p. 119871. DOI: 10.1016/j.apenergy.2022.119871.
- Le Boulzec, Hugo, Sandrine Mathy, François Verzier, Baptiste Andrieu, Daniel Monfort-Climent, and Olivier Vidal (Nov. 2023). “Material requirements and impacts of the building sector in the Shared Socioeconomic Pathways”. In: *Journal of Cleaner Production* 428, p. 139117. ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2023.139117. URL: <https://www.sciencedirect.com/science/article/pii/S0959652623032754> (visited on 01/17/2024).
- Lenton, T.M., Peter-Paul Pichler, and Helga Weisz (Apr. 2016). “Revolutions in energy input and material cycling in Earth history and human history”. In: *Earth System Dynamics* 7, pp. 353–370. DOI: 10.5194/esd-7-353-2016.
- Li, Mo, Thomas Wiedmann, Kai Fang, and Michalis Hadjikakou (July 2021). “The role of planetary boundaries in assessing absolute environmental sustainability across scales”. en. In: *Environment International* 152, p. 106475. ISSN: 0160-4120. DOI: 10.1016/j.envint.2021.106475. URL: <https://www.sciencedirect.com/science/article/pii/S0160412021001008> (visited on 04/07/2023).
- Li, Qiangfeng, Tao Dai, Tianming Gao, Weiqiong Zhong, Bojie Wen, Tianjiao Li, and Yanjing Zhou (2021). “Aluminum material flow analysis for production, consumption, and trade in China from 2008 to 2017”. en. In: *Journal of Cleaner Production* 296, p. 126444. ISSN: 09596526. DOI: 10.1016/j.jclepro.2021.126444. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959652621006648> (visited on 08/10/2021).
- McCollum, David L., Charlie Wilson, Hazel Pettifor, Kalai Ramea, Volker Krey, Keywan Riahi, Christoph Bertram, Zhenhong Lin, Oreane Y. Edelenbosch, and Sei Fujisawa (Aug. 2017). “Improving the behavioral realism of global integrated assessment models: An application to consumers’ vehicle choices”. en. In: *Transportation Research Part D: Transport and Environment* 55, pp. 322–342. ISSN: 1361-9209. DOI: 10.1016/j.trd.2016.04.003. URL: <https://www.sciencedirect.com/science/article/pii/S1361920915300900> (visited on 04/05/2023).
- Meadows, Donella H. (2008). *Thinking in Systems: A Primer*. en. Google-Books-ID: CpbLAgAAQBAJ. Chelsea Green Publishing. ISBN: 978-1-60358-055-7.
- Meadows, Donella H., Dennis L. Meadows, Jørgen Randers, and William W. Behrens (1972). *The Limits to Growth: A report for the Club of Rome’s Project on the Predicament of Mankind*. Universe Books. ISBN: 978-0-87663-

- 165-2. DOI: 10.1349/ddlp.1. URL: <http://www.dartmouth.edu/~library/digital/publishing/meadows/ltg/> (visited on 10/07/2021).
- Miller, Ronald E. and Peter D. Blair (July 2009). *Input-Output Analysis: Foundations and Extensions*. en. Google-Books-ID: viHaAgAAQBAJ. Cambridge University Press. ISBN: 978-1-139-47759-8.
- Nakicenovic, N., J. Alcamo, A. Grubler, K. Riahi, R. A. Roehrl, H.-H. Rogner, and N. Victor (2000). *Special Report on Emissions Scenarios (SRES), A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. en. Cambridge: Cambridge University Press. ISBN: 978-0-521-80493-6. URL: <https://iiasa.dev.local/> (visited on 04/11/2023).
- Nations, United (2015). “Transforming our world: the 2030 Agenda for Sustainable Development”. English. In: Accepted: 2016-10-11T20:16:10Z. URL: <https://wedocs.unep.org/xmlui/handle/20.500.11822/9814> (visited on 04/10/2023).
- Nordhaus, William (1975). “Can We Control Carbon Dioxide? (From 1975)”. In: *American Economic Review* 109.6. Publisher: American Economic Association, pp. 2015–35. URL: [https://econpapers.repec.org/article/aeaecrev/v\\_3a109\\_3ay\\_3a2019\\_3ai\\_3a6\\_3ap\\_3a2015-35.htm](https://econpapers.repec.org/article/aeaecrev/v_3a109_3ay_3a2019_3ai_3a6_3ap_3a2015-35.htm) (visited on 04/11/2023).
- Nordhaus, William D. (Mar. 1993). “Rolling the ‘DICE’: an optimal transition path for controlling greenhouse gases”. en. In: *Resource and Energy Economics* 15.1, pp. 27–50. ISSN: 0928-7655. DOI: 10.1016/0928-7655(93)90017-0. URL: <https://www.sciencedirect.com/science/article/pii/0928765593900170> (visited on 04/11/2023).
- O’Neill, Brian, Elmar Kriegler, Kristie Ebi, Eric Kemp-Benedict, Keywan Riahi, Dale Rothman, Bas van Ruijven, Detlef Vuuren, Joern Birkmann, Kasper Kok, Marc Levy, and William Solecki (Feb. 2015). “The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century”. In: *Global Environmental Change* 42. DOI: 10.1016/j.gloenvcha.2015.01.004.
- O’Neill, Daniel W., Andrew L. Fanning, William F. Lamb, and Julia K. Steinberger (Feb. 2018). “A good life for all within planetary boundaries”. en. In: *Nature Sustainability* 1.2. Number: 2 Publisher: Nature Publishing Group, pp. 88–95. ISSN: 2398-9629. DOI: 10.1038/s41893-018-0021-4. URL: <https://www.nature.com/articles/s41893-018-0021-4> (visited on 11/08/2022).
- Olafsdottir, Anna Hulda and Harald Ulrik Sverdrup (May 2020). “Assessing the Past and Future Sustainability of Global Helium Resources, Extraction, Supply and Use, Using the Integrated Assessment Model WORLD7”. en. In: *Biophysical Economics and Sustainability* 5.2, p. 6. ISSN: 2730-7204. DOI: 10.1007/s41247-020-00072-5. URL: <https://doi.org/10.1007/s41247-020-00072-5> (visited on 07/23/2023).
- (Apr. 2021). “Modelling Global Nickel Mining, Supply, Recycling, Stocks-in-Use and Price Under Different Resources and Demand Assumptions for 1850–2200”. en. In: *Mining, Metallurgy & Exploration* 38.2, pp. 819–840. ISSN: 2524-3470. DOI: 10.1007/s42461-020-00370-y. URL: <https://doi.org/10.1007/s42461-020-00370-y> (visited on 07/23/2023).
- Pauliuk, Stefan, Anders Arvesen, Konstantin Stadler, and Edgar Hertwich (Jan. 2017). “Industrial ecology in integrated assessment models”. In: *Nature Climate Change* 7, pp. 13–20. DOI: 10.1038/nclimate3148.
- Pauliuk, Stefan, Niko Heeren, Peter Berrill, Tomer Fishman, Andrea Nistad, Qingshi Tu, Paul Wolfram, and Edgar G. Hertwich (Aug. 2021). “Global scenarios of resource and emission savings from material efficiency in residential buildings and cars”. en. In: *Nature Communications* 12.1. Number: 1 Publisher: Nature Publishing Group, p. 5097. ISSN: 2041-1723. DOI: 10.1038/s41467-021-25300-4. URL: <https://www.nature.com/articles/s41467-021-25300-4> (visited on 04/05/2023).
- Pauliuk, Stefan and Edgar G. Hertwich (Nov. 2015). “Socioeconomic metabolism as paradigm for studying the biophysical basis of human societies”. en. In: *Ecological Economics* 119, pp. 83–93. ISSN: 0921-8009. DOI: 10.1016/j.ecolecon.2015.08.012. URL: <https://www.sciencedirect.com/science/article/pii/S0921800915003481> (visited on 04/06/2023).
- Pauliuk, Stefan and Daniel B. Müller (Jan. 2014). “The role of in-use stocks in the social metabolism and in climate change mitigation”. en. In: *Global Environmental Change* 24, pp. 132–142. ISSN: 0959-3780. DOI: 10.1016/

- j.gloenvcha.2013.11.006. URL: <https://www.sciencedirect.com/science/article/pii/S0959378013001982> (visited on 04/06/2023).
- Persson, Linn, Bethanie M. Carney Almroth, Christopher D. Collins, Sarah Cornell, Cynthia A. de Wit, Miriam L. Diamond, Peter Fantke, Martin Hassellöv, Matthew MacLeod, Morten W. Ryberg, Peter Søgaaard Jørgensen, Patricia Villarrubia-Gómez, Zhanyun Wang, and Michael Zwicky Hauschild (Feb. 2022). “Outside the Safe Operating Space of the Planetary Boundary for Novel Entities”. In: *Environmental Science & Technology* 56.3. Publisher: American Chemical Society, pp. 1510–1521. ISSN: 0013-936X. DOI: 10.1021/acs.est.1c04158. URL: <https://doi.org/10.1021/acs.est.1c04158> (visited on 04/10/2023).
- Pindyck, Robert S. (Jan. 2017). “The Use and Misuse of Models for Climate Policy”. In: *Review of Environmental Economics and Policy* 11.1. Publisher: The University of Chicago Press, pp. 100–114. ISSN: 1750-6816. DOI: 10.1093/reep/rew012. URL: <https://www.journals.uchicago.edu/doi/10.1093/reep/rew012> (visited on 04/05/2023).
- Pinto, Julian T. M., Harald U. Sverdrup, and Arnaud Diemer (May 2019). “Integrating life cycle analysis into system dynamics: the case of steel in Europe”. en. In: *Environmental Systems Research* 8.1, p. 15. ISSN: 2193-2697. DOI: 10.1186/s40068-019-0144-2. URL: <https://doi.org/10.1186/s40068-019-0144-2> (visited on 07/23/2023).
- Pulido-Sánchez, Daniel, Iñigo Capellán-Pérez, Carlos De Castro, and Fernando Frechoso (2022). “Material and energy requirements of transport electrification”. en. In: *Energy & Environmental Science* 15.12, pp. 4872–4910. ISSN: 1754-5692, 1754-5706. DOI: 10.1039/D2EE00802E. URL: <http://xlink.rsc.org/?DOI=D2EE00802E> (visited on 07/23/2023).
- Raworth, Kate (Jan. 2012). *A safe and just space for humanity: Can we live within the doughnut*. Vol. 8. Journal Abbreviation: Oxfam Policy Pract. Clim. Change Resil Publication Title: Oxfam Policy Pract. Clim. Change Resil.
- (May 2017). “A Doughnut for the Anthropocene: humanity’s compass in the 21st century”. English. In: *The Lancet Planetary Health* 1.2. Publisher: Elsevier, e48–e49. ISSN: 2542-5196. DOI: 10.1016/S2542-5196(17)30028-1. URL: [https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196\(17\)30028-1/fulltext](https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(17)30028-1/fulltext) (visited on 04/10/2023).
- Realmonte, Giulia, Laurent Drouet, Ajay Gambhir, James Glynn, Adam Hawkes, Alexandre C. Köberle, and Massimo Tavoni (July 2019). “An inter-model assessment of the role of direct air capture in deep mitigation pathways”. en. In: *Nature Communications* 10.1. Number: 1 Publisher: Nature Publishing Group, p. 3277. ISSN: 2041-1723. DOI: 10.1038/s41467-019-10842-5. URL: <https://www.nature.com/articles/s41467-019-10842-5> (visited on 05/16/2023).
- Riahi, Keywan, Detlef P. van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O’Neill, Shinichiro Fujimori, Nico Bauer, Katherine Calvin, Rob Dellink, Oliver Fricko, Wolfgang Lutz, Alexander Popp, Jesus Crespo Cuaresma, Samir Kc, Marian Leimbach, Leiwen Jiang, Tom Kram, Shilpa Rao, Johannes Emmerling, Kristie Ebi, Tomoko Hasegawa, Petr Havlik, Florian Humpenöder, Lara Aleluia Da Silva, Steve Smith, Elke Stehfest, Valentina Bosetti, Jiyong Eom, David Gernaat, Toshihiko Masui, Joeri Rogelj, Jessica Strefler, Laurent Drouet, Volker Krey, Gunnar Luderer, Mathijs Harmsen, Kiyoshi Takahashi, Lavinia Baumstark, Jonathan C. Doelman, Mikiko Kainuma, Zbigniew Klimont, Giacomo Marangoni, Hermann Lotze-Campen, Michael Obersteiner, Andrzej Tabeau, and Massimo Tavoni (Jan. 2017). “The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview”. en. In: *Global Environmental Change* 42, pp. 153–168. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2016.05.009. URL: <https://www.sciencedirect.com/science/article/pii/S0959378016300681> (visited on 05/17/2023).
- Rockström, Johan, Will Steffen, Kevin Noone, Åsa Persson, F. Stuart Chapin, Eric F. Lambin, Timothy M. Lenton, Marten Scheffer, Carl Folke, Hans Joachim Schellnhuber, Björn Nykvist, Cynthia A. de Wit, Terry Hughes, Sander van der Leeuw, Henning Rodhe, Sverker Sörlin, Peter K. Snyder, Robert Costanza, Uno Svedin, Malin Falkenmark, Louise Karlberg, Robert W. Corell, Victoria J. Fabry, James Hansen, Brian Walker, Diana Liverman, Katherine Richardson, Paul Crutzen, and Jonathan A. Foley (Sept. 2009). “A safe operating space

- for humanity”. en. In: *Nature* 461.7263. Number: 7263 Publisher: Nature Publishing Group, pp. 472–475. ISSN: 1476-4687. DOI: 10.1038/461472a. URL: <https://www.nature.com/articles/461472a> (visited on 04/10/2023).
- Romero, José Carlos and Pedro Linares (May 2014). “Exergy as a global energy sustainability indicator. A review of the state of the art”. en. In: *Renewable and Sustainable Energy Reviews* 33, pp. 427–442. ISSN: 1364-0321. DOI: 10.1016/j.rser.2014.02.012. URL: <https://www.sciencedirect.com/science/article/pii/S1364032114001233> (visited on 05/16/2023).
- Rosen, Richard A. and Edeltraud Guenther (Feb. 2015). “The economics of mitigating climate change: What can we know?” en. In: *Technological Forecasting and Social Change* 91, pp. 93–106. ISSN: 0040-1625. DOI: 10.1016/j.techfore.2014.01.013. URL: <https://www.sciencedirect.com/science/article/pii/S0040162514000468> (visited on 05/16/2023).
- Santos, João, Tiago Domingos, Tânia Sousa, and Miguel St. Aubyn (June 2018). “Useful Exergy Is Key in Obtaining Plausible Aggregate Production Functions and Recognizing the Role of Energy in Economic Growth: Portugal 1960–2009”. en. In: *Ecological Economics* 148, pp. 103–120. ISSN: 0921-8009. DOI: 10.1016/j.ecolecon.2018.01.008. URL: <https://www.sciencedirect.com/science/article/pii/S0921800917302483> (visited on 05/16/2023).
- Seto, Karen C., Steven J. Davis, Ronald B. Mitchell, Eleanor C. Stokes, Gregory Unruh, and Diana Ürge-Vorsatz (2016). “Carbon Lock-In: Types, Causes, and Policy Implications”. In: *Annual Review of Environment and Resources* 41.1. eprint: <https://doi.org/10.1146/annurev-environ-110615-085934>, pp. 425–452. DOI: 10.1146/annurev-environ-110615-085934. URL: <https://doi.org/10.1146/annurev-environ-110615-085934> (visited on 05/16/2023).
- Sluijs, Jeroen van der, Josee van Eijndhoven, Simon Shackley, and Brian Wynne (1998). “Anchoring Devices in Science for Policy: The Case of Consensus around Climate Sensitivity”. In: *Social Studies of Science* 28.2. Publisher: Sage Publications, Ltd., pp. 291–323. ISSN: 0306-3127. URL: <https://www.jstor.org/stable/285604> (visited on 04/11/2023).
- Smith, Pete, Steven J. Davis, Felix Creutzig, Sabine Fuss, Jan Minx, Benoit Gabrielle, Etsushi Kato, Robert B. Jackson, Annette Cowie, Elmar Kriegler, Detlef P. van Vuuren, Joeri Rogelj, Philippe Ciais, Jennifer Milne, Josep G. Canadell, David McCollum, Glen Peters, Robbie Andrew, Volker Krey, Gyami Shrestha, Pierre Friedlingstein, Thomas Gasser, Arnulf Grübler, Wolfgang K. Heidug, Matthias Jonas, Chris D. Jones, Florian Kraxner, Emma Littleton, Jason Lowe, José Roberto Moreira, Nebojsa Nakicenovic, Michael Obersteiner, Anand Patwardhan, Mathis Rogner, Ed Rubin, Ayyoob Sharifi, Asbjørn Torvanger, Yoshiki Yamagata, Jae Edmonds, and Cho Yongsung (Jan. 2016). “Biophysical and economic limits to negative CO<sub>2</sub> emissions”. en. In: *Nature Climate Change* 6.1. Number: 1 Publisher: Nature Publishing Group, pp. 42–50. ISSN: 1758-6798. DOI: 10.1038/nclimate2870. URL: <https://www.nature.com/articles/nclimate2870> (visited on 05/16/2023).
- Steffen, Will, Katherine Richardson, Johan Rockström, Sarah E. Cornell, Ingo Fetzer, Elena M. Bennett, Reinette Biggs, Stephen R. Carpenter, Wim de Vries, Cynthia A. de Wit, Carl Folke, Dieter Gerten, Jens Heinke, Georgina M. Mace, Linn M. Persson, Veerabhadran Ramanathan, Belinda Reyers, and Sverker Sörlin (Feb. 2015). “Planetary boundaries: Guiding human development on a changing planet”. In: *Science* 347.6223. Publisher: American Association for the Advancement of Science, p. 1259855. DOI: 10.1126/science.1259855. URL: <https://www.science.org/doi/10.1126/science.1259855> (visited on 04/10/2023).
- “The Anthropocene Era” (2005). “The Anthropocene Era: How Humans are Changing the Earth System”. en. In: *Global Change and the Earth System: A Planet Under Pressure*. Ed. by Will Steffen, Angelina Sanderson, Peter Tyson, Jill Jäger, Pamela Matson, Berrien Moore, Frank Oldfield, Katherine Richardson, H. John Schellnhuber, B. L. Turner, and Robert J. Wasson. Global Change — The IGBP Series. Berlin, Heidelberg: Springer, pp. 81–141. ISBN: 978-3-540-26607-5. DOI: 10.1007/3-540-26607-0\_3. URL: [https://doi.org/10.1007/3-540-26607-0\\_3](https://doi.org/10.1007/3-540-26607-0_3) (visited on 04/10/2023).

- Sverdrup, Harald U., Deniz Koca, and Peter Schlyter (May 2017). “A Simple System Dynamics Model for the Global Production Rate of Sand, Gravel, Crushed Rock and Stone, Market Prices and Long-Term Supply Embedded into the WORLD6 Model”. en. In: *BioPhysical Economics and Resource Quality* 2.2, p. 8. ISSN: 2366-0120. DOI: 10.1007/s41247-017-0023-2. URL: <https://doi.org/10.1007/s41247-017-0023-2> (visited on 07/23/2023).
- Sverdrup, Harald Ulrik and Anna Hulda Olafsdottir (May 2018). “A System Dynamics Model Assessment of the Supply of Niobium and Tantalum Using the WORLD6 Model”. en. In: *BioPhysical Economics and Resource Quality* 3.2, p. 5. ISSN: 2366-0120. DOI: 10.1007/s41247-018-0038-3. URL: <https://doi.org/10.1007/s41247-018-0038-3> (visited on 07/23/2023).
- (May 2019). “Assessing the Long-Term Global Sustainability of the Production and Supply for Stainless Steel”. en. In: *BioPhysical Economics and Resource Quality* 4.2, p. 8. ISSN: 2366-0120. DOI: 10.1007/s41247-019-0056-9. URL: <https://doi.org/10.1007/s41247-019-0056-9> (visited on 07/23/2023).
- (2020). “System Dynamics Modelling of the Global Extraction, Supply, Price, Reserves, Resources and Environmental Losses of Mercury”. en. In: *Water, Air, & Soil Pollution* 231.8, p. 439. ISSN: 0049-6979, 1573-2932. DOI: 10.1007/s11270-020-04757-x. URL: <http://link.springer.com/10.1007/s11270-020-04757-x> (visited on 04/21/2021).
- (Mar. 2023a). “Dynamical Modelling of the Global Cement Production and Supply System, Assessing Climate Impacts of Different Future Scenarios”. en. In: *Water, Air, & Soil Pollution* 234.3, p. 191. ISSN: 1573-2932. DOI: 10.1007/s11270-023-06183-1. URL: <https://doi.org/10.1007/s11270-023-06183-1> (visited on 07/23/2023).
- (Sept. 2023b). “Modelling the dynamics of the industrial vanadium cycle using the WORLD7 Integrated Assessment Model”. en. In: *Resources, Environment and Sustainability* 13, p. 100121. ISSN: 2666-9161. DOI: 10.1016/j.resenv.2023.100121. URL: <https://www.sciencedirect.com/science/article/pii/S2666916123000142> (visited on 07/23/2023).
- Sverdrup, Harald Ulrik, Anna Hulda Olafsdottir, and Kristin Vala Ragnarsdottir (2019). “On the long-term sustainability of copper, zinc and lead supply, using a system dynamics model”. en. In: *Resources, Conservation & Recycling: X* 4, p. 100007. ISSN: 2590289X. DOI: 10.1016/j.rcrx.2019.100007. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2590289X19300052> (visited on 04/21/2021).
- Sverdrup, Harald Ulrik, Anna Hulda Olafsdottir, Kristin Vala Ragnarsdottir, and Deniz Koca (July 2018). “A System Dynamics Assessment of the Supply of Molybdenum and Rhenium Used for Super-alloys and Specialty Steels, Using the WORLD6 Model”. en. In: *BioPhysical Economics and Resource Quality* 3.3, p. 7. ISSN: 2366-0120. DOI: 10.1007/s41247-018-0040-9. URL: <https://doi.org/10.1007/s41247-018-0040-9> (visited on 07/23/2023).
- Sverdrup, Harald Ulrik, Anna Hulda Olafsdottir, Kristin Vala Ragnarsdottir, Ingrid Stjernquist, Peter Schlyter, and Jenneth Parker (2019). *Development of the WORLD7 global integrated assessment model*. Deliverable 4.3. This project has received funding from the European Union’s Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 675153. Hamar, Norway; Reykjavik, Iceland; Stockholm, Sweden; Karlskrona, Sweden; Bristol, Great Britain: AdaptEconII.
- Sverdrup, Harald Ulrik, Kristin Vala Ragnarsdottir, and Deniz Koca (Mar. 2017). “Integrated Modelling of the Global Cobalt Extraction, Supply, Price and Depletion of Extractable Resources Using the WORLD6 Model”. en. In: *BioPhysical Economics and Resource Quality* 2.1, p. 4. ISSN: 2366-0120. DOI: 10.1007/s41247-017-0017-0. URL: <https://doi.org/10.1007/s41247-017-0017-0> (visited on 07/23/2023).
- Thacker, Scott, Daniel Adshead, Marianne Fay, Stéphane Hallegatte, Mark Harvey, Hendrik Meller, Nicholas O’Regan, Julie Rozenberg, Graham Watkins, and Jim W. Hall (Apr. 2019). “Infrastructure for sustainable development”. en. In: *Nature Sustainability* 2.4. Number: 4 Publisher: Nature Publishing Group, pp. 324–331. ISSN: 2398-9629. DOI: 10.1038/s41893-019-0256-8. URL: <https://www.nature.com/articles/s41893-019-0256-8> (visited on 04/07/2023).

- Vaughan, Naomi E. and Clair Gough (Aug. 2016). “Expert assessment concludes negative emissions scenarios may not deliver”. en. In: *Environmental Research Letters* 11.9. Publisher: IOP Publishing, p. 095003. ISSN: 1748-9326. DOI: 10.1088/1748-9326/11/9/095003. URL: <https://dx.doi.org/10.1088/1748-9326/11/9/095003> (visited on 05/16/2023).
- Verzier, François, Hugo Le Boulzec, Baptiste Andrieu, and Olivier Vidal (2023). *Multi-regional Assessment of Technologies, Energy and Resources*.
- Vidal, O., H. Le Boulzec, B. Andrieu, and F. Verzier (2022). “Modelling the Demand and Access of Mineral Resources in a Changing World”. In: *Sustainability* 14.11. DOI: 10.3390/su14010011.
- Vidal, Olivier, Baptiste Andrieu, Hugo Le Boulzec, François Verzier, Florian Fizaine, and Nicholas Arndt (2023). *Modeling production energy and thermodynamic prices of metals from 1900 to 2100*.
- Vidal, Olivier, Fatma Zahra Rostom, Cyril François, and Gaël Giraud (2019). “Prey–Predator Long-Term Modeling of Copper Reserves, Production, Recycling, Price, and Cost of Production”. en. In: *Environmental Science & Technology* 53.19, pp. 11323–11336. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/acs.est.9b03883. URL: <https://pubs.acs.org/doi/10.1021/acs.est.9b03883> (visited on 05/28/2021).
- Wagner, Philip L. and Vaclav Smil (Jan. 1993). “General Energetics: Energy in the Biosphere and Civilization”. In: *Geographical Review*. Vol. 83. ISSN: 00167428 Issue: 1 Journal Abbreviation: Geographical Review, p. 110. DOI: 10.2307/215395. URL: <https://www.jstor.org/stable/215395?origin=crossref> (visited on 04/10/2023).
- Weisz, Helga, Sangwon Suh, and T. E. Graedel (May 2015). “Industrial Ecology: The role of manufactured capital in sustainability”. en. In: *Proceedings of the National Academy of Sciences* 112.20, pp. 6260–6264. ISSN: 0027-8424, 1091-6490. DOI: 10.1073/pnas.1506532112. URL: <https://pnas.org/doi/full/10.1073/pnas.1506532112> (visited on 04/25/2023).
- Whiting, Kai, Luis Gabriel Carmona, and Angeles Carrasco (Mar. 2022). “The resource service cascade: A conceptual framework for the integration of ecosystem, energy and material services”. en. In: *Environmental Development*. Sustainable Resource Use and Management from Extraction to Service Provision 41, p. 100647. ISSN: 2211-4645. DOI: 10.1016/j.envdev.2021.100647. URL: <https://www.sciencedirect.com/science/article/pii/S2211464521000440> (visited on 04/07/2023).
- Wiedmann, Thomas (Dec. 2009). “A review of recent multi-region input–output models used for consumption-based emission and resource accounting”. en. In: *Ecological Economics*. Special Section: Analyzing the global human appropriation of net primary production - processes, trajectories, implications 69.2, pp. 211–222. ISSN: 0921-8009. DOI: 10.1016/j.ecolecon.2009.08.026. URL: <https://www.sciencedirect.com/science/article/pii/S0921800909003577> (visited on 05/16/2023).

This chapter presents the DyMEMDS and MATER models

- Dynamic Modelling of Energy and Matter Demand and Supply (DyMEMDS) is a stock and flow model that links the energy consumption, GDP, and population with raw materials consumption, greenhouse gases emissions, global warming, and additional environmental impacts such as the consumption of water and used land for mining. It includes about 50 technologies of transportation, construction, and energy; 10 metals, cement, and gravel; and 9 geographical regions covering the world.
- MATER (Multi-regional Assessment of Technologies, Energy and Resources) is the second version of DyMEMDS, coded in python for easier collaboration whereas DyMEMDS was coded in Vensim. One of the main strengths of MATER is the fact that the industrial energy consumption is endogenized, meaning that feedback loops allow to calculate the energy and raw materials needed to build the infrastructure needed to build and operate existing stocks.
- The third part of chapter 3 demonstrates that utilizing a single S-curve (as a function of GDP per capita) equation precisely replicates historical stocks in every country worldwide and is thus a good entry point into MATER/DyMEMDS

## 2.1. MODELLING THE DEMAND AND ACCESS OF MINERAL RESOURCES IN A CHANGING WORLD

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### ABSTRACT

Humanity is using mineral resources at an unprecedented level and demand will continue to grow over the next few decades before stabilizing by the end of the century, due to the economic development of populated countries and the energy and digital transitions. The demand for raw materials must be estimated with a bottom-up and regionalised approach and the supply capacity with approaches coupling long-term prices with energy and production costs controlled by the quality of the resource and the rate of technological improvement that depends on thermodynamic limits. Such modelling provides arguments in favour of two classically opposed visions of the future of mineral resources: an unaffordable increase in costs and prices following the depletion of high quality deposits or, on the contrary, a favourable compensation by technological improvements. Both views are true, but not at the same time. After a period of energy and production cost gains, we now appear to be entering a pivotal period of long-term production cost increases as we approach the minimum practical energy and thermodynamic limits for many metals.

### 2.1.1. INTRODUCTION

The per-capita consumption of global resources has doubled between 1950 and 2010 (Schafartzik et al., 2014) and the consumption of raw materials and mineral resources (gravel and sand, cement, ores, industrial minerals) used to build the energy, transportation and building infrastructures and consumer goods of modern societies has increased at an average rate of 2-5%/year over the past century. Humanity is now using mineral resources at an unprecedented level, with 70 billion tons of material extracted from the ground per year (T. E. Graedel and J. Cao, 2010; T. E. Graedel, 2011; Wiedmann et al., 2015; Elshkaki, T. E. Graedel, et al., 2018; Elshkaki, 2019). This acceleration naturally raises the question of supply sustainability, which has been discussed repeatedly since the 1950s (Hubbert, 1956; Ugo Bardi and Lavacchi, 2009; Ugo Bardi and Pagani, 2007; Meadows et al., 1972; H. Sverdrup et al., 2014; Kerr, 2014; Northey et al., 2014; U. Bardi, 2007; Ugo Bardi, Lavacchi, and Yaxley, 2018; Laherrère, 2010). Recurring predictions of short-term depletion of fossil resources have so far not been verified by actual shortages. On the contrary, and despite the exponential growth in consumption observed for more than a century, metal reserves have never been higher than they are today. The increase in reserves, despite the strong growth in consumption, can be explained by technological progress, which makes it possible to exploit new fossil resources of lower quality at the same cost. Unconventional hydrocarbons, which were undevelopable at a competitive cost a

few decades ago, are now a major source and most metal deposits developed today are less concentrated than those developed in the past (Mudd, 2009). Because the amount of low-grade deposits is much greater than concentrated deposits, reserves have increased with technological improvements. This trend gives the misleading impression that perpetual growth is possible in a finite world, the Earth. Misleading because there is a thermodynamic limit to the potential of technological improvements and what was possible in the past will not necessarily be possible in the future.

The future availability of fossil resources depends on production capacity, which in turn depends on production technologies, the type and quality of ore deposits controlling production costs, and the proportion of recycled products at the end of their lives. It also depends on demand, which in turn depends on population and standard of living, economic and geopolitical cycles, and technological development associated with energy and digital transitions. All these parameters define the conditions for economically viable production. They vary over time, are coupled and should not be analysed separately. Over the past decades, the demand for non-energy materials has been intensively studied through material flow or input-output analyses. The development of materials databases (UN, 2021; Worldsteel, 2021; USGS, 2021) has enabled a comprehensive understanding of metal and mineral stocks and flows within society at different scales through top-down studies (e.g. (Q. Li et al., 2021; Streeck et al., 2021; Ciacci et al., 2020; Wiedenhofer, Fishman, et al., 2019; Pfaff et al., 2018; Krausmann et al., 2017)). Many recent efforts have been devoted to estimating future demand for raw materials through bottom-up stock-based analysis in the energy (e.g. (S. Deetman et al., 2021; Ren et al., 2021; F. Li et al., 2020; Watari et al., 2019; Moreau et al., 2019; Dong et al., 2019; Vidal, Boulzec, et al., 2018; Tokimatsu et al., 2017; Elshkaki and T. Graedel, 2013; Vidal, Goffé, et al., 2013)), transportation (e.g. (Dunn et al., 2021; Pauliuk and Heeren, 2021; Yang et al., 2021; Zhu et al., 2021; M. Liu et al., 2020; Watari et al., 2019)) and construction sectors (e.g. (Pauliuk and Heeren, 2021; Sebastiaan Deetman et al., 2020; Marinova et al., 2020; Y. Liu et al., 2020; Z. Cao et al., 2018; Wiedenhofer, Steinberger, et al., 2015)), its energy demand and production cost (e.g. (Pauliuk and Heeren, 2021; Elshkaki, 2019)), environmental impacts (e.g. (Kalt et al., 2021; Pauliuk and Heeren, 2021; Beylot et al., 2019; Huang et al., 2013)) or to reserve estimation (e.g. (Hunt et al., 2021; H. U. Sverdrup, Olafsdottir, and Ragnarsdottir, 2019; Ayres et al., 2002)) and production capacities. However, very few studies have attempted to combine all these dimensions into single models. Notable exceptions are the dynamic models World7 Olafsdottir et al., 2018; H. U. Sverdrup and Olafsdottir, 2020 and MEDEAS-World (Capellán-Pérez et al., 2020), which couple global gross domestic product (GDP) and demographic changes with commodity and energy demand. These models are valuable and powerful tools for discussing the global resource issue in relation to socioeconomic changes. However, they sometimes rely on disputable empirical assumptions such as the linear dependence of the total demand of metals on GDP evolution assumed in MEDEAS (Capellán-Pérez et al., 2020). This assumption, based on an empirical fit of global historical data covering too short a period, is in conflict with the historical evolution in developed countries (Bleischwitz, Nechifor, et al., 2018; Bleischwitz and Nechifor, 2016; Wårell, 2014). Moreover, it assumes that the future de-

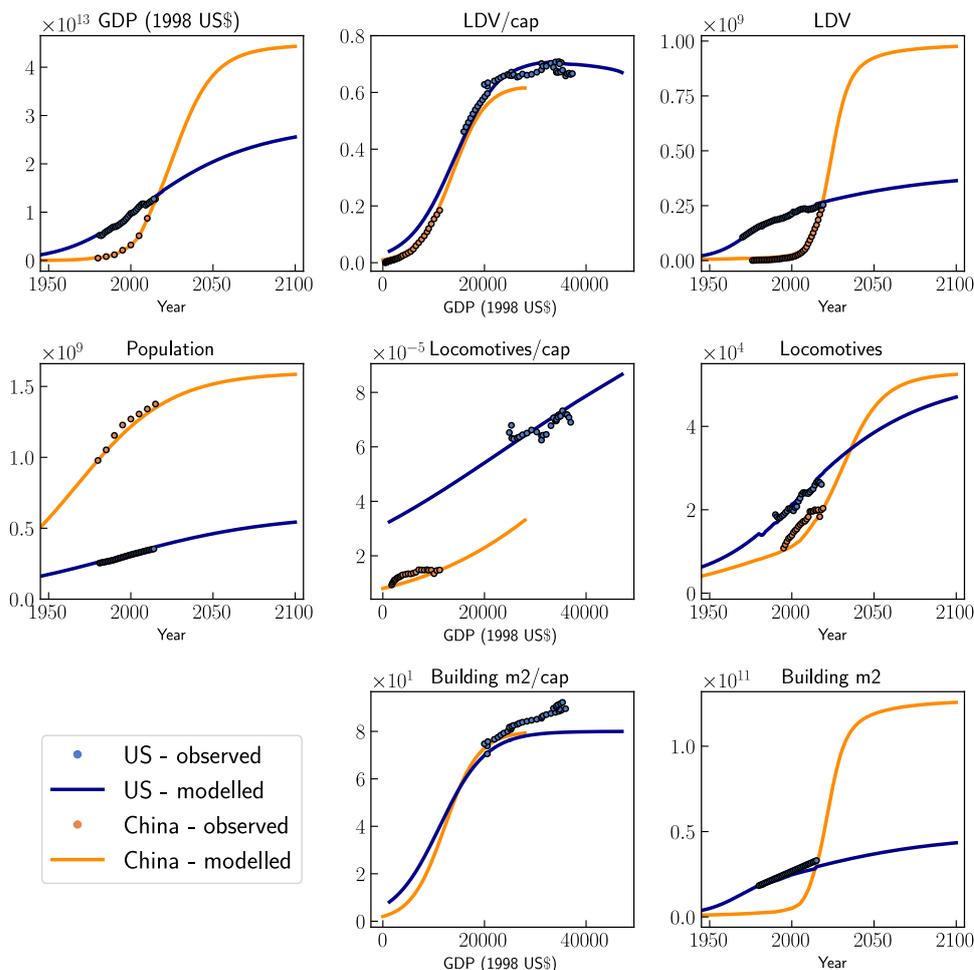
mand for metal per GDP will be the same as in the past, whereas new technologies that did not exist two decades ago are developing fast in the sectors of energy, transport, information and communications. The estimation of global demand requires a comprehensive bottom-up approach, i.e., by technologies whose material intensities, use intensities, energy consumption and efficiencies change at different rates over time, and by geographic regions with contrasting transportation patterns and material intensities. The modelling of raw material supply can also be improved by developing standardized approaches coupling long-term resource prices with energy and production costs (Vidal, 2021). The minimum production energy and the minimum practical production energies can be estimated from the quality of the resource exploited (ore grade) and on technological improvement constrained in the last resort by thermodynamic limits that cannot be overstepped. Finally, and before attempting to apply the models to future developments, it must be demonstrated that they are capable of reproducing the historical evolution of the demand for infrastructure and raw materials over long periods of time, by country or geographical region. These different points are discussed in the present contribution, along with a brief review of anticipated future needs and production capacities. Our objective is not to provide a single answer to the complex issues raised by the consumption and supply of mineral resources, but rather to identify some of the key points that seem important to consider in their modelling.

## 2.1.2. THE DRIVERS OF MINERAL RESOURCES CONSUMPTION

### 2.1.2.1. THE BASE METALS AND CEMENT CONSUMPTION FROM TRADITIONAL APPLICATIONS

The prospective analysis of metals and minerals in society requires a dynamic model describing the evolution of stocks and flows. An inverted U-shape of demand with economic growth was first proposed in the late 20th century (Malenbaum, 1973) and later validated for steel for middle-income countries (Wårell, 2014). Growing stock analysis has led to a better understanding of stock and flow dynamics, and to the identification of a three-stage model of the stock curve in use: growth, maturation, and saturation (Bleischwitz, Nechifor, et al., 2018). The first stage of economic growth in all countries is characterized by the construction of raw materials demanding infrastructures of heavy industry, housing, transport, communications and energy. This phase of development mainly consumes "structural" raw materials produced in present global quantities of more than one million tons per year (Mt/yr), such as sand and aggregates, concrete, steel and iron, aluminium, copper, manganese, zinc, chromium, lead, titanium and nickel. Then, the annual consumption of structural raw materials levels off when the gross domestic product (GDP) per capita reaches about 15,000 US\$/cap (maturing stage) and eventually declines as the in-use stock reaches its saturation limit (saturation stage) (Bleischwitz and Nechifor, 2016; Bleischwitz, Nechifor, et al., 2018). When saturation level of in-use stocks is reached, the size of the infrastructure becomes mainly controlled by the evolution of population and the material content of technologies. The number of technological units per capita (number of cars, trucks, planes, ships, m<sup>2</sup> building, etc) as a function of GDP/capita thus follows the sigmoidal pattern of a logistic function, whose parameters can be constrained by fitting

the historical evolution of each technology by countries (e.g. (Huo et al., 2012; Z. Cao et al., 2018; Shi et al., 2012)). These parameters depend on the geography, population density and lifestyle of the countries, with average values in the order of 0.7 LDV/cap,  $7 \cdot 10^{-5}$  locomotive/cap,  $1.5 \cdot 10^{-5}$  aircraft/cap and  $90 \text{ m}^2/\text{cap}$ . From these figures, the future evolution of infrastructure can be estimated for given future GDP and population evolutions. This is illustrated in Figure 2.1, which shows the number of observed and estimated light vehicles, locomotives, airplanes and the surface of buildings in the USA and China from 1950 until 2100. The results were obtained with the model DyMEMDS (dynamic modelling of energy and matter demand and supply) available online. DyMEMDS is a stock and flow model that links the energy consumption, GDP, population with the raw materials consumption, greenhouse gases emissions, global warming and additional environmental impacts such as the consumption of water and used land for mining. It includes about fifty technologies of transportation, construction and energy, ten metals, cement and gravel, and nine geographical regions covering the world. From the evolution of infrastructure calculated for imposed future GDP and population evolutions (Figure 2.1), the stocks of materials by technologies are estimated using dynamic raw materials intensities in kg of material per technological unit.



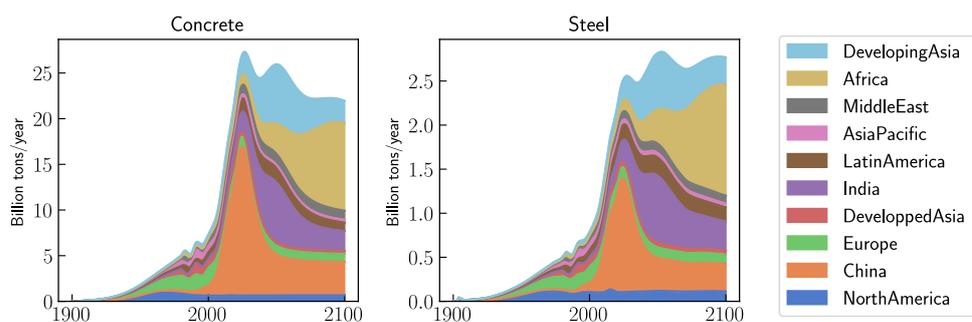
**FIGURE 2.1:** Evolution of the demand in infrastructure per capita as a function of GDP/cap or time in China (grey lines and open circles) and USA (black line and black circles).

The same material intensities were used for all countries except for the building sector, which shows strong disparities between countries. The concrete and steel intensities are for instance lower in the US than in China (IEA, 2018). The stocks of materials in the infrastructure of all regions are obtained by adding up the needs of all technologies, and the global demand by adding up the demand of each geographical region (Figure 2.2). The annual consumptions are then obtained by deriving the stocks over time and the annual flows of primary, recycled and lost materials are calculated for imposed lifetimes of goods, collection and recycling rates (Figure 2.3). This full bottom-up approach starting from regional GDP and population evolutions makes it possible to link the global raw material consumptions with the economic development, population and technological evolutions of each geographical region. It reproduces the incremental increase of demand for base metals, cement and gravels observed since World War II. The period 1950-1970 was marked by a strong increase in global consumption driven by the construction of the infrastructure of currently developed countries. Consumption growth declined during the 1970-2000 period, as saturation thresholds were approached in rich countries and no poor country was economically emerging. Then the rapid economic emergence of China in the late 1990s led to a second period of increase in global consumption (Figure 2.3). China's consumption is expected to level off over the next decade, and then decline between 2030 and 2050. After 2050, the need for new infrastructure in this country is no longer controlled by the evolution of GDP/capita because the saturation thresholds are reached. Moreover, the amount of recyclable material that was negligible before 2030 increases after 2030 as fast as the increase of consumption observed between 2000 and 2025. The amount of steel available for recycling between 2050 and 2075 is even higher than the apparent consumption. A peak in steel consumption was also observed in the US in the 1970's, although less pronounced than in China in 2030, because previous growth was slower. Since then, the US steel consumption has remained relatively constant, which is a common observation made for all rich countries, as well as in China after 2050. An incremental evolution of demand is also observed for Ni, Cr and Mn, which are mainly used as alloying elements of steel. The incremental evolution is less clear for other base metals such as copper and aluminium involved in a variety of new applications with lower lifetimes than steel since the fifties. The decrease of Chinese consumption in 2030-2050 is likely to be compensated by the increase due to the economic emergence India and African countries. Assuming that these countries will achieve their economic development within the century, the Indian peak of cement and steel consumption might occur in 2050 and 2100, and those of copper and aluminium one or two decades latter. The African consumption peaks are expected to occur fifteen years latter. In this scenario, the yearly global demand in steel and cement in 2100 is fourfold the present value, and six fold the present consumption for aluminium and copper.

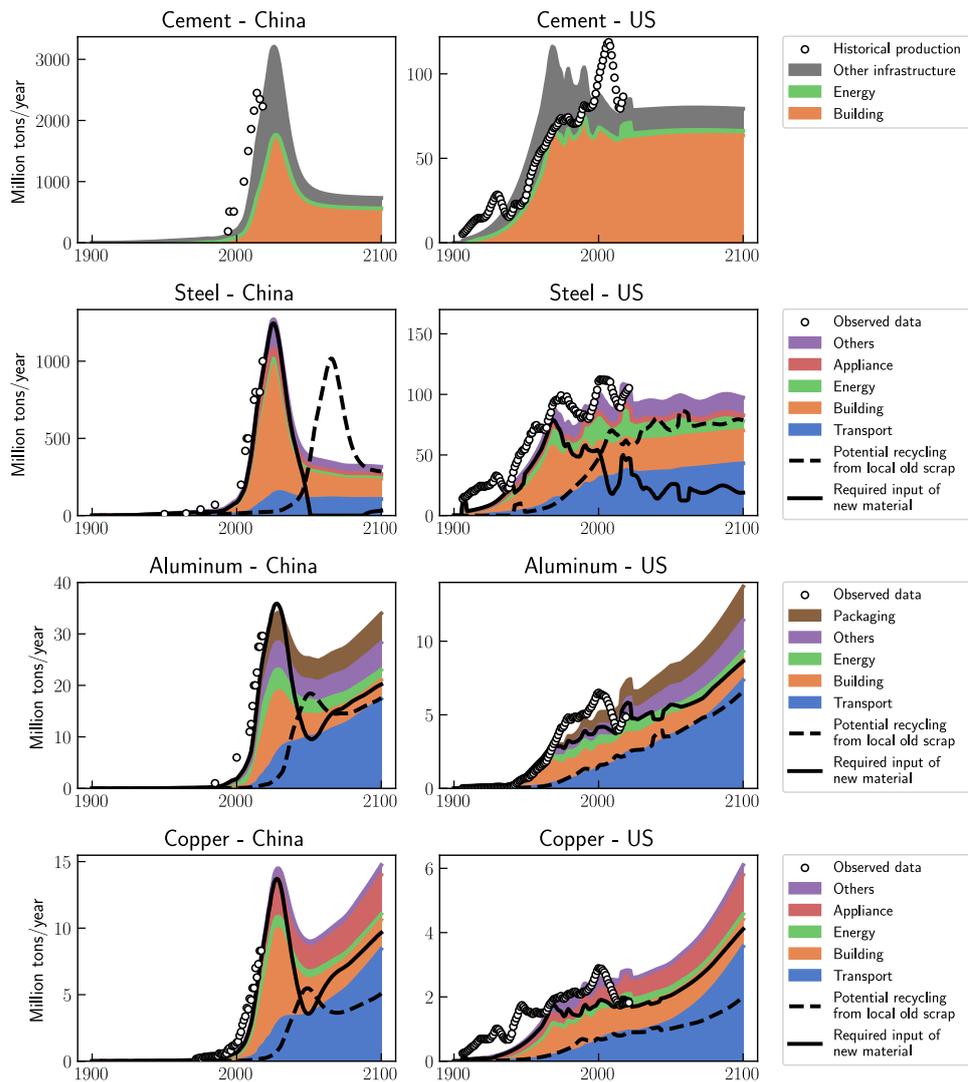
#### 2.1.2.2. THE NEW APPLICATIONS AND HIGH-TECH METALS

In parallel or after building its basic infrastructure, economies are moving towards advanced technologies, which use many properties resulting from the electronic structure, catalytic, quantum or semiconductor properties specific to almost all the elements of the periodic table. Rapid changes in the use of metals have emerged during the last decades in the Information and Com-

munication Technology (ICT) sector: in 2019, there were approximately 13 billion mobile phones and tablets (Radicati, 2019) and 2 billion computers (1 billion in 2008) in use, Facebook had more than 1 billion users and global data centre traffic was estimated at 4.8 zettabytes, representing more than 26,000 centuries of streaming video. This ICT sector is a large consumer of rare and high-purity substances (Cu, In, Ga, Sb, Ge, Co, Li, Ge, Ta, Nb, Au, Ag, rare earths, etc.) with dispersive uses resulting from high dilution in many short-lived devices, which limits the potential for recycling on the order of one percent. While the base metal consumption since 1990 has increased by 2-5%/year, the annual growth of rare metals production is about 10%/year. These huge growth rates and possible supply problems have attracted most of the attention over the last decade (European Commission, 2020). However, assessing the future of high-technology metals demand is difficult, because it depends on rapid technical innovation and the use of high technologies is much less dependent on GDP/cap than base metals. New technologies also concern the energy sector, which is evolving to reduce our greenhouse gases (GHG) emissions and comply with the Paris agreement. This agreement of COP21 aims at achieving the "carbon neutrality" in the second half of the 21st century, which implies a deep review of the existing fossil-based energy system. Unfortunately, solar and wind infrastructures require more raw materials per installed capacity and energy supplied than fossil fuel-based facilities (Kleijn et al., 2011; Hertwich et al., 2015; Vidal, Goffé, et al., 2013; Vidal, Boulzec, et al., 2018; Vidal, F. Rostom, et al., 2017). The same observation is made for the storage of energy, its transport and use at the end of the energy chain. It follows that large amounts of structural and high-tech mineral commodities will be consumed for the energy transition.



**FIGURE 2.2:** Concrete and steel consumption by geographical regions based on a logistic growth of regional infrastructures calculated for logistic GDP and population growths (Figure 2.1).



**FIGURE 2.3:** Raw material demand by sectors (Mt/year) calculated from the evolution of infrastructure (Figure 2.1) for China (**Left panel**) and USA (**Right panel**). The plain and dashed black lines show, respectively, the input and theoretical recycled flows (assuming no export or import of scrap). The dots show the historical data (USGS).

Figures 2.2 and 2.3 have been calculated under the assumption that the penetration of low-carbon energy technologies will remain moderate. For the same evolution of GDP and population, and thus of building, transport and energy infrastructure, the demand for metals will be different for a higher penetration of renewables. Examples are shown in Figure 2.4, which illustrate the differences in global Cu, Li, Co and Ni consumption for the two contrasted energy scenarios Reference Technology Scenario (RTS) and Beyond 2 Degree Scenario (B2DS) of the International Energy Agency (IEA) IEA, 2017. In contrast to previous estimates based on GDP/cap evolutions (Figures 2.2 and 2.3), the demand in raw materials in Figure 2.4 is calculated from the consumed energies listed in the scenarios, which are transformed into an infrastructure for assumed evolutions of energy consumption (-1%/yr) and material content. The evolution of infrastructure is then transformed into raw materials demand using the same material intensities as those used to build Figures 2.2 and 2.3. The demands in Cu, Li, Co and Ni are noticeably higher for the B2DS scenario, which foresees a massive incorporation of re-

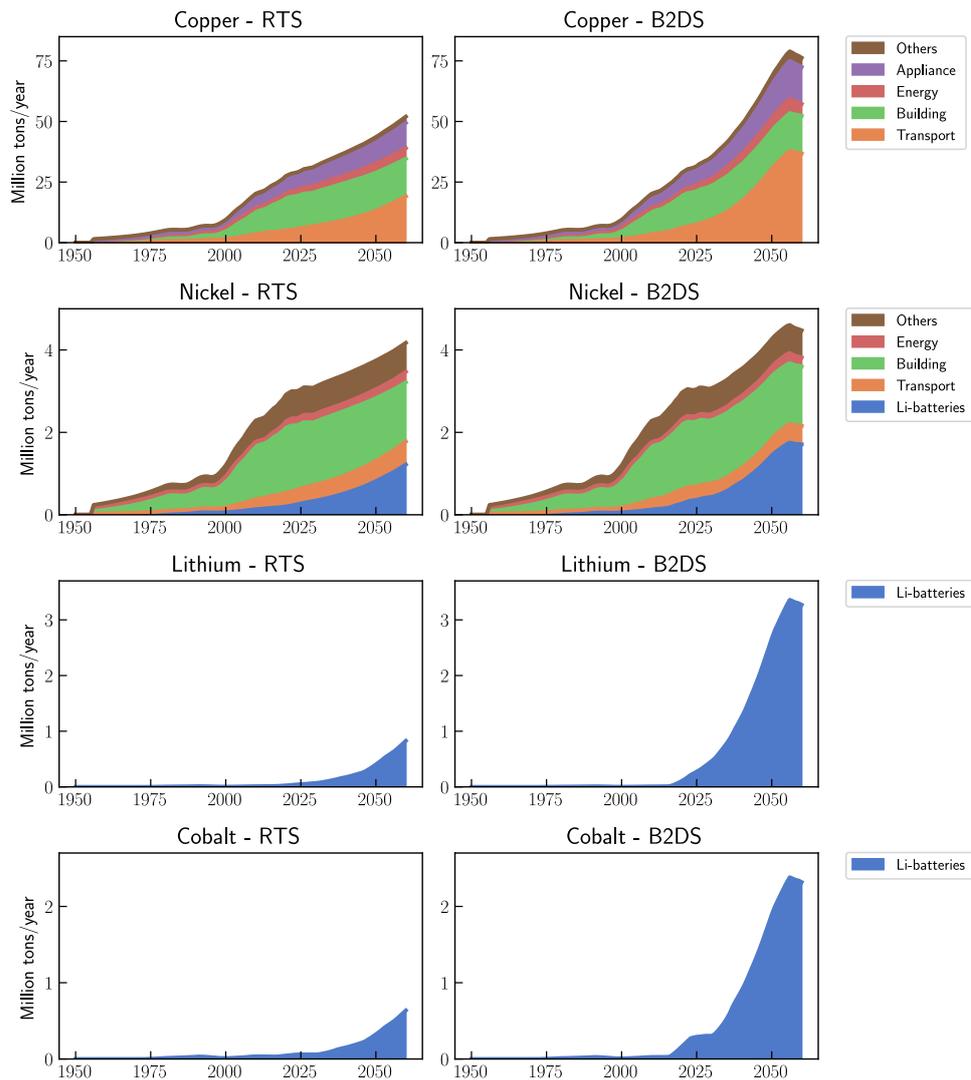
newable energy in the energy mix. Rare Earth Elements (REE) and in particular neodymium are also elements of concern, as they are used in the permanent magnets of a wide variety of technologies using electric motors and in the generators of off-shore wind turbines.

The estimates in Figure 2.4 must be handled with care because the present technologies, intensity of use and recycling rates are not necessarily representative of the future situation. The price of cobalt, used as a cathode in lithium-ion batteries, increased from 55,000 to 83,000 \$/t between March 2017 and February 2018. This situation has prompted the manufacturers to find solutions to reduce or ban the use of cobalt in lithium batteries<sup>1</sup> and to develop efficient recycling solutions<sup>2</sup>. Similarly, during the REE crisis in 2011, engineers were able to find solutions to either reduce the amount of used REE while maintaining the efficiency of technologies, or to change technologies. This illustrates the high potential of technological innovation to reduce the use of rare elements in high or/and energy technologies. For this reasons, it is extremely difficult to provide reliable estimates of their future demand.

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<sup>1</sup>Increasing investments into cobalt-free batteries research and development and production are currently observed by small to large companies.

<sup>2</sup>Such as the development of closed loop recycling processes.



**FIGURE 2.4:** Annual demand for Cu, Li, Ni and Co calculated for the evolution of infrastructure in the reference technology (RTS) (**Left panel**) and the "Beyond 2°C" scenario (B2DS) (**Right panel**) of the International Energy Agency.

Even though it will depend on the rate of economic development, energy and numerical transitions, the estimated cumulative amount of metals to be produced over the next 35 years is likely to be equivalent or exceed the cumulative amount produced from antiquity to the present. These dizzying figures, which are consistent with previous estimates (T. E. Graedel and J. Cao, 2010; T. E. Graedel, 2011), illustrate the reality of a forever growth of GDP. For a constant growth rate of 5%/year, the quantity doubles every 12 years. It has been possible to double aluminium production since 2000, will it be possible to quadruple it in the next 40 years? This question is addressed in the following section.

### 2.1.3. CAN FUTURE PRODUCTION MEET THE DEMAND?

Several studies suggest that the future supply of raw materials will not be able to keep pace with demand, because the stock of exploitable non-renewable resources is declining over time

and the production of several metals has already peaked or will peak in the near future (Meadows et al., 1972; Ugo Bardi and Lavacchi, 2009; Kerr, 2014; H. Sverdrup et al., 2014; Northey et al., 2014; Laherrère, 2009; H. U. Sverdrup, Koca, et al., 2013; Laherrère, 2010). Although it was initially developed for the oil production, application of Hubbert's theory to mineral resources led Sverdrup et al. (H. U. Sverdrup, Koca, et al., 2013) to the conclusion that the production of gold, silver, copper, nickel, zinc, molybdenum, iron, platinum and indium should peak at or before 2050. The same authors described a similar situation for conventional fossil energy resources, and a peak of non-conventional oil by 2075. However, a major flaw of Hubbert's approach lies in the assumption that production is limited by the sole availability of resources at continuously growing demand. According to this logic, the observed decline in the growth rate of steel production between 1970 and 2000 (Figure 2.2) could have been misinterpreted as a sign of resource depletion, while it was actually resulting from temporarily declining growth of demand. Another pitfall is the assumption that the Ultimate Recoverable Resource (URR) is finite and quantifiable. Metals and minerals are currently exploited from a small fraction of the continental crust. The maximum value of reserves can be estimated from the log-Gaussian Ore-Tonnage (OT) versus Ore-Grade (OG) relationship of ore deposits (Gerst, 2008; Singer, 2013):

$$OT = \frac{A}{OG \cdot \sigma \cdot \sqrt{2\pi}} \cdot \exp\left(\frac{-\log(OG) - \mu^2}{2 \cdot \sigma^2}\right) \quad (2.1)$$

where  $\mu$  is the central tendency,  $\sigma$  the dispersion and A the scaling factor that determines the function amplitude. The additional amount of metal  $M_{OG}$  that can be extracted with varying OG reads:

$$M_{OG} = OT \cdot \frac{OG}{100} \quad (2.2)$$

$M_{OG}$  is the amount of additional available metal deduced from its geological distribution in the crust, whatever the cost of its extraction. The integral of  $M_{OG}$  gives the evolution of reserves plus cumulative production, which increases exponentially as long as the average OG remains below the value of the peak of OT vs OG (Equation 2.1). By combining equations 2.1 and 2.2 with the expected evolution of demand (Section 2.1.2), it is possible to estimate the required evolution of average OG and thus OT and metal reserves. Based on the historical evolution of copper reserves, production, ore tonnage and OG with time, Vidal et al. (Vidal, F. Z. Rostom, et al., 2019) have estimated an URR of copper between 5 and 7.5 Gt in 2100 for a copper price ranging between 10 and 15 thousands US\$1998/t. Although these estimated reserves are within the range of those made by (Arndt et al., 2017; K. Johnson et al., 2014; Henckens et al., 2016; Singer, 2017), the approach is fraught with large uncertainties arising from equally large uncertainties in the distribution of metals in the earth's crust. Vidal et al.'s estimates assumed a bimodal distribution (Vidal, F. Z. Rostom, et al., 2019), one centred at the average grade of copper in the crust ( $OG \approx 30$  ppm (Rudnick et al., 2003)) and another corresponding to the peak OT of ore deposits centred at  $OG \approx 0.3\%$  Gerst, 2008. However, the bimodal OT vs OG distribution is questionable (Arndt et al., 2017), and if a unimodal

distribution centred at the average crustal concentration is assumed, future reserves could be at least an order of magnitude higher. Estimates of future reserves and resource availability from geologic criteria and OT vs. OG distributions are thus quite uncertain. The question of availability is above all a question of price and environmental impacts we will be willing to pay. Historical data show that so far, technological improvements have made it possible to mine less and less concentrated and accessible ores (deeper, offshore) without unaffordable increases in production costs and metal prices. Is this trend sustainable in the future? To answer the question, we must now understand the links between energy and production costs, between metal prices and OG, and between technological improvements and thermodynamic limits.

### 2.1.3.1. ENERGY OF METAL PRIMARY PRODUCTION, PRICES AND RESERVES

Currently, about 12% of global energy consumption and about 35% of the energy consumed by the industry worldwide is used for the production of iron and steel, cement, aluminium and non-ferrous metals (IEA, 2021). The production of mineral resources is therefore very energy-intensive. The energy of primary metal production can be estimated as the sum of three contributions (Vidal, F. Rostom, et al., 2017; Vidal, 2021) : i) the comminution energy proportional to the inverse of the mass concentration of metals in ore deposits ( $\frac{1}{C}$ ), ii) the minimum energy to separate the metal-bearing minerals from the disaggregated ore given by the mixing entropy of an ideal mixture of two components with no interaction ( $E_{s_i}$ ), and iii) the minimum energy of metallurgy given by the Gibb's free energy of formation of the ore mineral from its constituents ( $-\Delta G_f^\circ_i$ ):

$$E_i(2005) = \overline{\eta(2005)} \cdot (-\Delta G_f^\circ_i + E_{s_i} + \frac{a}{C_i(2005)}) \quad (2.3)$$

with  $\overline{\eta(2005)}$  the inverse of energy efficiency compared to the thermodynamic minimum ( $\eta=1$  at the thermodynamic minimum). Based on the observed evolution of production energies of twenty metals (i) diluted from 1.9 (iron) to  $2 \cdot 10^5$  (gold, platinum), average values of  $\overline{\eta(2005)} = 3$  and  $a = 0.2$  are obtained (Figure 2.5a). Several studies have shown that the average price of metals is proportional to the energy of their production, which also varies as a power law of dilution ( $\frac{1}{C}$ ) Phillips et al., 1976; J. Johnson et al., 2007; Gutowski et al., 2013; Vidal, F. Rostom, et al., 2017; Vidal, 2021. For the twenty metals used to derive the values  $\overline{\eta(2005)}$  and  $a$  in Equation 2.3, a plot of the observed production energies  $E(2005)$  as a function of their price in 2005 ( $P(2005)$ ) confirms this proportionality and the following relationship is derived Vidal, Andrieu, et al., 2021 (Figure 2.5c):

$$P(2005) = 26 \cdot \alpha \cdot E(2005)^{1.1} \quad (2.4)$$

A systematic deviation is observed between the observed and calculated price evaluated with Equation 2.4. The ratio of observed to calculated price is proportional to the metal dilution (Figure 2.6b), which suggests that the share of energy cost in price also depends on metal dilution. This effect is taken into account by multiplying the RHS of Equation 2.3 by  $\alpha =$

$\frac{2}{C(2005)^{0.2}}$  (Figure 2.5b).

The evolution of production energy with time can be estimated with Equation 2.3 by replacing the 2005 values of  $\eta$  and  $C$  by their values at year  $t$ . In order to account for the variations of energy price with time, Equation 2.3 must also be corrected by the price of energy at time  $t$  ( $PE(t)$ ) relative to 2005 ( $PE(2005)$ ):

$$P(t) = 26 \cdot \alpha \cdot E(t)^{1.1} \cdot \left( \frac{PE(t)}{PE(2005)} \right)^\gamma \quad (2.5)$$

with  $\gamma$  the elasticity of metals prices variations relative to the variation of energy price. Using the price of crude oil as a proxy of energy price,  $\gamma = 0.7$  for copper and  $\gamma = 0.1$  for aluminum.

At  $C < 1\%$ , the metallurgy and separation energies are negligible compared to the term  $\frac{a_i}{C}$  that represents the comminution energy. It means that at constant technology and price of energy, the energy of primary production of precious metals, copper or nickel are expected to increase exponentially with the decrease in ore grade observed over the last century (Mudd, 2009; Norgate et al., 2010). Proponents of a looming shortage of metals often use this argument to claim that production will become prohibitively expensive in the future. However, long-term historical data do not support this figure and the inflation-adjusted commodity prices have actually been falling between 1900 and 2000 (Mariscal et al., 2014). This fall, also observed for copper or nickel, indicates that the expected increase in production energy due to falling ore grades has actually been offset by the improvements of energy efficiency and productivity at constant ore grade (EC in the Figure 2.6a). The improvement of energy efficiency was 1-2%/year between 1900 and 2000 (Yellishetty et al., 2010; Gutowski et al., 2013; Vidal, Andrieu, et al., 2021) and until 2000, the energy gains of all metals production have more than compensated the decrease of ore quality. Since the regeneration of reserves increases with falling grade (Equations 2.1 and 2.2), these figures explain why both the produced quantities of metals and their reserves have grown exponentially since 1900. However, this trend is not sustainable on the long term because there is a thermodynamic limit (ETL) to the extraction of metals, which is given by Equation 2.3 with  $\eta = 1$ . This physical limit cannot be overstepped, whatever the technological improvement. Steel production consumed about 50 MJ/kg in the 1950 and it has been halved between the 1950s and 2000 (Yellishetty et al., 2010). It will most likely not be halved again by 2050 to reach the thermodynamic limit equal to about 10 MJ/kg for iron oxide ore<sup>3</sup> ( $-\Delta G_f^\circ = 7$  MJ/kg of hematite), as the investment required to gain a few MJ when approaching this limit becomes prohibitive. More worrying, the thermodynamic limit of metals at  $C < 1\%$  is expected to increase exponentially with falling ore grade due to the term  $\frac{a_i}{C}$ . In practice, this limit cannot be reached because industrial processes cannot be 100% efficient, and the minimum value of  $\eta$  in Equation 2.3 is unlikely to be lower than 1.5 (PME = 1.5·ETL). In the case of copper,  $\eta$  decreased at an annual rate of -1.5%/yr from about 10 in 1930 to 2 in 2000 (dashed line in Figure 2.6b). It will not be possible to continue on this trend because the minimum value of  $\eta = 1.5$  will be reached before the end of the century (continuous line in Figure 2.6c). For an average ore grade of copper deposits decreasing at 1.5%/yr since 1900, improving current me-

<sup>3</sup>For metals at high concentration in ore deposits such as iron ( $C = 30\text{-}50\%$ ) or aluminium (15-30%), the energy demand of crushing and grinding ore ( $\frac{a_i}{C}$ ) is negligible compared to the energy of metallurgy ( $-\Delta G_f^\circ$ ) in Equation 2.3.

chanical crushing and grinding technologies will thus not compensate for the additional energy to switch to lower grade ore in the future, as it has been the case during the 20<sup>th</sup> century. The energy of copper production, which declined between 1900 and 2000, is thus expected to increase from 2000 onward and parallels the PME in the second half of the century (Figure 2.6a). Similar conclusions are drawn for precious metals and nickel, zinc and manganese.

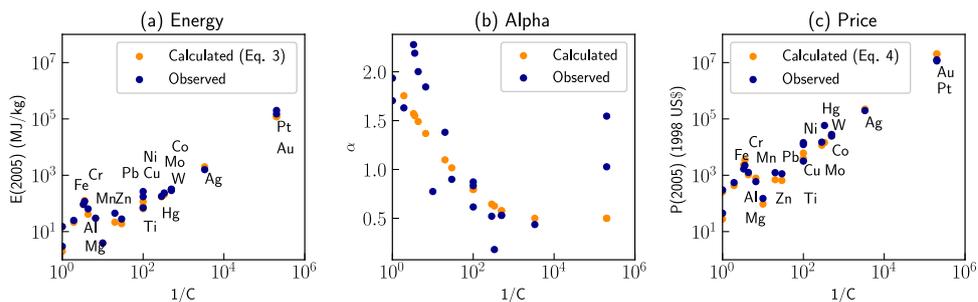
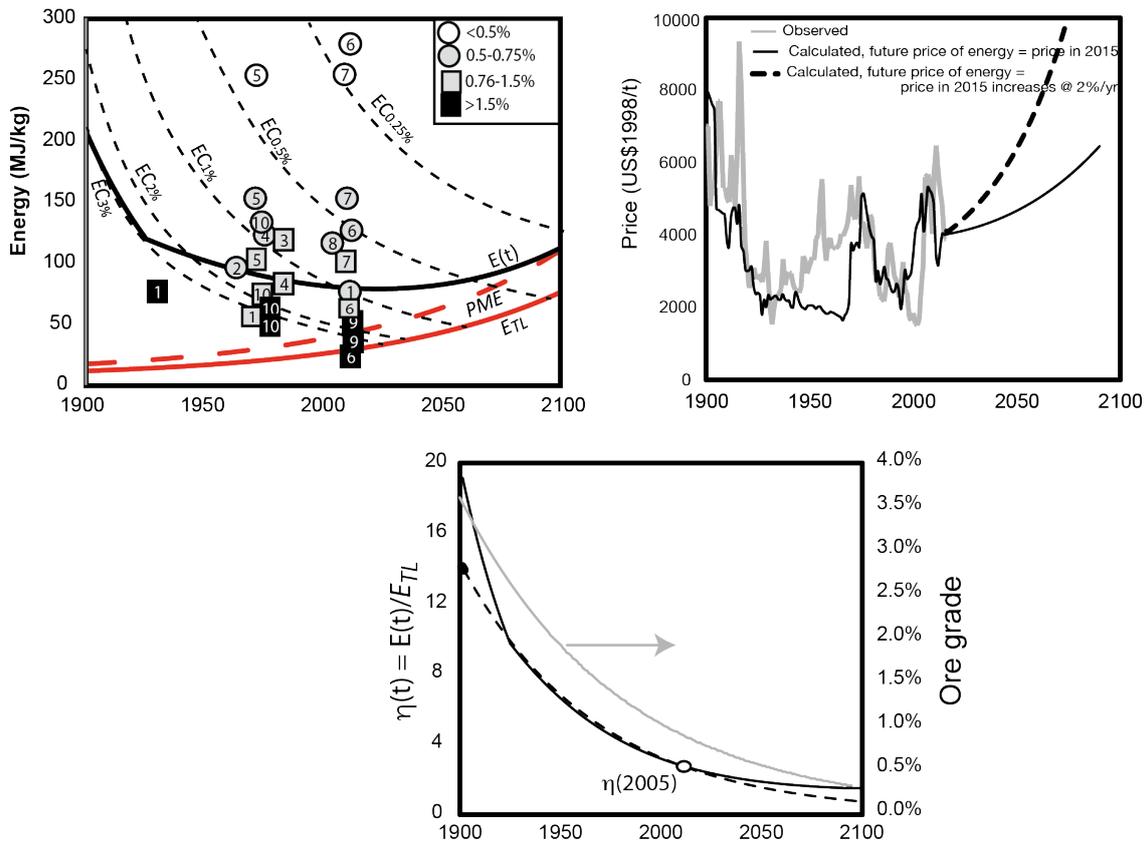


FIGURE 2.5: Energy (a),  $\alpha$  in year 2005 (b) and price (c)



**FIGURE 2.6: a)** Calculated and observed (numbers) energies of copper production: the heavy black line shows the energy of copper production with varying ore grade and technology  $E(t)$ , the thin black dashed line show the energy at constant ore grade with varying technology (EC), and the red dashed and continuous lines show the practical minimum energy (PME) and thermodynamic limit (ETL), respectively. The observed data are plotted at the time of publication and reported ore grades: 1) Rötzer and Schmidt Rötzer et al., 2020 **c)** 2) Rosenkranz 1976; 3) Gaines 1980; 4) Kellogg 1974; 5) Page and Creasy 1975; 6) Norgate et al., 2010; 7) Marsden 2008; 8) Office of Energy Efficiency & Renewable Energy 2002; 9) Rankin 2011 ; 10) Chapman 1973. **b)** Observed copper price (grey line) and calculated price (black line). The future price is calculated at constant future price of energy (=PE2015, continuous line) or at 2%/yr increasing price of energy after 2015 (dashed line).  $\eta(t)$  (black continuous line, left scale) and ore grade (gray line, right scale) used to compute **a)** and **b)**. The black dashed line in **c)** shows  $\eta(t)$  calculated from  $\eta(2005)$  and a -1.5%/yr of change.

**2.1.4. DISCUSSION**

The above overview of some parameters controlling the demand and primary production provides arguments for two classically opposed views of the future of mineral resources: an unaffordable increase in costs and prices following the depletion of high quality deposits or, on the contrary, a favourable compensation by technological improvements. Both visions are true, but not at the same time. After a period of gains in energy and production costs, it seems that we are now entering a pivotal period of long-term increasing production costs as we approach the practical minimum energy and thermodynamic limits for several metals. To reduce this increase of price, unknown breakthrough but affordable grinding technologies based on non-mechanical processes will have to be found. Another possibility is to reduce the price of energy. Renewable energies are virtually unlimited and once the infrastructure of production is built,

they are cheap. If we could use renewable energy sources at a low and stable price in the future, the increasing weight of energy intensity in the cost of production would no longer be an issue. This is illustrated by Iceland, which became in 2016 the world's ninth largest producer of aluminium from imported bauxite thanks to cheap geothermal and hydroelectric power, even though it has no ore and most of its production is destined to foreign markets. If the use of renewable energy sources were to become significant enough to cover the needs of the raw material production sector, it would become possible to exploit low-grade resources that cannot be exploited at an affordable cost today. However, energy transition scenarios present another constraint: in order to cope with the targeted decrease of CO<sub>2</sub> emissions, they generally assume a strong reduction in energy consumption. For example, the amount of energy available for the industrial sector in the scenario B2DS already used in Figure 2.2 is 65% that of RTS, while the energy consumed for the production of raw materials is similar. The future share of industrial energy consumed to produce the raw materials is thus higher in B2DS than RTS and the remaining energy available for the other industrial sectors is lower. These figures will impact the intensive industries and in particular the raw material production sector, which will already face the problem of declining resource quality. It thus seems extremely difficult to switch to renewable energies while reducing global energy demand. Neither the developed countries, which are expected to replace their fossil fuel-based energy infrastructure in two or three decades, nor the developing countries that produce raw materials to build their basic infrastructure will spontaneously follow this path. Until 2050, the demand for energy will thus continue to grow on a global scale. On the longer term, the energy demand for the production of raw materials is expected to decrease after 2050 in both scenarios B2DS and RTS. This is due to the combined effects of: **i**) approaching the saturation levels of infrastructure at the global scale, which entails a reduction of the annual demand in raw materials, **ii**) completing the energy transition, and **iii**) increasing rapidly the share of less energy-intensive recycled metals at the saturation levels and unaffordable prices of primary metals.

The above overview of the parameters controlling the demand and primary production also indicates that the question of the future of mineral resources cannot be based solely on knowledge of current geological availability for a constant rate of growth in demand and technology. It must be studied using dynamic models that integrate the value chain from primary production to recycling, coupling energy requirements and thermodynamic limits, geological, environmental, technological, social, economic and and geopolitical dimensions. Such models are intrinsically complex, but it is illusory to address complex issues with empirical and deterministic models such as Hubbert's model, or any model neglecting the role of technological improvement including the development of advanced exploration technologies, change in resource quality and variations of energy prices with time. Coupling material flows with GDP and population evolution is quite straightforward using sigmoid evolutions of the infrastructure/cap with GDP/cap, and assumptions on the materials contents. The consumed energy can also be estimated for assumed intensities of use and energy efficiencies. In contrast, coupling the materials and energy flows with economic models is more difficult, because economic models lack physical basis and constraints and are derived from observations made in growing

economies. Since the industrial activities and consuming sectors are strongly coupled, it is difficult to analyse one sector of metal production isolated from the whole economic system. To circumvent the problem, a possible approach based on a prey-predator dynamics has been proposed by Vidal, F. Z. Rostom, et al., 2019, in line of previous study by Bardi and Lavacchi Ugo Bardi and Lavacchi, 2009. This approach is also empirical, but it allows one to combine physical units (tons) with monetary units without requiring a detailed and comprehensive description of all economic sectors. It analyses the evolution of industrial capital (the predator, in monetary units) and the metal reserves (the prey, in tonnes) with two coupled differential equations involving four parameters controlling the yearly regeneration of reserves, metal production, regeneration and erosion of capital. Interestingly, the cost (price) of metal production is given by the ratio of two of them, corresponding to the capital growth to metal production. Applying the model to the case of copper, we showed that the expected price evolution is similar to the production energy-based independent estimate reported in Figure 2.6. Independently of any economic consideration, the long-term price of metals derived from the production energy calculated with the simple thermodynamic formalism proposed in Equations 2.4 to 2.5 thus provides first order constraints on the future evolution of metals production. In the case of copper, Vidal, F. Z. Rostom, et al., 2019 predicted a peak in primary production by 2050, followed by a rapid collapse if the future demand is assumed to follow the historical trends (+3%/year). In contrast, a scenario no longer based on a steady growing demand but on the need for a population stabilizing at 11 billion inhabitants in 2100 and an average GDP per capita of 10,000\$ provides more optimistic results. A peak of primary production is still observed, but it is a peak of demand. A decrease of primary production occurs in the second half of the century, when the saturation of infrastructures is approached and recycled copper becomes the major source. Here again, this example shows that the future of natural resources cannot be dissociated from a scenario of demand, which is another illustration of the limit of Hubbert-like approaches. The prey-predator model applied to other metals suggests that the supply of most base and precious metals (except gold) should also meet the demand until the end of the century. The situation is much less clear for rare metals, as historical data on reserves and production are missing, imprecise or cover too short a time period to be used as reliable constraints for the models.

In addition to the reserves, price and energy production issues, the environmental impacts of raw materials and energy production must also be integrated in the models. These impacts might become a limiting factor to production in the future. An emblematic example is given by El Salvador that made history as first nation to impose blanket ban on metal mining in response to diminishing water sources from polluting mining projects<sup>4</sup>. The huge expected increase in mineral resources consumption and primary production will increase conflicts and social opposition. The surface occupied by mines and quarries at the world level has been estimated to be about 400,000 km<sup>2</sup> Hooke et al., 2012, it could be doubled by 2050 and quadrupled by 2100. The embodied water consumption and other environmental impacts are expected to follow the same trends. These figures are naturally concerning, especially in arid production areas. To our knowledge, no model currently exists that describes the local societal response to water and land

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<sup>4</sup>This decision was approved by the Parliament of El Salvador in early 2017.

use and more broadly to environmental impacts, even though this could significantly hamper future resources supply. This response is expected to depend on the level of GDP/capita and population density, the industrial typology, the level of agricultural production and geographical characteristics of the producing countries, such as the availability of water. Modelling the feedback of resource consumption and environmental changes on social opposition is a very important research topic to address the issue of future mineral resource availability in a world of increasing environmental constraints, and increasingly compromised access to water and arable land.

## 2.2. MATER MODEL

**Authors** François Verzier, Hugo Le Boulzec, Baptiste Andrieu, Olivier Vidal

The MATER model is a bottom-up, time-dependent, demand-driven framework where exogenous scenarios of end-use sector stocks (passenger transport, buildings, food consumption, textiles, numeric, etc.) and product characteristics (lifetime, material intensity, energy consumption, etc.) drive a Material and Energy Flow Analysis (MEFA) to compute certain physical indicators (energy consumption, material consumption, impact production, etc.) by adding the direct demand and production of each good. Industrial sector stocks and activities are endogenously linked to other sectors by production capacities.

The exogenous scenarios stocks can derive from three different input types (Figure 2.7):

- Socio-economic inputs such as GDP and population, disaggregated into good stocks through logistic functions calibrated on historical data.
- Energy demand inputs by good, converted to stock data through energy consumption and service intensity parameters.
- Service demand inputs by good, calculated into stock data through service intensity parameters.

The accounting component of the model is drawn from the DyMEMDS model (see chapter 2.1), and closely resembles the Resource Efficiency and Climate Change (RECC) mitigation framework. The input for the accounting is the reference stock of goods necessary for the socio-economic system to function. Each good demands industrial and energy supply services throughout its construction phase (Figure 2.8.a) and operational phase (Figure 2.8.b), but it only consumes energy and resources during its operational phase (Figure 2.8.b). The model parameters are direct consumptions, not Life Cycle Assessment (LCA) embodied consumptions, avoiding double counting. Dynamic LCAs are computed by the model according to the evolution of the links between the sectors and the direct consumptions of each technology.

### 2.2.1. CONSTRUCTION PHASE (FIGURE 2.A)

The MATER model performs a mass balance, tracking the flow of goods from demand to material production, down to resource extraction. First, the quantity of goods needed for construction is calculated as the derivative of the stock, plus the quantity of old goods to be replaced. If the result is negative, surplus goods are not dismantled but halted, allowing their later reuse when the reference stock rises again, instead of constructing new ones. Second, the built cohort, characterized by a dynamic lifetime lognormal distribution, is used to calculate future goods replacements. These old goods are collected and recycled to create a supply of recycled materials, primarily used by the total materials demand and supplemented by primary material supply when needed. Finally, primary materials supply and energy supply are disaggregated by fuels and minerals produced by primary mineral supply industries.

### 2.2.2. OPERATIONAL PHASE (FIGURE 2.B)

In-use goods consume and/or produce energy, resources, and impacts. They are characterized by an intensity of use (in service per good per year) and a consumption (or production) per service. For example, a car that travels 'x' km per year, consumes 'y' L/km and produces 'z' kg of fine particles per km, will consume 'x\*y' L of fuel and emit 'x\*z' kg of fine particles in a year. A computer has only direct electricity consumption, while a steel mill consumes several energy carriers and resources, produces steel and co-produces blast furnace slag, and emits CO<sub>2</sub> as well as other pollutants. By summing the direct consumptions and productions of each good, the model assesses the global consumptions and productions of the entire socio-economic system.

### 2.2.3. INDUSTRIAL ENDOGENIZATION AND ELECTRICITY PRODUCTION

Every good, resource, or energy production requires one or more industrial and energy supply activities, resulting in a strong link between energy and resources. The MATER model seeks to endogenize this relationship as much as possible. Consequently, industrial energy and resources consumptions and co-productions are entirely endogenized, enabling the model to account for differences between production technologies of a given good or resource. For instance, with a single scenario of end-use sector electricity consumption, the overall electricity production will vary depending on the electricity mix. If renewable power plants are more material-intensive per kWh than thermal power plants, the materials-producing industries will consume more electricity per year to build the power plants, resulting in even greater electricity production. To sum up, we need materials to produce power plants, these materials require electricity for their production, and electricity production itself needs power plants. To solve these feedback loops in the model, we use a Gauss-Seidel method, which involves making several calculation iterations per year of simulation. At the start of each iteration, the reference stock of endogenous goods is equal to the reference stock calculated in the previous iteration. With each iteration, the stock grows until it converges on the quantity needed for its own production, in addition to the production for other sectors.

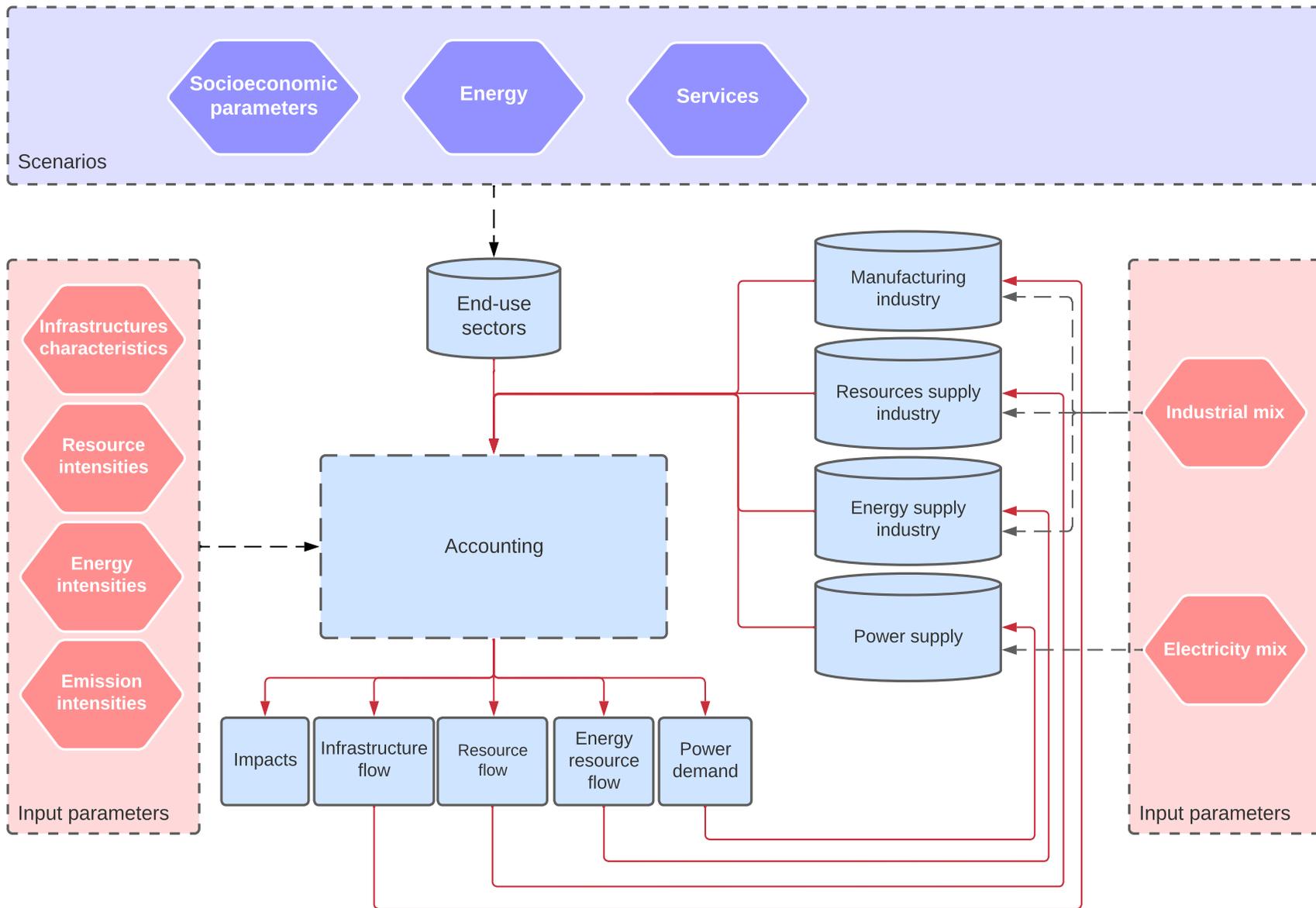


FIGURE 2.7: MATER model general framework. Stocks are represented by blue barrels, output flows by full blue rectangles and input parameters by hexagons. Full red arrows and pointed black arrows describe the links between inputs, outputs and stocks. The accounting pointed blue area is described in detail on 2.8.

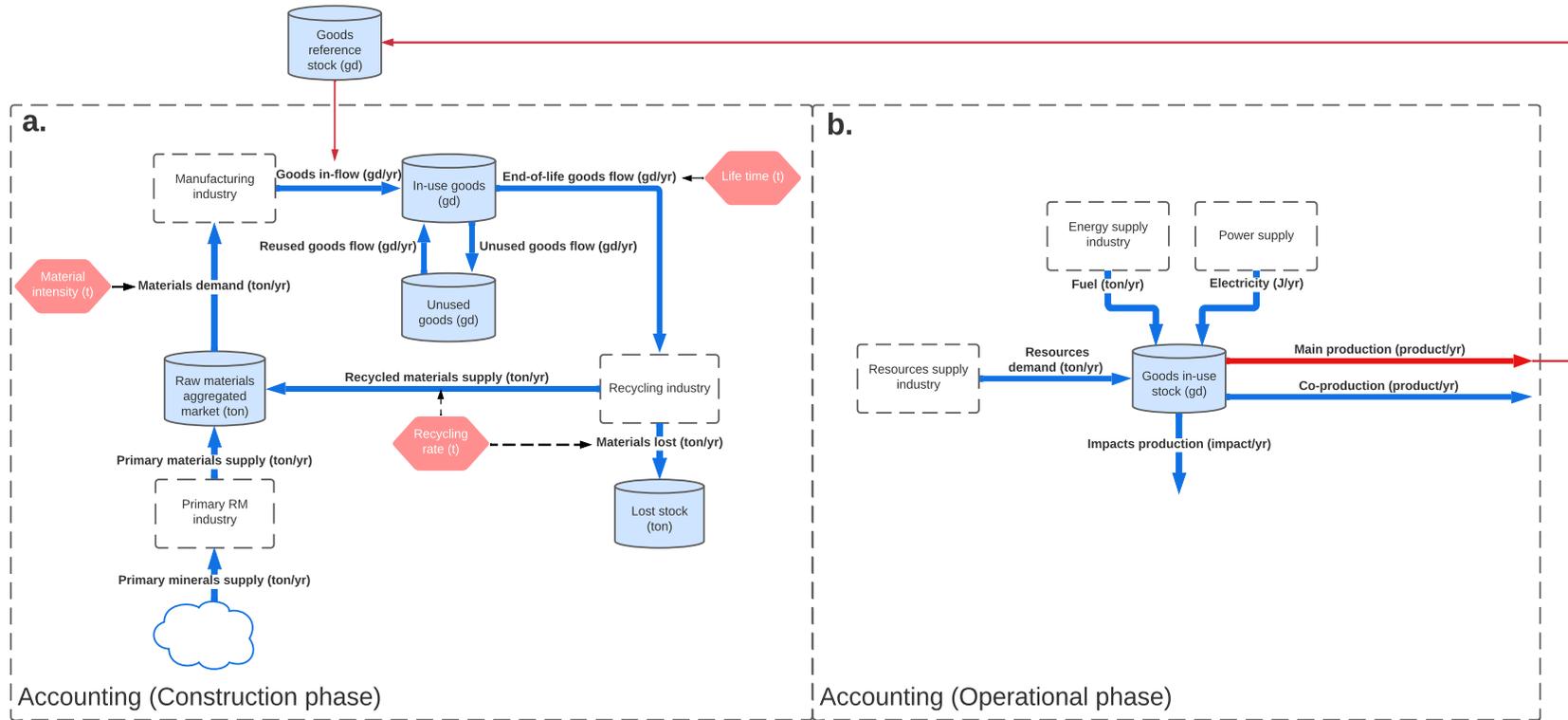


FIGURE 2.8: Accounting loop framework. Stocks are represented by blue barrels, flows by blue arrows, links between variables by black and red arrows, exogenous inputs by hexagons and industrial activities by black pointed rectangles.

## 2.3. TRANSPORT SECTOR

A central element to the MATER model is to predict the levels of stocks. This chapter presents reflexions on how to do that for the transport sector, through the example of Personal Light Duty Vehicles (PLDV). The PLDV s-curves presented in this chapter are also built for every other infrastructure sector in MATER.

### 2.3.1. INTRODUCTION

Understanding the accumulation and dynamics of physical stocks is critical for the study of sustainability. Stocks are the cumulative results of past production and consumption processes. These processes not only contribute to raw material depletion, but they also create a technological and behavioural lock-in, thereby shaping future emissions and waste flows. However, the representation of these stocks in Integrated Assessment Models (IAMs) remains largely underdeveloped. This gap in the literature calls for an innovative strategy to account for the levels of stocks in these models.

A promising approach is to explicitly describe stocks to provide a given service. For instance, the number of PLDV required for personal transport services. However, doing so will imply important breaks between the projected stocks and the historical stocks (because we must reduce the numbers of PLDV to tackle climate change). Building business-as-usual scenarios would allow to detect the scale of the slope breakage. Historically, a strong coupling exists between stocks and gross domestic product (GDP) per capita. These relationships typically follow S-shaped logistic growth curves, also known as S-curves. For instance, the number of PLDVs per capita as a function of GDP per capita follows such a curve.

In this study, we develop an equation to accurately reproduce the historical stocks of PLDVs, enabling the exploration of future trends under business-as-usual conditions. We then compare our results with those obtained with two other models, GCAM -an IAM- and Odym-RECCs -an industrial ecology model-. The comparisons are conducted for two shared socioeconomic pathways (SSPs): SSP1, which represents a green growth or sustainability scenario, and SSP2, which represents a middle-of-the-road scenario.

### 2.3.2. METHODS

#### 2.3.2.1. S-CURVES

S-curves provide a methodology to predict per capita infrastructure stocks as a function of GDP. Figure 2.9 represents the historical data of PLDV as a function of GDP per capita for every country in the world. The curves are superimposed so all the trends cannot be clearly distinguished but they do tend to follow an S-curve. In multi-regional investigations, one curve is adjusted for each region with variant parameters (Dargay et al., 2007).

This approach is, however, not fully predictive since it doesn't clarify the inter-regional dis-

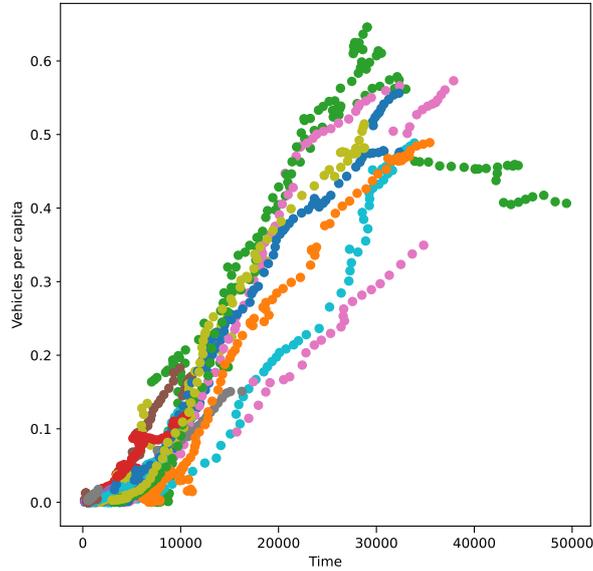


FIGURE 2.9: Historical data of PLDV per capita

parities. It only becomes predictive for regions that are on the second half of the S-curve and have ample data. For regions either lacking data or only at the inception of the S-curve, the saturation level cannot be anticipated.

In this section, we strive to establish a single formula that can describe PLDVs stocks for all regions. The inter-regional discrepancies will be accounted for by physical indicators like GDP or population density.

Various functions, such as Logistic, Gompertz, or Richards, can be utilized to create S-curves. We opt for a logistic function (Eq. 2.6) due to its straightforward interpretation, where  $\gamma$  symbolizes saturation,  $\theta$  represents slope, and  $Y_0$  is the GDP value where  $V(Y_0) = \frac{\gamma}{2}$ .

$$V = \frac{\gamma}{1 + \exp^{-\theta(Y - Y_0)}} \tag{2.6}$$

To best accommodate each region with a single equation, these parameters must be adapted for each region ( $i$ ) and can vary with time ( $t$ ). As a result, Eq. 2.6 becomes:

$$V(t, i) = \frac{\gamma(t, i)}{1 + \exp^{-\theta(i)(Y(t, i) - Y(t_0, i))}} \tag{2.7}$$

Let's note that rather than defining  $Y(t_0, i)$  so that  $V(t_0, i) = \frac{\gamma}{2}$ , we can adjust Eq 2.7 to define any intersection point on the curve  $V(t_0, i) = V(t_0, i)$ :

$$V(t, i) = \frac{\gamma(t, i)}{1 + \left(\frac{\gamma(t, i)}{V(t_0, i)} - 1\right) \cdot \exp^{-\theta(i)(Y(t, i) - Y(t_0, i))}} \tag{2.8}$$

We notice that at any given point in time, the PLDVs stock per capita in between-regions (cross-sectional analysis) also follows a logistic curve. Eq 2.9 delineates the curve shape for the

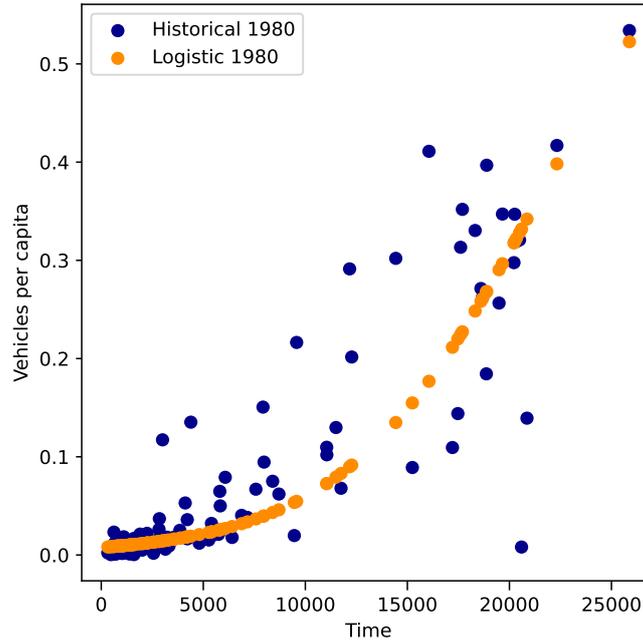


FIGURE 2.10: Logistic curve for year 1980 in between regions

year 1980 (as depicted in figure 2.10):

$$V(1980, i) = \frac{0.72}{1 + \left(\frac{0.72}{0.036} - 1\right) \cdot \exp^{-0.00021(Y(1980,i)-7500)}} \quad (2.9)$$

The numerical coefficients in Eq. 2.9 demonstrate that, in 1980, the saturation level was 0.72 and that, for a GDP per capita of 7500 US\$ppp2005, individuals had 0.036 PLDV per capita.

This data from 1980 helps to solve  $t_0$  and  $V(t_0)$  in Eq. 2.8. A significant benefit of this is that we can specify a crossing point in 1980 for any region simply by knowing its GDP per capita (even if no PLDVs data exists). As a result, Eq. 2.8 becomes:

$$V(t, i) = \frac{\gamma(i)}{1 + \left(\frac{\gamma(t,i)}{V(1980,i)} - 1\right) \cdot \exp^{-\theta(i)(Y(t,i)-Y(1980,i))}} \quad (2.10)$$

We are now tasked with solving for  $\gamma$  and  $\theta$ . One plausible reason for  $\gamma$  (the saturation level) to vary could be population density. We expect  $\gamma$  to be lower in densely populated regions and higher in less dense regions. Regarding  $\theta$ , we observed that regions with lesser wealth today tend to follow a steeper curve compared to affluent regions in previous decades. This essentially implies that the elasticity of purchasing a car today is higher than it was in previous decades. Hence, we construct functions such that  $\gamma$  depends on population density and  $\theta$  relies on the GDP per capita for the year 2015 (regions with the least wealth in 2015 will have the steepest curve). We then determine constants to optimize the overall  $R^2$  of the fits and derive the following equations:

$$\theta(i) = \frac{12.6 - \log(Y(2015, i) + 6012)}{1000} \quad (2.11)$$

$$\gamma(i) = 0.9 - 0.092 \cdot \log(1000 \cdot apd + 8) \quad (2.12)$$

Here, *apd* represents the adjusted population density, a variable that incorporates geographical data to correct population density for actual habitable surface area.

Figures 2.11 and 2.12 depict the 24 regions with the highest population in 2015. The historical data is represented by the blue lines, while the orange lines depict the logistic fit. This fit, obtained through a single equation, aligns surprisingly well with historical data. We can thus rely on it to construct a business-as-usual scenario.

### 2.3.2.2. ODYM-RECC DATA

The Resource Efficiency and Climate Change (RECC) model calculates the size and operation of in-use stocks (e.g., passenger vehicles, residential buildings) needed to deliver services. It translates stock demand into the production and recycling of vehicles and buildings, using the concept of stock-flow-service nexus and energy service cascade. RECC incorporates representative single-product descriptions, or 'archetypes', with varying degrees of material and energy efficiency, and utilizes engineering tools for simulation. The model translates product flows into material flows and calculates energy demand and related greenhouse gas emissions. RECC generates scenarios exploring different degrees of material efficiency under varied socioeconomic, technological, and climate-political contexts. It doesn't predict the likelihood of scenarios but checks for potential infeasibility due to mass balance constraints (Pauliuk, Heeren, et al., 2021; Pauliuk, Fishman, et al., 2021; Pauliuk and Heeren, 2020).

For the RECC model, Fishman and colleagues designed three intricate scenarios that span across 20 global regions, extending to the year 2060. These scenarios detail the provisioning of services within personal transport and dwelling areas. Grounded within the Low Energy Demand (LED) and Shared Socioeconomic Pathways (SSP1 and SSP2) narratives, their scenarios deliver specific regional and temporal narratives along with corresponding parameters. These parameters include per capita floor space and vehicle stocks, variations in building and vehicle archetypes, passenger-kilometres and vehicle-kilometres, vehicle occupancy rates, and the implementation potential of nine material efficiency strategies. Instead of relying on aggregate GDP-driven extrapolations or historical trend forecasts for service or energy demands, Fishman and colleagues offer an alternative method by adopting an explicit storyline extension approach (Fishman et al., 2021).

We extract the PLDV data from the RECC model for SSP1 and SSP2 for a scenario without material efficiency and a scenario with all material efficiency levers activated (only car sharing and ride sharing affect the total stock of PLDV).

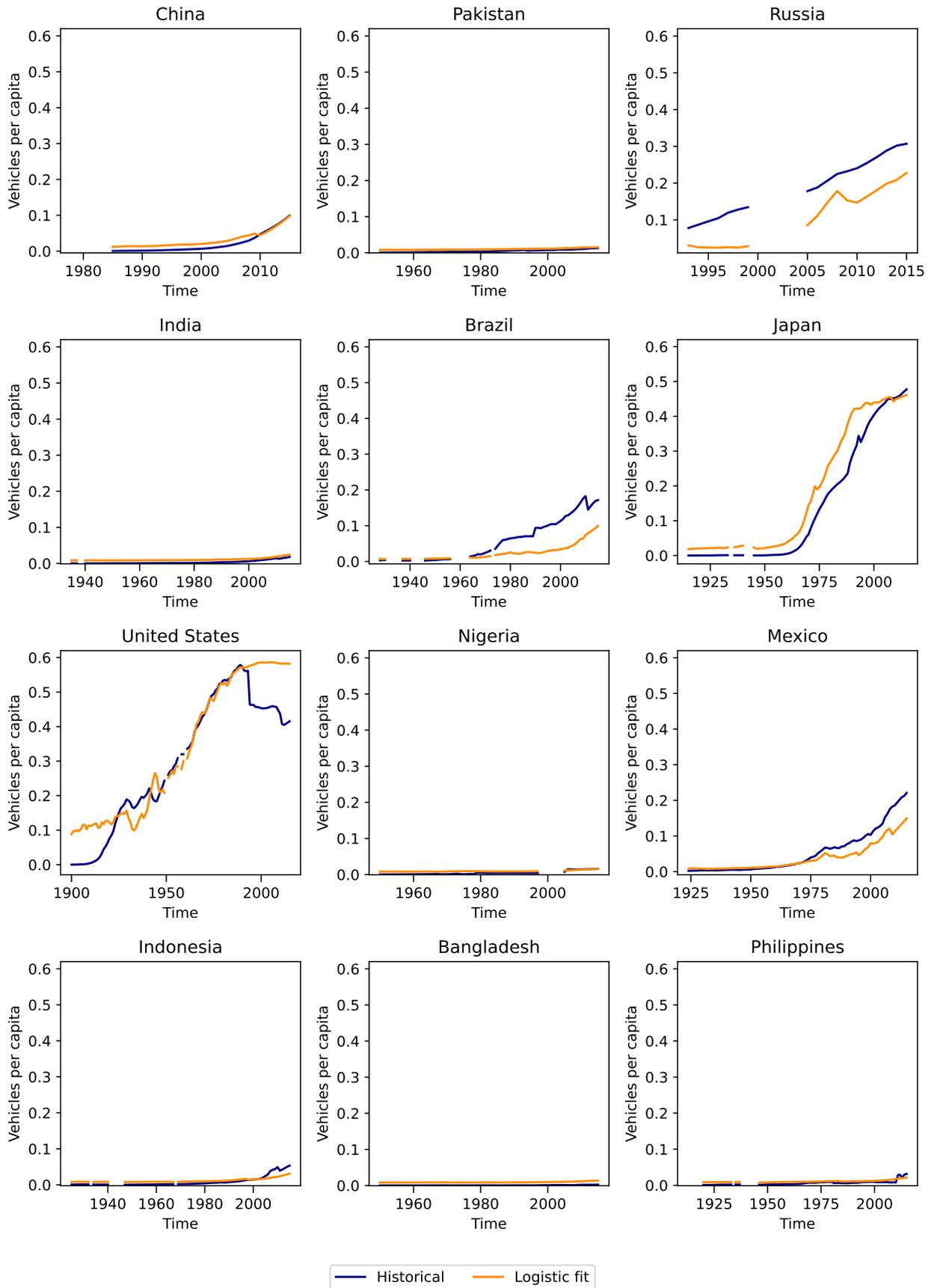


FIGURE 2.11: Results of the logitic approach for the 12 regions with highest population

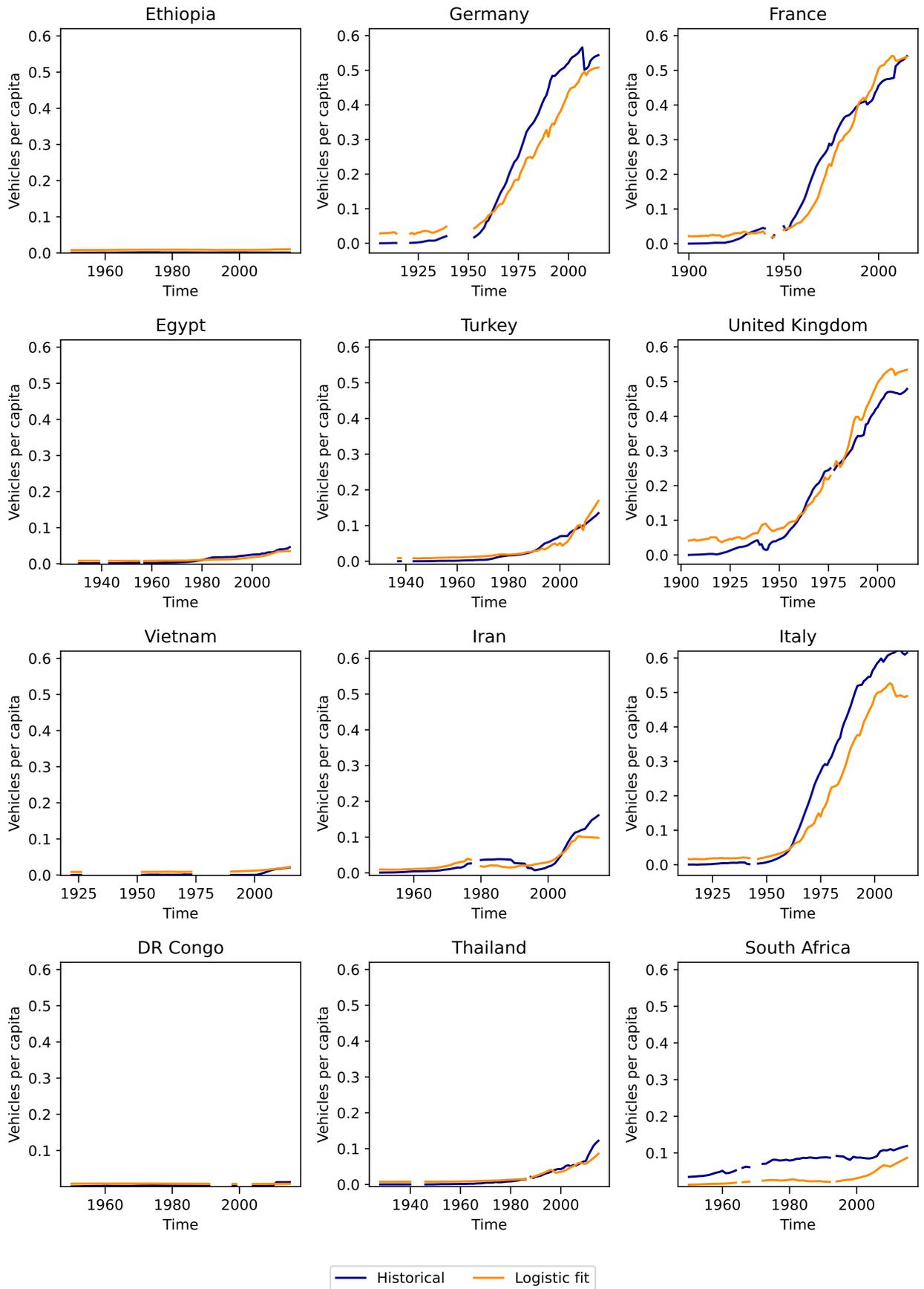


FIGURE 2.12: Results of the logitic approach for the 13-24 regions with highest population

### 2.3.2.3. GCAM DATA

The Global Change Assessment Model (GCAM), developed and maintained by the Pacific Northwest National Laboratory, is a detailed, technologically focused, partial-equilibrium IAM that runs in 5-year increments from 2005 to 2095, integrating global energy supply chains, agriculture, land-use, and climate systems. The model accounts for the industrial, buildings (commercial and residential), and transportation sectors, and includes a simplified climate model monitoring multiple greenhouse gases and pollutants (Calvin et al., 2019).

The modelling of the transport sector of the GCAM model is explained thoroughly in Mishra et al., 2013. The demand for passenger transport in passenger-kilometers (pkm),  $D_p$ , for region  $r$  and time  $t$  is given by

$$D_p^{r,t} = \sigma^r \left( Y_I^{r,t} \right)^\alpha \left( P_I^{r,t} \right)^\beta \left( N_I^{r,t} \right) \quad (2.13)$$

Where  $\sigma$  is a base year (2005) calibration parameter.  $Y_I$  is per-capita GDP.  $P_I$  is the index of price of transportation aggregated across all modes, size classes, and technologies.  $N_I$  is the population.  $\alpha$  and  $\beta$  are income and price elasticities to per capita passenger demand.

The modal share of each technology  $i$  (such as PLDV) for region  $r$  and time  $t$  ( $S^{i,r,t}$ ) is endogenous and calculated as:

$$S^{i,r,t} = \frac{(SW^{i,r}) (P^{i,r,t})^{\lambda_i}}{\sum_i (SW^{i,r}) (P^{i,r,t})^{\lambda_i}} \quad (2.14)$$

With  $SW$  the share weight, a calibration parameter,  $P^i$  the cost of transport for a mode  $i$ , and  $\lambda$  a logit exponent that regulates the degree to which future price changes will be reflected in modal shifts.

Based on these results in pkm for SSP1, SSP2 and all RCPs, as well as GCAM hypothesis on vehicles lifetimes, yearly distances travelled per vehicle and occupancy rates, we calculate stocks of PLDV.

### 2.3.2.4. COMPARISONS

The logistic approach was carried out for every world region while the GCAM is based on the 32 SSP regions and Odym-RECC studied 20 regions. Only Canada, the USA, Japan, China, and India are commonly included in all three approaches. These countries are thus the ones that will be compared here. SSP1 and SSP2 are compared. The logistic curves are obtained from using the reference GDP per capita trajectories for both of these scenarios.

### 2.3.3. RESULTS

Figures 2.13 and 2.14 show the results for Canada, USA, Japan, China and India, for both SSP1 and SSP2. The black lines represent the historical data and the blue lines the historical fits. The light and dark pink lines represent the results from Odym-RECC without material efficiency and with material efficiency, respectively. The orange, green, red and purple lines

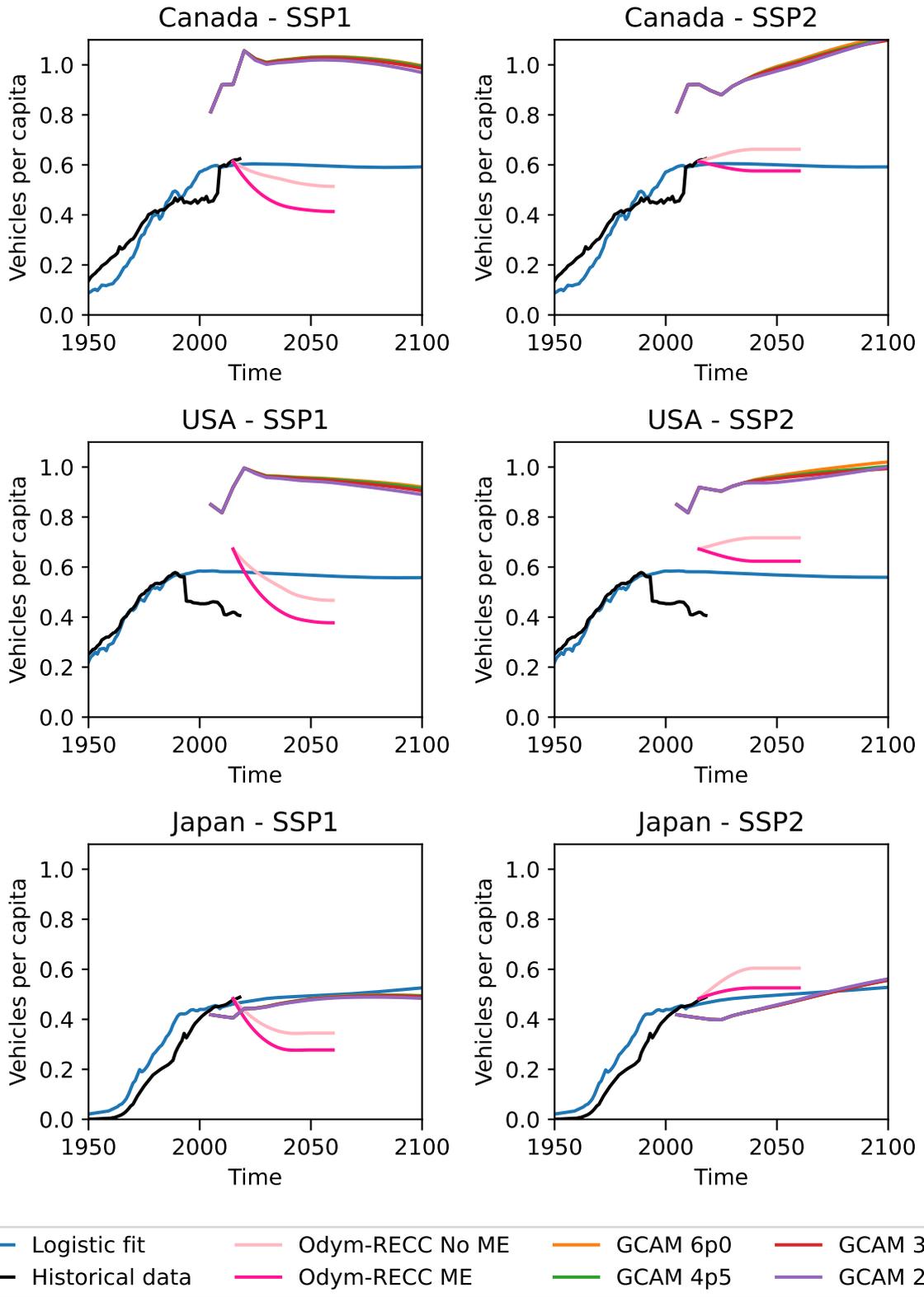
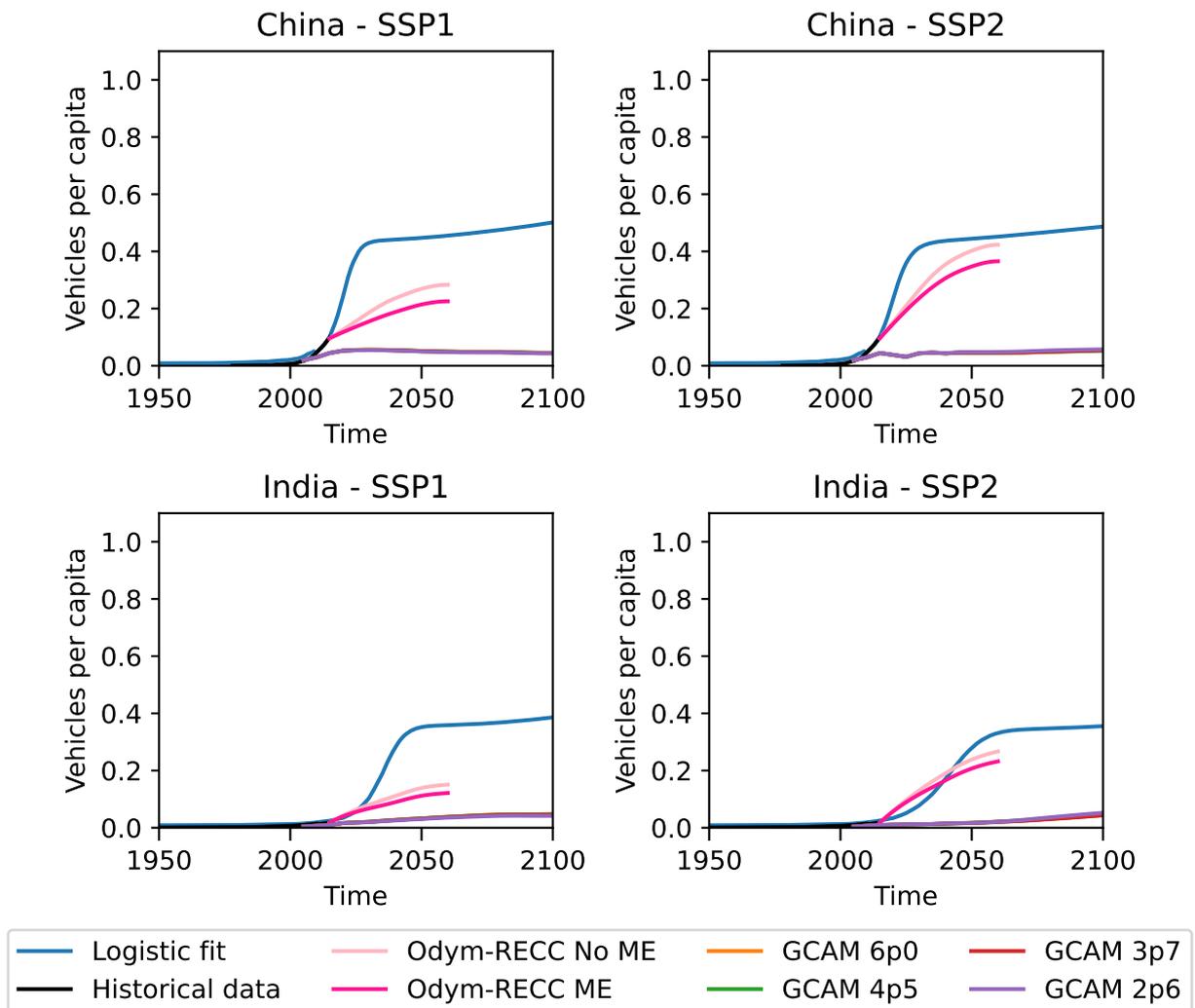


FIGURE 2.13: Comparison of the three models for Canada, USA and Japan. The black lines represent the historical data and the blue lines the historical fits. The light and dark pink lines represent the results from OdyM-RECC without material efficiency and with material efficiency, respectively. The orange, green, red and purple lines represent the results from the GCAM model for radiative concentration pathways 6.0, 4.5, 3.7 and 2.6, respectively.



**FIGURE 2.14:** Comparison of the three models for China and India. The black lines represent the historical data and the blue lines the historical fits. The light and dark pink lines represent the results from OdyM-RECC without material efficiency and with material efficiency, respectively. The orange, green, red and purple lines represent the results from the GCAM model for radiative concentration pathways 6.0, 4.5, 3.7 and 2.6, respectively.

represent the results from the GCAM model for radiative concentration pathways 6.0, 4.5, 3.7 and 2.6, respectively.

#### 2.3.3.1. CANADA

For Canada, the logistic curve fits well the data and saturates at 0.6 PLDV/capita for both scenarios. In Odym-RECC, the stocks decrease for SSP1 while they stay around 0.6 in SSP2 (in both cases, the stocks are lower with material efficiency). As for the GCAM, the stocks are overestimated compared to the historical data, they reach 1 PLDV/capita in 2100 in SSP1 and 1.1 in SSP2.

#### 2.3.3.2. UNITED STATES

For the United-States, the logistic curve does not fit well the data and saturates at 0.6 PLDV/capita for both scenarios. This is due to a change in accounting method for PLDV in the United-States which leads to an apparent decreases in stocks. In reality, the stock did not decrease but pick-ups that are used for personal travel are accounted for as commercial vehicles. In Odym-RECC, the stocks decrease for SSP1 while they stay around 0.65 in SSP2 (in both cases, the stocks are lower with material efficiency). As for the GCAM, the stocks reach 0.9 PLDV/capita in 2100 in SSP1 and 1 in SSP2.

#### 2.3.3.3. JAPAN

For Japan, the three models give similar results for SSP2 with a saturation around 0.5 PLDV per capita. For SSP1, the stocks decrease in Odym-RECC.

#### 2.3.3.4. CHINA

For China, the logistic model fits perfectly the data and saturates at 0.5 PLDV/capita for both scenarios. The growth is slower for SSP2 in Odym-RECC and even slower for SSP1. In the GCAM model, the stocks are not consistent with historical data and stay close to 0 for both SSP1 and SSP2 all the way to 2100.

#### 2.3.3.5. INDIA

For India, the logistic model fits perfectly the data and saturates at 0.4 PLDV/capita for both scenarios. The growth is close to the logistic for SSP2 in Odym-RECC but much slower for SSP1. In the GCAM model, the stocks are not consistent with historical data and stay close to 0 for both SSP1 and SSP2 all the way to 2100.

## 2.3.4. DISCUSSION

### 2.3.4.1. LOGISTIC METHOD

This method allows to fit the historical data really well. However, it is a business as usual method, which assumes that in the future, the relationship between GDP per capita and PLDV ownership will stay the same as in the past. Such an approach makes sense only with an SSP2 (business as usual) narrative and not with an SPP1 (sustainable development) narrative. This approach must therefore only serve as a reference to compare the breaks in trends obtained using other methods that are deemed to be more consistent with a given narrative.

### 2.3.4.2. ODYM-RECC METHOD

This method which starts by translating a given SSP narrative into services and these services into stocks, with differences in stocks also depending on car-sharing and ride-sharing seems to be the best approach to build consistent scenarios. However, the curves should look like logistic curves in the SSP2, which is not totally the case. For regions that have reached saturation levels (Canada, USA and Japan), OdyM-RECC is consistent with the logistic approach. However, for India and China, the slopes from OdyM-RECC do not match those of the logistics.

### 2.3.4.3. GCAM METHOD

The results obtained from the GCAM model are not convincing at all. In the USA and Canada, PLDV stocks are higher than 1 PLDV per capita. This is not at all consistent with the historical data. PLDV are just a part of the light duty fleet, which also includes light commercial vehicles, so the overall fleet would be much higher than 1 light duty vehicle per capita. And when PLDV “per capita” are calculated, the whole population is taken, including all the people who do not drive (the children and the disabled for example, which represent a significant share of the population). It is thus highly unlikely that such scenarios would ever be reached.

As for China and India, the results make even less sense, with levels of stocks close to 0 PLDV per capita, whereas even current stock levels are significantly higher.

To understand these results, one must look at equations 2.13 and 2.14. First, demand for passenger-kilometers cannot saturate but increases indefinitely together with GDP growth, population growth or price reduction (equation 2.13). This lack of saturation limit explains why in SSP2 in Canada the demand for passenger-kilometers is much higher than what could be reasonably expected.

Second, the disaggregation of passenger-kilometers by mode also follows a dynamic of prices with elasticities (equation 2.14). But for that to work initial conditions of share weights are set for year 2005. For the shares to change, the price has to change. For example, from a transition from buses to personal vehicles, the price of personal vehicles must decrease or the price of bus increases. The shares of PLDV in the total PLDV and buses passenger-kilometers are shown on figure 2.15 for China and India. Between 2005 and 2100 the shares of PLDV in the total PLDV and buses keep the same order of magnitude (95% in the USA vs. 20% in China).

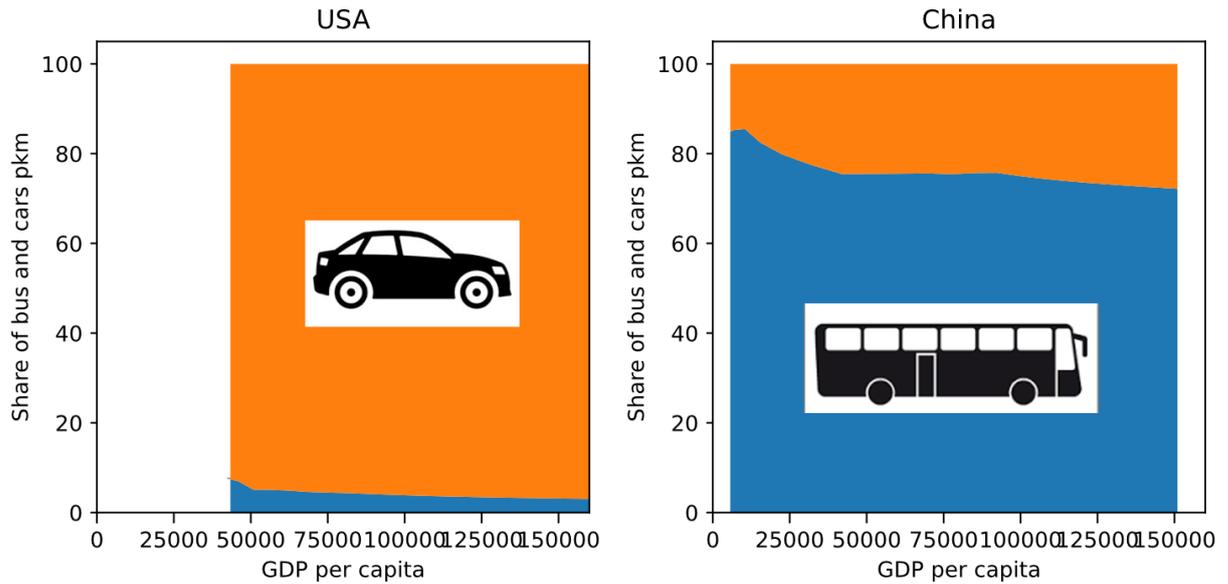


FIGURE 2.15: PLDV and bus shares in total passenger-kilometers demand

This means that changes in prices are not sufficient to significantly change the initial conditions. However, these initial conditions can be explained and are not just parameters that can be defined randomly. The reason why in 2005 the share of PLDV in China is so low and that of the USA is so high is that China has a low GDP per capita and the USA has a high GDP per capita.

When describing the methods for the logistic curves we insisted on the need to have a single equation working for every region and to explain the differences in parameters in between regions (by GDP per capita or population density for example). The results obtained by the GCAM shows what can happen when calibration parameters are not explained but simply fitted for a given. Overall, for all the Global South, considering a 10 years lifetime for cars, the GCAM underestimates the number of cars that have to be built by around 10 billion (though the number of cars that need to be built has no impact on the model since it does not consider stocks and flows, as discussed in the introduction of the present thesis). These 10 billion cars would also require energy to function during their whole lifetime so the GCAM model drastically underestimates the greenhouse gas emissions associated with personal transport.

### 2.3.5. CONCLUSION

We have demonstrated that utilizing a single S-curve equation precisely replicates historical PLDV stocks in every country worldwide, thus enabling accurate predictions of future stock levels in business-as-usual scenarios. It is essential to physically explain the regional differences within this equation; failing to do so could yield unreliable results. For instance, it is likely that the GCAM model underestimates the number of cars needing to be built by 2100 in a business-as-usual scenario by 10 billion.

The S-curve approach is only applicable to business-as-usual scenarios. For alternative sce-

narios such as the "sustainability" of SSP1, a different approach is needed. The most logical appears to involve translating human needs into services and these services into stocks. The work done by the OdyM-RECC team represents a significant advancement in this direction. However, for scenarios to be truly consistent, stock and flow integration into IAMs is required, rather than just post-processing.

There also needs to be a feedback loop between GDP assumptions and stock levels. Currently, GDP is an exogenous parameter in IAMs. If translating SSP1 into stocks necessitates stock reduction, this will inevitably decrease GDP. Although GDP could grow in other sectors, this would need to be explicitly described in IAMs, which is currently not the case. The same holds true for material efficiency: producing lighter, more efficient cars will result in less GDP in that sector. Incorporating this into IAMs necessitates a paradigm shift towards a post-growth approach, where GDP is a model result rather than a political imperative.

## 2.4. REFERENCES

- Arndt, Nicholas T., Lluís Fontboté, Jeffrey W. Hedenquist, Stephen E. Kesler, John F.H. Thompson, and Daniel G. Wood (2017). “Future Global Mineral Resources”. en. In: *Geochemical Perspectives*, pp. 1–171. ISSN: 22237755, 22242759. DOI: 10.7185/geochempersp.6.1. URL: <http://www.geochemicalperspectives.org/online/v6n1> (visited on 06/09/2021).
- Ayres, R. U. and Leslie W. Ayres (2002). *The Life Cycle of Copper, its Co-Products and By-Products*. URL: <https://pubs.iied.org/sites/default/files/pdfs/migrate/G00740.pdf> (visited on 06/21/2021).
- Bardi, U. (2007). “Energy Prices and Resource Depletion: Lessons from the Case of Whaling in the Nineteenth Century”. en. In: *Energy Sources, Part B: Economics, Planning, and Policy* 2.3, pp. 297–304. ISSN: 1556-7249, 1556-7257. DOI: 10.1080/15567240600629435. URL: <http://www.tandfonline.com/doi/abs/10.1080/15567240600629435> (visited on 10/23/2021).
- Bardi, Ugo and Alessandro Lavacchi (2009). “A Simple Interpretation of Hubbert’s Model of Resource Exploitation”. en. In: *Energies* 2.3, pp. 646–661. ISSN: 1996-1073. DOI: 10.3390/en20300646. URL: <http://www.mdpi.com/1996-1073/2/3/646/> (visited on 09/29/2017).
- Bardi, Ugo, Alessandro Lavacchi, and Leigh Yaxley (2018). “EROEI and Net Energy in the Exploitation of Natural Resources. A Study based on the Lotka-Volterra Model”. en. In: p. 7.
- Bardi, Ugo and Marco Pagani (2007). *Peak Minerals*. URL: <http://theoil Drum.com/node/3086> (visited on 10/21/2021).
- Beylot, Antoine, Dominique Guyonnet, Stéphanie Muller, Stéphane Vaxelaire, and Jacques Villeneuve (2019). “Mineral raw material requirements and associated climate-change impacts of the French energy transition by 2050”. en. In: *Journal of Cleaner Production* 208, pp. 1198–1205. ISSN: 09596526. DOI: 10.1016/j.jclepro.2018.10.154. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959652618331718> (visited on 05/29/2019).
- Bleischwitz, Raimund and Victor Nechifor (2016). “Saturation and Growth Over Time: When Demand for Minerals Peaks”. en. In: p. 37.
- Bleischwitz, Raimund, Victor Nechifor, Matthew Winning, Beijia Huang, and Yong Geng (2018). “Extrapolation or saturation – Revisiting growth patterns, development stages and decoupling”. en. In: *Global Environmental Change* 48, pp. 86–96. ISSN: 09593780. DOI: 10.1016/j.gloenvcha.2017.11.008. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959378016306550> (visited on 09/05/2021).
- Calvin, Katherine, Pralit Patel, Leon Clarke, Ghassem Asrar, Ben Bond-Lamberty, Ryna Yiyun Cui, Alan Di Vittorio, Kalyn Dorheim, Jae Edmonds, Corinne Hartin, Mohamad Hejazi, Russell Horowitz, Gokul Iyer, Page Kyle, Sonny Kim, Robert Link, Haewon McJeon, Steven J. Smith, Abigail Snyder, Stephanie Waldhoff, and Marshall Wise (2019). “GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems”. In: *Geoscientific Model Development* 12.2, pp. 677–698. DOI: 10.5194/gmd-12-677-2019.
- Cao, Zhi, Lei Shen, Shuai Zhong, Litao Liu, Hanxiao Kong, and Yanzhi Sun (2018). “A Probabilistic Dynamic Material Flow Analysis Model for Chinese Urban Housing Stock: A Probabilistic Dynamic MFA Model”. en. In: *Journal of Industrial Ecology* 22.2, pp. 377–391. ISSN: 10881980. DOI: 10.1111/jie.12579. URL: <https://onlinelibrary.wiley.com/doi/10.1111/jie.12579> (visited on 08/27/2021).
- Capellán-Pérez, Iñigo, Ignacio de Blas, Jaime Nieto, Carlos de Castro, Luis Javier Miguel, Oscar Carpintero, Margarita Mediavilla, Luis Fernando Lobejón, Noelia Ferreras-Alonso, Paula Rodrigo, Fernando Frechoso, and David Álvarez-Antelo (2020). “MEDEAS: a new modeling framework integrating global biophysical and socioeconomic constraints”. In: *Energy & Environmental Science* 13.3. Publisher: Royal Society of Chemistry (RSC), pp. 986–1017. DOI: 10.1039/c9ee02627d.
- Ciacci, L., T. Fishman, A. Elshkaki, T.E. Graedel, I. Vassura, and F. Passarini (2020). “Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28”. en. In: *Global Environmental*

- Change* 63, p. 102093. ISSN: 09593780. DOI: 10.1016/j.gloenvcha.2020.102093. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959378019313251> (visited on 08/04/2021).
- Dargay, Joyce, Dermot Gately, and Martin Sommer (Oct. 2007). "Vehicle Ownership and Income Growth, Worldwide: 1960-2030". en. In: *The Energy Journal* 28.4. ISSN: 01956574. DOI: 10.5547/ISSN0195-6574-EJ-Vol28-No4-7. URL: <http://www.iaee.org/en/publications/ejarticle.aspx?id=2234> (visited on 05/11/2021).
- Deetman, S., H.S. de Boer, M. Van Engelenburg, E. van der Voet, and D.P. van Vuuren (2021). "Projected material requirements for the global electricity infrastructure – generation, transmission and storage". en. In: *Resources, Conservation and Recycling* 164, p. 105200. ISSN: 09213449. DOI: 10.1016/j.resconrec.2020.105200. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344920305176> (visited on 05/27/2021).
- Deetman, Sebastiaan, Sylvia Marinova, Ester van der Voet, Detlef P. van Vuuren, Oreane Edelenbosch, and Reinout Heijungs (2020). "Modelling global material stocks and flows for residential and service sector buildings towards 2050". en. In: *Journal of Cleaner Production* 245, p. 118658. ISSN: 09596526. DOI: 10.1016/j.jclepro.2019.118658. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959652619335280> (visited on 12/08/2020).
- Dong, Di, Arnold Tukker, and Ester Van der Voet (2019). "Modeling copper demand in China up to 2050: A business-as-usual scenario based on dynamic stock and flow analysis". en. In: *Journal of Industrial Ecology* 23.6, pp. 1363–1380. ISSN: 1088-1980, 1530-9290. DOI: 10.1111/jiec.12926. URL: <https://onlinelibrary.wiley.com/doi/10.1111/jiec.12926> (visited on 09/02/2021).
- Dunn, Jessica, Margaret Slattery, Alissa Kendall, Hanjiro Ambrose, and Shuhan Shen (2021). "Circularity of Lithium-Ion Battery Materials in Electric Vehicles". en. In: *Environmental Science & Technology* 55.8, pp. 5189–5198. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/acs.est.0c07030. URL: <https://pubs.acs.org/doi/10.1021/acs.est.0c07030> (visited on 10/01/2021).
- Elshkaki, Ayman (2019). "Materials, energy, water, and emissions nexus impacts on the future contribution of PV solar technologies to global energy scenarios". en. In: *Scientific Reports* 9.1, p. 19238. ISSN: 2045-2322. DOI: 10.1038/s41598-019-55853-w. URL: <http://www.nature.com/articles/s41598-019-55853-w> (visited on 05/27/2021).
- Elshkaki, Ayman, T. E. Graedel, Luca Ciacci, and Barbara K. Reck (2018). "Resource Demand Scenarios for the Major Metals". en. In: *Environmental Science & Technology* 52.5, pp. 2491–2497. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/acs.est.7b05154. URL: <https://pubs.acs.org/doi/10.1021/acs.est.7b05154> (visited on 06/04/2021).
- Elshkaki, Ayman and T.E. Graedel (2013). "Dynamic analysis of the global metals flows and stocks in electricity generation technologies". en. In: *Journal of Cleaner Production* 59, pp. 260–273. ISSN: 09596526. DOI: 10.1016/j.jclepro.2013.07.003. URL: <http://linkinghub.elsevier.com/retrieve/pii/S0959652613004575> (visited on 09/15/2017).
- European Commission (2020). *Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability*. en. Tech. rep. COM(2020) 474 final. Brussels: European Commission, p. 24. URL: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0474&from=EN> (visited on 11/30/2021).
- Fishman, Tomer, Niko Heeren, Stefan Pauliuk, Peter Berrill, Qingshi Tu, Paul Wolfram, and Edgar G. Hertwich (2021). "A comprehensive set of global scenarios of housing, mobility, and material efficiency for material cycles and energy systems modeling". en. In: *Journal of Industrial Ecology* 25.2. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.13122>. pp. 305–320. ISSN: 1530-9290. DOI: 10.1111/jiec.13122. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.13122> (visited on 04/05/2023).
- Gerst, M. D. (2008). "Revisiting the Cumulative Grade-Tonnage Relationship for Major Copper Ore Types". en. In: *Economic Geology* 103.3, pp. 615–628. ISSN: 0361-0128. DOI: 10.2113/gsecongeo.103.3.615. URL:

- <https://pubs.geoscienceworld.org/economicgeology/article/103/3/615-628/127978> (visited on 10/21/2021).
- Graedel, T. E. (2011). “On the future availability of the energy metals”. In: *Annual Review of Materials Research* 41, pp. 323–335. URL: <http://www.annualreviews.org/doi/abs/10.1146/annurev-matsci-062910-095759> (visited on 09/13/2017).
- Graedel, T. E. and J. Cao (2010). “Metal spectra as indicators of development”. en. In: *Proceedings of the National Academy of Sciences* 107.49, pp. 20905–20910. ISSN: 0027-8424, 1091-6490. DOI: 10.1073/pnas.1011019107. URL: <http://www.pnas.org/content/107/49/20905> (visited on 10/11/2017).
- Gutowski, T. G., S. Sahni, J. M. Allwood, M. F. Ashby, and E. Worrell (2013). “The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand”. en. In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 371.1986, pp. 20120003–20120003. ISSN: 1364-503X, 1471-2962. DOI: 10.1098/rsta.2012.0003. URL: <http://rsta.royalsocietypublishing.org/cgi/doi/10.1098/rsta.2012.0003> (visited on 06/06/2019).
- Henckens, M.L.C.M., E.C. van Ierland, P.P.J. Driessen, and E. Worrell (2016). “Mineral resources: Geological scarcity, market price trends, and future generations”. en. In: *Resources Policy* 49, pp. 102–111. ISSN: 03014207. DOI: 10.1016/j.resourpol.2016.04.012. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0301420716300861> (visited on 10/23/2021).
- Hertwich, Edgar G., Thomas Gibon, Evert A. Bouman, Anders Arvesen, Sangwon Suh, Garvin A. Heath, Joseph D. Bergesen, Andrea Ramirez, Mabel I. Vega, and Lei Shi (2015). “Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies”. In: *Proceedings of the National Academy of Sciences* 112.20, pp. 6277–6282. URL: <http://www.pnas.org/content/112/20/6277.short> (visited on 09/28/2017).
- Hooke, Roger LeB. and José F. Martín-Duque (2012). “Land transformation by humans: A review”. en. In: *GSA Today* 12.12, pp. 4–10. ISSN: 10525173. DOI: 10.1130/GSAT151A.1. URL: <http://www.geosociety.org/gsatoday/archive/22/12/abstract/i1052-5173-22-12-4.htm> (visited on 10/23/2021).
- Huang, Tao, Feng Shi, Hiroki Tanikawa, Jinling Fei, and Ji Han (2013). “Materials demand and environmental impact of buildings construction and demolition in China based on dynamic material flow analysis”. en. In: *Resources, Conservation and Recycling* 72, pp. 91–101. ISSN: 09213449. DOI: 10.1016/j.resconrec.2012.12.013. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344912002273> (visited on 08/12/2021).
- Nuclear Energy and the Fossil Fuel* (Jan. 1956). Vol. All Days. Drilling and Production Practice. API-56-007. eprint: <https://onepetro.org/APIIDPP/proceedings-pdf/API56/A11-API56/API-56-007/2059843/api-56-007.pdf>.
- Hunt, C., J. Romero, J. Jara, and G. Lagos (2021). “Copper demand forecasts and predictions of future scarcity”. en. In: *Resources Policy* 73, p. 102123. ISSN: 03014207. DOI: 10.1016/j.resourpol.2021.102123. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0301420721001379> (visited on 10/07/2021).
- Huo, Hong and Michael Wang (2012). “Modeling future vehicle sales and stock in China”. en. In: *Energy Policy* 43, pp. 17–29. ISSN: 03014215. DOI: 10.1016/j.enpol.2011.09.063. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0301421511007774> (visited on 08/18/2021).
- IEA (2017). *Energy Technology Perspectives 2017*. en. Tech. rep. IEA, p. 443.
- (2018). *Global Status Report 2018*. Tech. rep. IEA, p. 73. URL: <https://www.worldgbc.org/sites/default/files/2018%20GlobalABC%20Global%20Status%20Report.pdf> (visited on 10/13/2020).
- (2021). *IEA Sankey Diagram*. URL: <https://www.iea.org/sankey/> (visited on 10/21/2021).
- Johnson, Jeremiah, E. M. Harper, Reid Lifset, and T. E. Graedel (2007). “Dining at the Periodic Table: Metals Concentrations as They Relate to Recycling”. en. In: *Environmental Science & Technology* 41.5, pp. 1759–1765. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/es060736h. URL: <https://pubs.acs.org/doi/10.1021/es060736h> (visited on 06/04/2021).

- Johnson, KM, JM Hammarstrom, ML Zientek, and CL Dicken (2014). *Estimate of Undiscovered Copper Resources of the World, 2013*. en. Fact Sheet 2014. Series: Fact Sheet. USGS, p. 3.
- Kalt, Gerald, Philipp Thunshirn, Dominik Wiedenhofer, Fridolin Krausmann, Willi Haas, and Helmut Haberl (2021). “Material stocks in global electricity infrastructures – An empirical analysis of the power sector’s stock-flow-service nexus”. en. In: *Resources, Conservation and Recycling* 173, p. 105723. ISSN: 09213449. DOI: 10.1016/j.resconrec.2021.105723. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344921003323> (visited on 09/01/2021).
- Kerr, Richard A. (2014). “The Coming Copper Peak”. en. In: *Science* 343.6172, pp. 722–724. ISSN: 0036-8075, 1095-9203. DOI: 10.1126/science.343.6172.722. URL: <http://science.sciencemag.org/content/343/6172/722> (visited on 09/13/2017).
- Kleijn, René, Ester van der Voet, Gert Jan Kramer, Laurant van Oers, and Coen van der Giesen (2011). “Metal requirements of low-carbon power generation”. en. In: *Energy* 36.9, pp. 5640–5648. ISSN: 03605442. DOI: 10.1016/j.energy.2011.07.003. URL: <http://linkinghub.elsevier.com/retrieve/pii/S0360544211004518> (visited on 09/15/2017).
- Krausmann, Fridolin, Heinz Schandl, Nina Eisenmenger, Stefan Giljum, and Tim Jackson (2017). “Material Flow Accounting: Measuring Global Material Use for Sustainable Development”. en. In: *Annual Review of Environment and Resources* 42.1, pp. 647–675. ISSN: 1543-5938, 1545-2050. DOI: 10.1146/annurev-environ-102016-060726. URL: <http://www.annualreviews.org/doi/10.1146/annurev-environ-102016-060726> (visited on 08/09/2021).
- Laherrère, Jean (2009). *Peak Gold, Easier to Model than Peak Oil?* URL: <http://theoil Drum.com/node/5995> (visited on 10/21/2021).
- (2010). “Copper peak”. In: *The Oil Drum: Europe* 6307, pp. 1–27. URL: <http://theoil Drum.com/node/5995> (visited on 10/21/2021).
- Li, Fangyi, Zhaoyang Ye, Xilin Xiao, Jingjing Xu, and Gang Liu (2020). “Material stocks and flows of power infrastructure development in China”. en. In: *Resources, Conservation and Recycling* 160, p. 104906. ISSN: 09213449. DOI: DevelopmentandvalidationofadynamicmaterialflowanalysismodelforFrenchcoppercycle. URL: <https://linkinghub.elsevier.com/retrieve/pii/S092134492030224X> (visited on 08/10/2021).
- Li, Qiangfeng, Tao Dai, Tianming Gao, Weiqiong Zhong, Bojie Wen, Tianjiao Li, and Yanjing Zhou (2021). “Aluminum material flow analysis for production, consumption, and trade in China from 2008 to 2017”. en. In: *Journal of Cleaner Production* 296, p. 126444. ISSN: 09596526. DOI: 10.1016/j.jclepro.2021.126444. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959652621006648> (visited on 08/10/2021).
- Liu, Manzhi, Xuhui Chen, Mengya Zhang, Xueqing Lv, Haihao Wang, Zhizhi Chen, Xiaorong Huang, Xixi Zhang, and Shiru Zhang (2020). “End-of-life passenger vehicles recycling decision system in China based on dynamic material flow analysis and life cycle assessment”. en. In: *Waste Management* 117, pp. 81–92. ISSN: 0956053X. DOI: 10.1016/j.wasman.2020.08.002. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0956053X20304347> (visited on 10/01/2021).
- Liu, Yupeng, Jiajia Li, Linlin Duan, Min Dai, and Wei-qiang Chen (2020). “Material dependence of cities and implications for regional sustainability”. en. In: *Regional Sustainability* 1.1, pp. 31–36. ISSN: 2666-660X. DOI: 10.1016/j.regsus.2020.07.001. URL: <https://www.sciencedirect.com/science/article/pii/S2666660X20300049> (visited on 08/12/2021).
- Malenbaum, Wilfred (1973). “World Resources for the Year 2000”. en. In: *The Annals of the American Academy of Political and Social Science* 408, pp. 30–46. URL: <http://www.jstor.org/stable/1039384>.
- Marinova, Sylvia, Sebastiaan Deetman, Ester van der Voet, and Vassilis Daioglou (2020). “Global construction materials database and stock analysis of residential buildings between 1970-2050”. en. In: *Journal of Cleaner Production* 247, p. 119146. ISSN: 09596526. DOI: 10.1016/j.jclepro.2019.119146. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0959652619340168> (visited on 11/17/2020).

- Mariscal, Rodrigo and Andrew Powell (2014). “Commodity Price Booms and Breaks: Detection, Magnitude and Implications for Developing Countries”. en. In: *SSRN Electronic Journal*. ISSN: 1556-5068. DOI: 10.2139/ssrn.2384422. URL: <http://www.ssrn.com/abstract=2384422> (visited on 10/21/2021).
- Meadows, Donella H., Dennis L. Meadows, Jørgen Randers, and William W. Behrens (1972). *The Limits to Growth: A report for the Club of Rome’s Project on the Predicament of Mankind*. Universe Books. ISBN: 978-0-87663-165-2. DOI: 10.1349/ddlp.1. URL: <http://www.dartmouth.edu/~library/digital/publishing/meadows/ltg/> (visited on 10/07/2021).
- Mishra, Gouri Shankar, Jacob Teter, Geoffrey M Morrison, Sonia Yeh, Page Kyle, and Son H Kim (2013). “Transportation Module of Global Change Assessment Model (GCAM)”. en. In.
- Moreau, Vincent, Piero Dos Reis, and François Vuille (2019). “Enough Metals? Resource Constraints to Supply a Fully Renewable Energy System”. en. In: *Resources* 8.1, p. 29. ISSN: 2079-9276. DOI: 10.3390/resources8010029. URL: <http://www.mdpi.com/2079-9276/8/1/29> (visited on 05/27/2021).
- Mudd, Gavin M (2009). *The sustainability of mining in Australia: key production trends and environmental implications*. en. OCLC: 511439437. Clayton: Monash University, Department of Civil Engineering. ISBN: 978-0-9803199-4-1.
- Norgate, T. and S. Jahanshahi (2010). “Low grade ores – Smelt, leach or concentrate?” en. In: *Minerals Engineering* 23.2, pp. 65–73. ISSN: 08926875. DOI: 10.1016/j.mineng.2009.10.002. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0892687509002568> (visited on 06/08/2021).
- Northey, S., S. Mohr, G.M. Mudd, Z. Weng, and D. Giurco (2014). “Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining”. en. In: *Resources, Conservation and Recycling* 83, pp. 190–201. ISSN: 09213449. DOI: 10.1016/j.resconrec.2013.10.005. URL: <http://linkinghub.elsevier.com/retrieve/pii/S0921344913002127> (visited on 09/28/2017).
- Olafsdottir, Anna Hulda and Harald Ulrik Sverdrup (2018). “Modelling Global Mining, Secondary Extraction, Supply, Stocks-in-Society, Recycling, Market Price and Resources, Using the WORLD6 Model; Tin”. en. In: *BioPhysical Economics and Resource Quality* 3.3, p. 11. ISSN: 2366-0112, 2366-0120. DOI: 10.1007/s41247-018-0041-8. URL: <http://link.springer.com/10.1007/s41247-018-0041-8> (visited on 10/07/2021).
- Pauliuk, Stefan, Tomer Fishman, Niko Heeren, Peter Berrill, Qingshi Tu, Paul Wolfram, and Edgar G. Hertwich (2021). “Linking service provision to material cycles: A new framework for studying the resource efficiency–climate change (RECC) nexus”. en. In: *Journal of Industrial Ecology* 25.2. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/jieec.13023>, pp. 260–273. ISSN: 1530-9290. DOI: 10.1111/jieec.13023. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/jieec.13023> (visited on 06/29/2023).
- Pauliuk, Stefan and Niko Heeren (2020). “ODYM—An open software framework for studying dynamic material systems: Principles, implementation, and data structures”. en. In: *Journal of Industrial Ecology* 24.3. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/jieec.12952>, pp. 446–458. ISSN: 1530-9290. DOI: 10.1111/jieec.12952. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/jieec.12952> (visited on 04/05/2023).
- (2021). “Material efficiency and its contribution to climate change mitigation in Germany: A deep decarbonization scenario analysis until 2060”. en. In: *Journal of Industrial Ecology* 25.2, pp. 479–493. ISSN: 1088-1980, 1530-9290. DOI: 10.1111/jieec.13091. URL: <https://onlinelibrary.wiley.com/doi/10.1111/jieec.13091> (visited on 10/01/2021).
- Pauliuk, Stefan, Niko Heeren, Peter Berrill, Tomer Fishman, Andrea Nistad, Qingshi Tu, Paul Wolfram, and Edgar G. Hertwich (Aug. 2021). “Global scenarios of resource and emission savings from material efficiency in residential buildings and cars”. en. In: *Nature Communications* 12.1. Number: 1 Publisher: Nature Publishing Group, p. 5097. ISSN: 2041-1723. DOI: 10.1038/s41467-021-25300-4. URL: <https://www.nature.com/articles/s41467-021-25300-4> (visited on 04/05/2023).
- Pfaff, Matthias, Simon Glöser-Chahoud, Lothar Chrubasik, and Rainer Walz (2018). “Resource efficiency in the German copper cycle: Analysis of stock and flow dynamics resulting from different efficiency measures”. en. In:

- Resources, Conservation and Recycling* 139, pp. 205–218. ISSN: 09213449. DOI: 10.1016/j.resconrec.2018.08.017. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344918303057> (visited on 09/02/2021).
- Phillips, W. G. B. and D. P. Edwards (1976). “Metal prices as a function of ore grade”. In: *Resources Policy* 2.3, pp. 167–178. ISSN: 0301-4207. DOI: 10.1016/0301-4207(76)90016-7. URL: <http://www.sciencedirect.com/science/article/pii/0301420776900167> (visited on 09/13/2017).
- Radicati (2019). *Mobile Statistics Report, 2019-2023*. Tech. rep. London: Radicati, p. 3. URL: [https://www.radicati.com/wp/wp-content/uploads/2019/01/Mobile\\_Statistics\\_Report,\\_2019-2023\\_Executive\\_Summary.pdf](https://www.radicati.com/wp/wp-content/uploads/2019/01/Mobile_Statistics_Report,_2019-2023_Executive_Summary.pdf) (visited on 10/11/2021).
- Ren, Kaipeng, Xu Tang, Peng Wang, Jakob Willerström, and Mikael Höök (2021). “Bridging energy and metal sustainability: Insights from China’s wind power development up to 2050”. en. In: *Energy* 227, p. 120524. ISSN: 03605442. DOI: 10.1016/j.energy.2021.120524. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0360544221007738> (visited on 10/01/2021).
- Rötzer, Nadine and Mario Schmidt (2020). “Historical, Current, and Future Energy Demand from Global Copper Production and Its Impact on Climate Change”. en. In: *Resources* 9.4, p. 44. ISSN: 2079-9276. DOI: 10.3390/resources9040044. URL: <https://www.mdpi.com/2079-9276/9/4/44> (visited on 06/02/2021).
- Rudnick, R.L. and S. Gao (2003). “Composition of the Continental Crust”. en. In: *Treatise on Geochemistry*. Elsevier, pp. 1–64. ISBN: 978-0-08-043751-4. DOI: 10.1016/B0-08-043751-6/03016-4. URL: <https://linkinghub.elsevier.com/retrieve/pii/B0080437516030164> (visited on 10/21/2021).
- Schaffartzik, Anke, Andreas Mayer, Simone Gingrich, Nina Eisenmenger, Christian Loy, and Fridolin Krausmann (2014). “The global metabolic transition: Regional patterns and trends of global material flows, 1950–2010”. en. In: *Global Environmental Change* 26, pp. 87–97. ISSN: 09593780. DOI: 10.1016/j.gloenvcha.2014.03.013. URL: <http://linkinghub.elsevier.com/retrieve/pii/S095937801400065X> (visited on 06/27/2018).
- Shi, Feng, Tao Huang, Hiroki Tanikawa, Ji Han, Seiji Hashimoto, and Yuichi Moriguchi (2012). “Toward a Low Carbon-Dematerialization Society: Measuring the Materials Demand and CO<sub>2</sub> Emissions of Building and Transport Infrastructure Construction in China”. en. In: *Journal of Industrial Ecology* 16.4, pp. 493–505. ISSN: 10881980. DOI: 10.1111/j.1530-9290.2012.00523.x. URL: <https://onlinelibrary.wiley.com/doi/10.1111/j.1530-9290.2012.00523.x> (visited on 09/05/2021).
- Singer, Donald A. (2013). “The lognormal distribution of metal resources in mineral deposits”. en. In: *Ore Geology Reviews* 55, pp. 80–86. ISSN: 01691368. DOI: 10.1016/j.oregeorev.2013.04.009. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0169136813001133> (visited on 10/23/2021).
- (2017). “Future copper resources”. In: *Ore Geology Reviews* 86. Supplement C. ISSN: 0169-1368. DOI: 10.1016/j.oregeorev.2017.02.022. URL: <http://www.sciencedirect.com/science/article/pii/S0169136817300021> (visited on 09/23/2017).
- Strecek, Jan, Quirin Dammerer, Dominik Wiedenhofer, and Fridolin Krausmann (2021). “The role of socio-economic material stocks for natural resource use in the United States of America from 1870 to 2100”. en. In: *Journal of Industrial Ecology*, jiec.13166. ISSN: 1088-1980, 1530-9290. DOI: 10.1111/jiec.13166. URL: <https://onlinelibrary.wiley.com/doi/10.1111/jiec.13166> (visited on 09/01/2021).
- Sverdrup, Harald and K. Vala Ragnarsdóttir (2014). “Natural Resources in a Planetary Perspective”. en. In: *Geochemical Perspectives*, pp. 129–341. ISSN: 22237755, 22242759. DOI: 10.7185/geochempersp.3.2. URL: <http://www.geochemicalperspectives.org/online/v3n2> (visited on 10/21/2021).
- Sverdrup, Harald Ulrik, Deniz Koca, and Kristín Vala Ragnarsdóttir (2013). “Peak metals, minerals, energy, wealth, food and population: urgent policy considerations for a sustainable society”. In: *Journal of Environmental Science and Engineering*. B2.4B, p. 189. URL: <http://search.proquest.com/openview/d5f318046bf1bbe4c447882a9fd1117pq-origsite=gscholar&cbl=2029946> (visited on 10/05/2017).

- Sverdrup, Harald Ulrik and Anna Hulda Olafsdottir (2020). “System Dynamics Modelling of the Global Extraction, Supply, Price, Reserves, Resources and Environmental Losses of Mercury”. en. In: *Water, Air, & Soil Pollution* 231.8, p. 439. ISSN: 0049-6979, 1573-2932. DOI: 10.1007/s11270-020-04757-x. URL: <http://link.springer.com/10.1007/s11270-020-04757-x> (visited on 04/21/2021).
- Sverdrup, Harald Ulrik, Anna Hulda Olafsdottir, and Kristin Vala Ragnarsdottir (2019). “On the long-term sustainability of copper, zinc and lead supply, using a system dynamics model”. en. In: *Resources, Conservation & Recycling: X* 4, p. 100007. ISSN: 2590289X. DOI: 10.1016/j.rcrx.2019.100007. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2590289X19300052> (visited on 04/21/2021).
- Tokimatsu, Koji, Henrik Wachtmeister, Benjamin McLellan, Simon Davidsson, Shinsuke Murakami, Mikael Höök, Rieko Yasuoka, and Masahiro Nishio (2017). “Energy modeling approach to the global energy-mineral nexus: A first look at metal requirements and the 2°C target”. en. In: *Applied Energy* 207, pp. 494–509. ISSN: 03062619. DOI: 10.1016/j.apenergy.2017.05.151. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0306261917307055> (visited on 09/16/2020).
- UN (2021). *UN Comtrade - International Trade Statistics Database*. URL: <https://comtrade.un.org/> (visited on 09/09/2021).
- USGS (2021). *Mineral Commodity Summaries*. en. Tech. rep. USGS, p. 204.
- Vidal, Olivier (2021). “Modeling the Long-Term Evolution of Primary Production Energy and Metal Prices”. en. In: *Mineral Resources Economics 1: Context and Issues*. Fizaine, F.; Galiègue, X. Wiley. ISBN: 978-1-78945-024-8 978-1-119-85086-1. DOI: 10.1002/9781119850861. URL: <https://onlinelibrary.wiley.com/doi/book/10.1002/9781119850861> (visited on 10/21/2021).
- Vidal, Olivier, Baptiste Andrieu, Hugo Le Boulzec, and Florian Fizaine (2021). “Modeling the production energy and metal prices from 1900 to 2100”. In: *Manuscript submitted for publication*.
- Vidal, Olivier, Hugo Le Boulzec, and Cyril François (2018). “Modelling the material and energy costs of the transition to low-carbon energy”. In: *EPJ Web of Conferences* 189. Ed. by L. Cifarelli and F. Wagner. Publisher: EDP Sciences, p. 00018. DOI: 10.1051/epjconf/201818900018.
- Vidal, Olivier, Bruno Goffé, and Nicholas Arndt (2013). “Metals for a low-carbon society”. In: *Nature Geoscience* 6.11, pp. 894–896. ISSN: 1752-0894, 1752-0908. DOI: 10.1038/ngeo1993. URL: <http://www.nature.com/doi/10.1038/ngeo1993> (visited on 09/13/2017).
- Vidal, Olivier, Fatma Rostom, Cyril François, and Gael Giraud (2017). “Global Trends in Metal Consumption and Supply: The Raw Material–Energy Nexus”. en. In: *Elements* 13.5, pp. 319–324. ISSN: 1811-5217, 1811-5209. DOI: 10.2138/gselements.13.5.319. URL: <https://pubs.geoscienceworld.org/msa/elements/article/13/5/319/522742/Global-Trends-in-Metal-Consumption-and-Supply-The> (visited on 08/11/2021).
- Vidal, Olivier, Fatma Zahra Rostom, Cyril François, and Gaël Giraud (2019). “Prey–Predator Long-Term Modeling of Copper Reserves, Production, Recycling, Price, and Cost of Production”. en. In: *Environmental Science & Technology* 53.19, pp. 11323–11336. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/acs.est.9b03883. URL: <https://pubs.acs.org/doi/10.1021/acs.est.9b03883> (visited on 05/28/2021).
- Wårell, Linda (2014). “Trends and developments in long-term steel demand – The intensity-of-use hypothesis revisited”. en. In: *Resources Policy* 39, pp. 134–143. ISSN: 03014207. DOI: 10.1016/j.resourpol.2013.12.002. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0301420713001207> (visited on 07/29/2021).
- Watari, Takuma, Benjamin C. McLellan, Damien Giurco, Elsa Dominish, Eiji Yamasue, and Keisuke Nansai (2019). “Total material requirement for the global energy transition to 2050: A focus on transport and electricity”. en. In: *Resources, Conservation and Recycling* 148, pp. 91–103. ISSN: 09213449. DOI: 10.1016/j.resconrec.2019.05.015. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344919302290> (visited on 05/27/2021).
- Wiedenhofer, Dominik, Tomer Fishman, Christian Lauk, Willi Haas, and Fridolin Krausmann (2019). “Integrating Material Stock Dynamics Into Economy-Wide Material Flow Accounting: Concepts, Modelling, and

- Global Application for 1900–2050”. en. In: *Ecological Economics* 156, pp. 121–133. ISSN: 09218009. DOI: 10.1016/j.ecolecon.2018.09.010. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921800918305718> (visited on 02/01/2019).
- Wiedenhofer, Dominik, Julia K. Steinberger, Nina Eisenmenger, and Willi Haas (2015). “Maintenance and Expansion: Modeling Material Stocks and Flows for Residential Buildings and Transportation Networks in the EU25”. en. In: *Journal of Industrial Ecology* 19.4. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.12216>, pp. 538–551. ISSN: 1530-9290. DOI: 10.1111/jiec.12216. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12216> (visited on 10/14/2020).
- Wiedmann, Thomas O., Heinz Schandl, Manfred Lenzen, Daniel Moran, Sangwon Suh, James West, and Kei-ichiro Kanemoto (2015). “The material footprint of nations”. en. In: *Proceedings of the National Academy of Sciences* 112.20, pp. 6271–6276. ISSN: 0027-8424, 1091-6490. DOI: 10.1073/pnas.1220362110. URL: <http://www.pnas.org/lookup/doi/10.1073/pnas.1220362110> (visited on 05/29/2019).
- Worldsteel (2021). *Steel Statistical Yearbook*. en. URL: <http://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html> (visited on 09/09/2021).
- Yang, Hui, Xiaolong Song, Xihua Zhang, Bin Lu, Dong Yang, and Bo Li (2021). “Uncovering the in-use metal stocks and implied recycling potential in electric vehicle batteries considering cascaded use: a case study of China”. en. In: *Environmental Science and Pollution Research* 28.33, pp. 45867–45878. ISSN: 0944-1344, 1614-7499. DOI: 10.1007/s11356-021-13430-7. URL: <https://link.springer.com/10.1007/s11356-021-13430-7> (visited on 09/01/2021).
- Yellishetty, Mohan, P.G. Ranjith, and A. Tharumarajah (2010). “Iron ore and steel production trends and material flows in the world: Is this really sustainable?” en. In: *Resources, Conservation and Recycling* 54.12, pp. 1084–1094. ISSN: 09213449. DOI: 10.1016/j.resconrec.2010.03.003. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344910000674> (visited on 02/01/2019).
- Zhu, Yongxian, Laurent B. Chappuis, Robert De Kleine, Hyung Chul Kim, Timothy J. Wallington, George Luckey, and Daniel R. Cooper (2021). “The coming wave of aluminum sheet scrap from vehicle recycling in the United States”. en. In: *Resources, Conservation and Recycling* 164, p. 105208. ISSN: 09213449. DOI: 10.1016/j.resconrec.2020.105208. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344920305255> (visited on 10/01/2021).



## CHAPTER 3 | TECHNOLOGICAL PROGRESS VS. THERMODYNAMIC LIMITS

IAMs, in their current form, fail to incorporate thermodynamic limits when calculating technological progress rates. The aim of this chapter is thus to explore this relationship between technological progress and thermodynamic limits.

- The first paper presents a model that uses ore grade, technology improvement, energy prices, and thermodynamic limits to predict the long-term costs and prices of metals. This model has allowed to improve the calculation of raw materials production energy consumption in MATER.
- The second paper explores the energy efficiency of the overall economy. We find that high-income regions use more energy per unit of final consumption than low-income ones. To improve the modelling in MATER, energy intensities would need to be calculated as a function of time and be incorporated in a model similar to that of the first paper. Doing so would require to add exergy in input-output databases.

Technological progress plays a critical role in determining the cost and feasibility of various mitigation and adaptation scenarios in Integrated Assessment Models (IAMs). Technological progress in IAMs can be represented in two principal ways: exogenous and endogenous.

Exogenous technological change assumes that technological progress happens independently of model dynamics. The rates of technological improvement are provided as inputs to the model. This approach is less computationally demanding and thus is often employed in large-scale, aggregate IAMs. However, it fails to capture the feedback mechanisms between policy incentives and technological innovation. This approach is represented in models through (Popp et al., 2010):

- Hicks-neutral productivity, improving economic productivity but failing to capture en-

ergy efficiency or carbon reduction potential.

- Autonomous Energy-Efficiency Improvement (AEEI), a straightforward and transparent method (MacCracken et al., 1999) that presumes annual enhancements in the energy efficiency of the economy.
- Disaggregated models, which foster energy-saving progress by improving productivity in a more energy-efficient sector or by introducing a new energy-efficient technology at a certain time.
- Backstop technologies, which are potential carbon-free energy sources that could come into play when energy prices, inclusive of carbon policy costs, increase significantly (advanced solar power, nuclear fusion).
- Econometric models with flexible functional forms, incorporating multiple trends defining the overall level and direction of technological change.

Endogenous technological change, on the other hand, is a process influenced not only by time but also by historical prices, policies, and activities. This approach enables the representation of policy feedback loops, where policy incentives can stimulate technological innovation and vice versa and is often found in technology-rich IAMs. It posits that the cost function depends on historical prices and activity levels, encapsulated by the concept of a "knowledge stock". The challenge lies in understanding how this stock accumulates and affects future energy use and emissions. Endogenous change is typically modelled in three ways (Popp et al., 2010):

- Direct price-induced change, hypothesizing that shifts in relative prices inspire innovation to reduce the use of the more expensive input.
- R&D-induced change, suggesting that R&D investment impacts the rate and direction of technological change.
- Learning-induced change, where the unit cost of a technology decreases with cumulative experience.

Both exogenous and endogenous technological change models in Integrated Assessment Models (IAMs) help understand the technological transition required to mitigate climate change. However, a significant limitation in these approaches is their inability to consider thermodynamic limits, as these models primarily operate under economic and social assumptions without consideration of physical limits. Thermodynamics provides a physical boundary to the possible efficiencies of energy conversion and material processing. The first and second laws of thermodynamics dictate that energy cannot be created or destroyed and that the entropy (or disorder) of an isolated system always increases. This fundamentally means there are limits to the efficiencies achievable in energy transformations and material processes.

IAMs, in their current form, fail to incorporate these thermodynamic limits. They tend to assume perpetual improvements in energy efficiency or productivity, or an unbounded ability

to switch to alternative technologies. This overlooks the inherent limits of technological efficiency improvements and fails to consider the increasing energy costs and environmental impact associated with the extraction and use of less concentrated or lower quality resources.

In the context of raw materials production, this signifies that the extraction and processing of materials are constrained by the energy requirements, which are, in turn, bound by these laws of thermodynamics. As ores are depleted, for example, lower-grade ores with less concentrated resources are exploited, which means that the thermodynamic minimum for extraction and processing increases over time.

The aim of this chapter is thus to explore this relationship between technological progress and thermodynamic limits. The first paper of the chapter presents a model that uses ore grade, technology improvement, energy prices, and thermodynamic limits to predict the long-term costs and prices of metals. This model accurately reproduces the historical evolution of metal prices since 1900 and predicts that the trend of declining costs will eventually reverse as production energy approaches thermodynamic limits. This has already happened for precious metals and will occur before the end of the century for other metals. The model built has allowed to improve the calculation of raw materials production energy consumption in MATER. A module was added in MATER to calculate the energy per kg of metal as a function of technological progress (time dependent) and resource quality (inversely proportional to the integral of historical production).

The second paper explores the energy efficiency of the overall economy. Here, we calculate the energy necessary to produce households and governments' final consumption in 49 world regions in 2017. Energy intensities (energy use per dollar of final consumption) are then studied as a function of affluence. We find that high-income regions use more energy per unit of final consumption than low-income ones. This result contradicts the common belief that a higher GDP is correlated with a better efficiency and questions the feasibility of mainstream energy transition scenarios based on universal GDP growth.

This second study was performed only for year 2017. To improve the modelling in MATER, energy intensities would need to be calculated as a function of time and be incorporated in a model similar to that of this chapter's first paper. To do so would require to know the thermodynamic minimum of energy intensities. This could be done by using exergy. Exergy is a measure of the maximum useful work that can be extracted from a system or a flow of matter or energy as it comes into equilibrium with a reference environment. It is a thermodynamic property that quantifies the usefulness or quality of energy. However, exergy is not yet incorporated into EXIOBASE, the input-output database used in the second paper. Researchers are currently working on building exergy extensions for EXIOBASE. Building a model of energy intensity similar to that of paper 1 will therefore soon be possible.

### 3.1. MODELING PRODUCTION ENERGY AND THERMODYNAMIC PRICES OF METALS FROM 1900 TO 2100

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**Key words** Production energy of metals, price of metals, thermodynamic modelling, future metal supply

#### Spotlights

- Our model describes the competing effects of ore grade decline and technical progress on the production energy and long-term price of metals
- Technological advancements have offset the increase in production energy resulting from the decline in ore grade over the past century, but this trend is likely to reverse in the future.
- The technological improvement of metal production is limited by thermodynamic boundaries
- The future supply of metals will be controlled by the price of metals, which depend on the price of energy and declining ore grade

#### ABSTRACT

Global extraction of metallic ores surged by more than 250% between 1970 and 2010 and, despite increasing recycling, primary resources will remain necessary to meet demand for the foreseeable future. Historical data show a persistent decline in the ore grade, raising concerns over the energy costs of extracting metals. Metal prices are expected to be inversely proportional to ore content, and prohibitive extraction costs may jeopardize future metal availability. We describe here the first model that uses ore grade, technology improvement, energy prices, and thermodynamic limits to predict the long-term costs and prices of metals. Our model accurately reproduces the historical evolution of metal prices since 1900 and predicts that the trend of declining costs will eventually reverse as production energy approaches thermodynamic limits. This has already happened for precious metals and will occur before the end of the century for other metals.

### 3.1.1. INTRODUCTION

Mineral commodity prices have risen over the past two decades, driven by the economic emergence of China (Morrison, 2019) and more recently by the Covid-19 pandemic and the war in Ukraine. This sustained increase in prices, following a 20-year decline, raises concerns because it may portend systemic supply difficulties. Global demand for raw materials is expected to increase until the second half of the century due to the economic emergence of populous regions such as India, Southeast Asia, and Africa, along with the new demands of the energy transition (Giurco et al., 2014; McLellan et al., 2016; Tokimatsu et al., 2017; O. Vidal, Goffé, et al., 2013; Watari et al., 2018; Hund et al., 2020; Kelley et al., 2021; Wang et al., 2022; Jones, 2023).

Can we ensure future access to the raw materials needed for the economic growth of the Global South and for the energy transition, while avoiding excessive prices resulting from resource depletion? To answer this crucial question, we need a model capable of predicting mineral commodity prices to the end of the century while reproducing long-term historical trends. Economists have paid lot of attention to the dynamics of natural resource price since the seminal work of (Hotelling, 1931). They have developed various mathematical models to study the impact of resources depletion under the assumption that costs depend on cumulated production (Levhari et al., 1977; Deverajan et al., 1981), ore grade (Solow 1976), and technical progress (Slade, 1982; Farzin, 1995). Unfortunately, despite the increasing complexity of econometric models, comparison with observed prices gets mixed results (see Ozdemiroglu, 1993; Uri, 1995; Lee et al., 2006; Ferreira da Cunha et al., 2020).

On the long term, mineral commodity prices are strongly influenced by the work required to extract a resource, which explains why gold, which is present in ores at parts per million levels, is more expensive than lead, which occurs at percent levels. As consumption increases, high-grade ore deposits are depleted and replaced by less concentrated deposits, which results in a decline in the average ore grade of the mined material (G. M. Mudd, 2009; G. Mudd et al., 2013). This should result in an unavoidable increase in the embodied energy of production and the cost of extraction. Long-term historical data shows, however, that the embodied energies of copper, steel, and aluminum production decreased between 1950 and 2000 at an average rate of about 1% per year, due to increasing productivity and energy efficiency (Yellishetty et al., 2010; Gutowski et al., 2013; Birat et al., 2014). This has offset the increase in energy consumption associated with the decline of ore grade. Similarly, the inflation-adjusted price of most metals has declined during the same period. Two opposing views on the evolution of production energy and metals prices are thus found in the literature: one predicts an unaffordable increase due to the depletion of high-quality non-renewable resources; the other argues that technological improvements will compensate for the decline in resource quality. To gain a better understanding of these arguments, we propose a formalism based on the physical relationship between the energy of primary metal production and the "thermodynamic price" of primary metals which takes into account variations in ore grade, technology, energy prices, and first-order thermodynamic limits. We then use the model to estimate future trends in energy consumption and

metal prices. Our findings indicate that technological advancements have offset the increase in production energy resulting from the decline in ore grade over the past century, and will continue to do so in the near future, but this trend is likely to reverse as thermodynamic limits are approached.

### 3.1.2. MATERIALS AND METHODS

#### 3.1.2.1. RELATIONSHIP BETWEEN ORE GRADE AND PRODUCTION ENERGY

The energy ( $E_i$ ) consumed to process a mass unit of metal  $i$  from its raw form can be divided into three parts: i) the mining, grinding and comminution energy ( $E_{c_i}$ ), ii) the separation energy ( $E_{s_i}$ ) to extract the ore minerals from the disaggregated rock and iii) the energy of metallurgical processes ( $E_{m_i}$ ) to extract metal from the ore minerals.

The minimum separation energy of mineral particles from the disaggregated rock can be approximated as the mixing entropy of an ideal mixture of two components: the mineral  $j$  to be recovered, and the host rock. The minimum energy cost of separation reads:

$$E_{s_i}(\text{J/mol of ore}) = -RT(x_j \ln x_j + (1 - x_j) \ln (1 - x_j)) \quad (3.1)$$

where  $R$  is the universal gas constant (8.314 J/mol/K),  $T$  the standard state temperature (298.15 K) and  $x_j$  the molar fraction of the mineral  $j$  carrying the metal  $i$ .

The minimum metallurgical energy  $E_{m_i}$  to extract the metal  $i$  from the mineral  $j$  is given by the Gibb's free energy of formation of the mineral from its constituents:

$$E_{m_i}(\text{J/g of } i) = \frac{-\Delta G_f^{\circ} i}{M_i n_i} \quad (3.2)$$

The comminution energy  $E_{c_i}$  is proportional to the inverse of the concentration  $C_i$  (Norgate and Jahanshahi, 2010; Valero et al., 2013 and references therein; Calvo et al., 2016, Table 1):

$$E_{c_i}(\text{J/kg of } i) = a_i \left(\frac{1}{C_i}\right)^{u_i} \quad (3.3)$$

where  $a_i$  and  $u_i$  are parameters describing the hardness of rocks and grain size after grinding.

$E_{m_i}$  and  $E_{s_i}$  are state functions independent on path. They correspond to the minimum energies assuming ideal conditions and no energy losses. In real-world applications, however, current energies depend on processing paths and technologies, and  $E_{m_i}$  and  $E_{s_i}$  must be corrected by factors related to differences between the thermodynamic minimum and the real situation. Assuming that the energy efficiency is the same for all industrial processes, the production energy can be written as (assuming  $u_i = 1$ ):

$$E_i(t, C_i) = \eta_i(t) \left(\frac{a_{min}(i)}{C_i}\right) + E_{s_i} - \Delta G_f^{\circ} i \quad (3.4)$$

where  $\eta_i$  is the inverse of efficiency and  $a_{min}(i) = \frac{a_i}{\eta_i(t)}$ .

At constant technology, a decrease of the ore grade of exploited deposits should result in

an exponential increase of both the production energy and price for metals (Eqs 3.3 and 3.4). However, historical data show opposite trends; the deflated price of copper in 1900 ( $C = 3$  wt%) was higher than in 2000 ( $C < 1\%$ ). The same observation is made for all metals, whose deflated prices have decreased from 1900 to 2000 due to improvements of productivity and technologies. This suggests that the efficiency of production  $\eta$  has decreased with time. A perpetual improvement of energy efficiency (decrease of  $\eta$  in Eq. 3.4) is impossible, however, because the minimum value is constrained by the Energy at Thermodynamic Limit (ETL). This limit can only be approached, not attained, because no industrial process can reach 100% efficiency. In 2007, the United States Department of Energy estimated that the Practical Minimum Energy (PME) of metal production was 30% to 50% of the current value. Assuming that PME is 50% higher than ETL, the general equation of production energy as a function of the production energy at reference year  $tRef$  reads:

$$\begin{aligned} E_i(tRef) &= ETech_i(tRef) + PME_i(tRef) \\ &= (E_i(tRef) - PME_i(tRef))(1 - \tauTech)^{t-tRef} + 1.5E_{TL,i}(tRef) \end{aligned} \quad (3.5)$$

where  $E_{Tech_i}$  is the part of energy that can be reduced by technological improvement at a rate  $\tauTech_i$  (starting from  $tRef$ ) and  $PME_i$  the incompressible part stemming from thermodynamic limits. In the long run,  $ETech$  approaches zero and  $E$  asymptotically approaches PME.

As a result, the production energy  $E(t)$  exhibits a U-shaped curve if  $C(t)$  decreases over time (Fig. 3.1), or remains horizontal if the ore grade remains constant.

Combining equations 3.4 and 3.5, the inverse of the efficiency reads:

$$\eta_i(t) = \frac{ETech_i(t) + PME_i(t)}{E_{TL,i}(t)} \quad (3.6)$$

with

$$ETech(t) = \left( \frac{a_{min}(i)}{C_i(tRef)} \right) + E_{si} - \Delta G_{fi}^\circ (\eta_i(tRef) - 1.5)(1 - \tauTech)^{t-tRef} \quad (3.7)$$

$$\text{and } E_{TL,i}(C_i) = \eta_i(t) \left( \frac{a_{min}(i)}{C_i(tRef)(1-\tauOG_i)^{(t-tRef)}} \right) + E_{si} - \Delta G_{fi}^\circ$$

In Eq. 3.7, the rate  $\tauOG_i$  represents the annual change in ore grade compared to the grade in  $t_{Ref}$ . For metals like copper and nickel, literature data report series of historical  $E(t)$  values at various ore grades, which may differ from the average ore grade of exploited deposits. The production energy at any time and ore grade can be calculated using Eqs. 3.4 and 3.6, with  $\tauTech_i$  and  $\eta_i(t)$  constrained for each metal using the historical data on production energy.

### 3.1.2.2. RELATIONSHIP BETWEEN PRODUCTION ENERGY AND PRICE

The average metal prices at given year are also expected to vary as a power-law of the ore grade. This relationship suggests that the natural logarithm of the metal price is roughly linearly proportional to the natural logarithm of production energy:

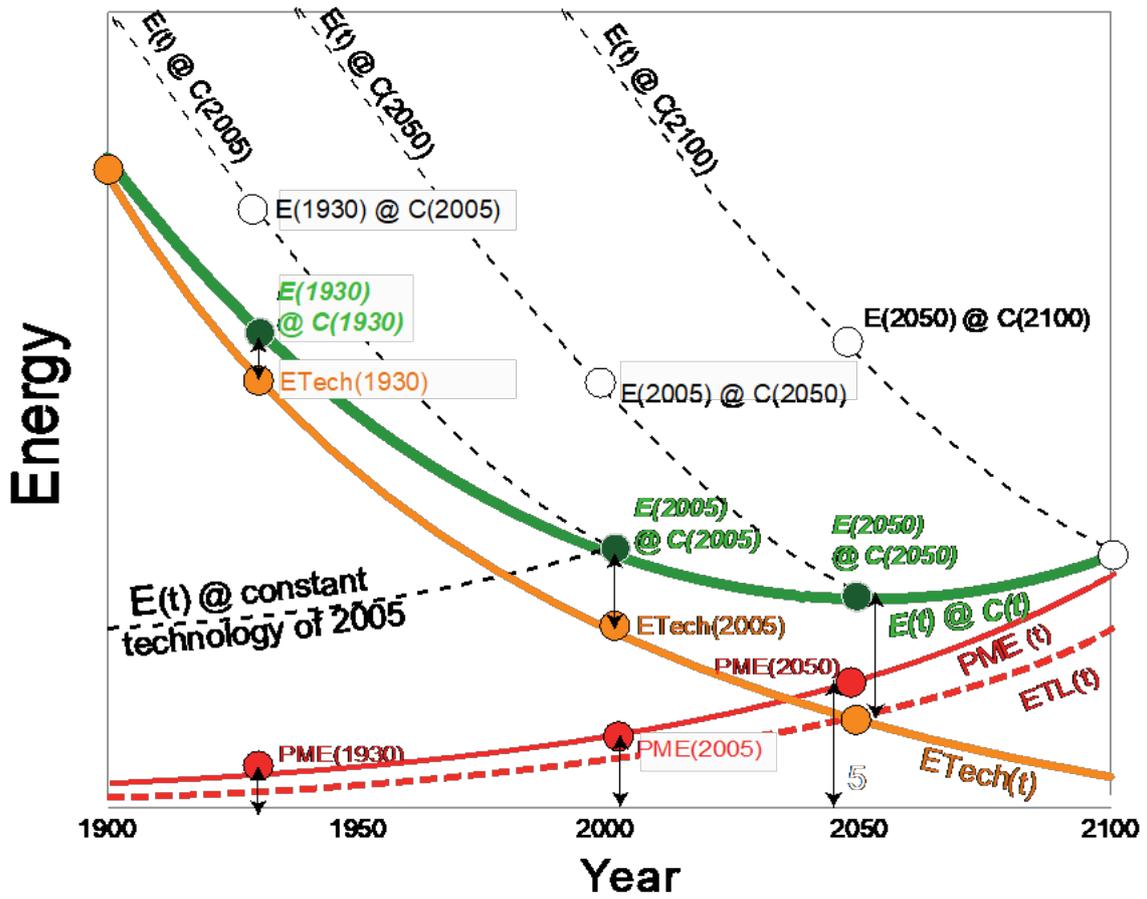


FIGURE 3.1: Relationships between the production energy (E), the practical minimum energy (PME) and the thermodynamic limit (ETL) with varying ore grade (C) and technology with time. *ETech* is the theoretical production energy without thermodynamic limit.

$$\log(P(t)) = \log(p_i) + w \log(E_i(t, C_i)) \quad (3.8)$$

where  $p_i$  is a constant in \$/MJ. The fraction of price corresponding to the direct energy consumption  $FP(\%)$  in 2005 reads:

$$FP\% = \frac{P_{energy} \cdot E_i(t, C_i)}{P(t)} = \frac{P_{energy} \cdot E_i(t, C_i)^{1-w}}{p_i} \quad (3.9)$$

To estimate the price of metals over long time series, the variation of energy prices over time must be incorporated into Eq. 3.8. As a first approximation, we assume that the price of energy follows the trend of crude oil prices ( $P_{Oil}$ ), leading to a rearrangement of Eq. 3.8:

$$P_i(t) = p_i \cdot E_i(t)^w \frac{1}{\alpha} \cdot \frac{POil(t)^\gamma}{POil(tRef)} \quad (3.10)$$

where  $\gamma$  is an elasticity coefficient that links the metal price to changes of the oil price.

### 3.1.3. RESULTS: THE EVOLUTION OF PRODUCTION ENERGY OR PRICE BETWEEN 1900 AND 2100

#### 3.1.3.1. CALIBRATION OF THE RELATIONSHIP BETWEEN PRODUCTION ENERGY OR PRICE AS A FUNCTION OF ORE GRADE BASED ON 2005 DATA

The total energy of production of metals as a function of ore grade was calibrated using data from the year 2005 3.1. This reference date was chosen because it predates the surge of price due to rapid growth of Chinese demand.

The values of  $\eta_i$  and  $a_{\min}(i)$  in Eq. 3.4 depend on parameters such as the type of mine, the type of ore, the technologies and type of processing route. They also depend on the energy mix and the energy losses incurred during the conversion of primary energy to its utilized form. Nonetheless, the mining and mineral processing energies of gold, copper, nickel, zinc, lead and iron in 2005 can be expressed in a single equation (Eq. 3.3) with  $u_i = 1$  and  $a_i = 0.6$ . (Fig. 3.8). The total energy of primary metal production estimated with Eq. 3.5 are in fair agreement with the observed energies for average values  $\bar{\eta}_i(2005) = 3$  and  $\bar{a}_{\min}(i) = 0.2$  (Table 3.1 and Fig. 3.9). This suggests that, on average, the minimum thermodynamic energy of comminution represents 30% of the current energy, which is consistent with theoretical analyses suggesting a two- to threefold possible improvement of the efficiency of comminution (Tromans, 2008). The values  $E_{C_i}$ ,  $E_{S_i}$  and  $E_{M_i}$ , calculated in year 2005 for a series of metals at concentrations ranging from 3 ppm to 50%, are reported in Table 3.1. The difference between calculated and observed consumed energy in 2005 is less than 35% for most metals. Since Eq. 3.4 is an oversimplification of the real industrial processes and given the additional difficulty in defining with precision average energies and ore grades for each metal, this difference is surprisingly low. Values of  $\eta_i$  that perfectly reproduce the observed production energy can be calculated for each metal. However, this should be done with caution because the values reported in the literature sometimes include energy contributions that are not included in Eq. 3.4. For example, the estimated production energy of In and Ga is overestimated because the two elements are

byproducts of Al and Zn production. For these metals, the observed energy constitutes only a portion of the estimated energy, because the energy expended in crushing and grinding has already been supplied to generate the primary metal. In the case of titanium, the observed energy reported in Tab. 3.1 is 264 MJ/kg, including 82 MJ/kg for the reductant production (Kroll process) and the semi-finished shaping. The latter contributions are not considered in Eq. 3.4. The production energy without reductant production and shaping is 132 MJ/kg, in fair agreement with the 117 MJ/kg estimated with Eq. 3.4, such that  $\eta_{\text{Ti}}$  is close to the average value ( $\bar{\eta}(2005) = 3$ ).

|        | (a)                              | (b)      | (c)                                | (c)                            | (c)                            | (d)                    | (e)                                       |   |   |   |  |                         |          |                             |                           |                          |          |      |
|--------|----------------------------------|----------|------------------------------------|--------------------------------|--------------------------------|------------------------|---|---|---|---|--|-------------------------|----------|-----------------------------|---------------------------|--------------------------|----------|------|
|        | Cmetal<br>(g/grock)              | 1/C      | $\Delta G^*f$<br>(kJ/mol<br>Metal) | Em* $\eta$<br>(MJ/kg<br>metal) | Es. $\eta$<br>(MJ/<br>kgmetal) | Ec<br>(MJ/<br>kgmetal) | Obs E <sub>cmin</sub><br>(MJ/<br>kgmetal) | Obs E <sub>cmax</sub><br>(MJ/<br>kgmetal) | Obs E <sub>c</sub><br>average<br>(MJ/<br>kgmetal) | Calc. E <sub>i</sub> ( $\eta = 3$ )<br>(MJ/<br>kgmetal) | Obs E <sub>i</sub><br>(MJ/<br>kgmetal) | ETL<br>(MJ/<br>kgmetal) | $\eta_i$ | Calc. P2005<br>(1998US\$/t) | Obs P2005<br>(1998US\$/t) | FP(%) @ 8<br>1998US\$/Gt | $\alpha$ |      |
| brick  | 100,00%                          | 1,0E+00  | -                                  | 0,30                           | 0,0E+00                        | 0,6                    |   |   |   | 2   | 3                                      | -                       | 4,5      | 28                          | 45                        | 57%                      | 2,00     |      |
| cement | CaCO <sub>3</sub>                | 10,00%   | 1,0E+01                            | -                              | 0,60                           | 0,0E+00                | 6,0                                       |   | 5,8   | 4   | 4                                      | -                       | 2,9      | 95                          | 150                       | 34%                      | 1,26     |      |
| glass  | SiO <sub>2</sub>                 | 100,00%  | 1,0E+00                            | -                              | 3,00                           | 0,0E+00                | 0,6                                       |   |   | 15  | 15                                     | -                       | 3,0      | 256                         | 300                       | 47%                      | 2,00     |      |
| Fe     | Fe <sub>2</sub> O <sub>3</sub>   | 52,00%   | 1,9E+00                            | -742,2                         | 20,24                          | 5,1E-02                | 1,2                                       | 0,8                                       | 2,5   | 1,7   | 21                                     | 25                      | 7,15     | 3,5                         | 432                       | 550                      | 40%      | 1,75 |
| Al     | Al <sub>2</sub> O <sub>3</sub>   | 30,00%   | 3,3E+00                            | -1582,3                        | 87,91                          | 1,7E-01                | 2,0                                       |   |   | 2,3   | 90                                     | 90                      | 30,02    | 3,0                         | 2335                      | 1670                     | 31%      | 1,57 |
| Mn     | MnO <sub>2</sub>                 | 15,00%   | 6,7E+00                            | -465,1                         | 25,40                          | 3,1E-01                | 4,0                                       |   |   | 23,5  | 30                                     | 30                      | 9,91     | 3,0                         | 790                       | 594                      | 30%      | 1,37 |
| Mg     | MgCO <sub>3</sub>                | 28,00%   | 3,6E+00                            | -1012,1                        | 124,95                         | 0,0E+00                | 2,1                                       |   |   | 127   | 117                                    | 42,36                   | 2,8      | 3465                        | 2240                      | 29%                      | 1,55     |      |
| Cr     | FeCr <sub>2</sub> O <sub>4</sub> | 23,00%   | 4,3E+00                            | -1340,0                        | 38,65                          | 1,3E-01                | 2,6                                       |   | 37,0  | 41  | 64                                     | 13,80                   | 4,6      | 1046                        | 1260                      | 32%                      | 1,49     |      |
| Cu     | calchopyrite                     | 1,00%    | 1,0E+02                            | -369,6                         | 17,60                          | 5,3E-01                | 60  | 20,0                                      | 55  | 37,5  | 78                                     | 70                      | 26,04    | 2,7                         | 3928                      | 3190                     | 16%      | 0,80 |
| Hg     | HgS                              | 0,35%    | 2,9E+02                            | -50,6                          | 0,65                           | 2,1E-01                | 171                                       |   |   | 172   | 179                                    | 57,43                   | 3,1      | 11613                       | 15000                     | 12%                      | 0,65     |      |
| Pb     | PbS                              | 3,40%    | 2,9E+01                            | -98,7                          | 1,24                           | 1,3E-01                | 17,6                                      | 10,0                                      | 20  | 15,0  | 19                                     | 28                      | 6,34     | 4,4                         | 652                       | 1130                     | 23%      | 1,02 |
| Mo     | MoS <sub>2</sub>                 | 0,30%    | 3,3E+02                            | -225,9                         | 4,23                           | 3,1E-01                | 200                                       |   |   | 53,2  | 204                                    | 235                     | 68,18    | 3,4                         | 14464                     | 58500                    | 11%      | 0,63 |
| Co     | CoS                              | 0,20%    | 5,0E+02                            | -86,2                          | 5,40                           | 1,0E+00                | 300                                       |   |   | 306   | 322                                    | 102,15                  | 3,2      | 24443                       | 28100                     | 10%                      | 0,58     |      |
| Ag     | Ag <sub>2</sub> S                | 0,03%    | 3,3E+03                            | -40,7                          | 0,57                           | 3,1E-01                | 2000                                      |   |   | 2001  | 1582                                   | 666,96                  | 2,4      | 2,2E+05                     | 2,0E+05                   | 7%                       | 0,50     |      |
| Pt     | Pt                               | 0,00050% | 2,0E+05                            | -100,0                         | 1,54                           | 5,0E-01                | 120000                                    |   |   | 1,2E+05   | 1,5E+05                                | 4,00E+04                | 3,7      | 2,01E+07                    | 1,250E+07                 | 5%                       | 0,50     |      |
| Au     | Or                               | 0,00050% | 2,0E+05                            | -100,0                         | 1,52                           | 5,0E-01                | 120000                                    | 50000                                     | 300000  | 175000  | 1,2E+05                                | 2,0E+05                 | 4,00E+04 | 5,0                         | 2,01E+07                  | 1,140E+07                | 5%       | 0,50 |
| Zn     | ZnS                              | 5,00%    | 2,0E+01                            | -201,3                         | 9,23                           | 4,0E-01                | 12  |   |   | 8,1   | 22                                     | 45                      | 7,21     | 6,3                         | 693                       | 1240                     | 25%      | 1,10 |
| Ti     | TiO <sub>2</sub>                 | 1,00%    | 1,0E+02                            | -890,7                         | 55,83                          | 7,9E-01                | 60  |   |   | 80,0  | 116                                    | 265                     | 38,87    | 6,8                         | 6114                      | 14440                    | 15%      | 0,80 |
| W      | MnWO <sub>4</sub>                | 0,20%    | 5,0E+02                            | -1172,0                        | 19,13                          | 2,7E-01                | 300                                       |   |   | 180,0   | 319                                    | 288                     | 106,47   | 2,7                         | 25607                     | 24900                    | 10%      | 0,58 |
| Ni     | NiS                              | 1,00%    | 1,0E+02                            | -91,0                          | 4,65                           | 6,5E-01                | 60  | 50  | 70,0  | 60,0  | 65                                     | 174                     | 21,77    | 8,0                         | 3228                      | 12300                    | 16%      | 0,80 |
| Ga     | Ga                               | 0,01%    | 2,0E+04                            | -890,7                         | 38,17                          | 8,63E-02               | 12000                                     |   |   | 12039   | 3030                                   | 4013                    | 0,8      | 2,90E+06                    | 4,49E+05                  | 3%                       | 0,28     |      |
| In     | In                               | 0,01%    | 2,0E+04                            | -890,7                         | 23,44                          | 8,63E-02               | 12000                                     |   |   | 12023   | 2875                                   | 4008                    | 0,7      | 2,90E+06                    | 2,50E+05                  | 3%                       | 0,28     |      |

(a) Priester et al. (2019), Norgate and Rankin (2011), Fizaine and Court (2015) and references therein, Leal-Ayala et al. (2015),

<https://www.mining.com/worlds-top-10-silver-mines/>, <https://www.proactiveinvestors.com.au/companies/news/195095/neometals-expands-titanium-vanadium-resource-at-barrambie-195095.html>

(b) Ziemniak et al. (2007), [https://www.engineeringtoolbox.com/standard-state-enthalpy-formation-definition-value-Gibbs-free-energy-entropy-molar-heat-capacity-d\\_1978.html](https://www.engineeringtoolbox.com/standard-state-enthalpy-formation-definition-value-Gibbs-free-energy-entropy-molar-heat-capacity-d_1978.html)

(c) Nuss and Eckelman (2014); Norgate and Jahanshahii (2006, 2010); Wei et al. (2020); Calvo et al. (2016), De Boer et al (1998); Office of Energy Efficiency & Renewable Energy (2002); Makhijani et al. (1992)

(d) Cement, Fe and Al: consummed energy (Gutowsky et al., 2012); Mn: Van der Voet et al. (2018); Mg: Tian et al. (2020); Cr, Co, Ag: Fizaine and Cort (2015); Cu: Rötzer and Schmidt (2020); Hg, Pb, Mo, Ga, In: Nuss and Eckelman (2014); Zn, Au, Pt: Ashby (2013); Ti: US department of energy (2017); W: Leal-Ayala et al. (2015); Ni: Wei et al. (2020)

TABLE 3.1: Data used for calculations

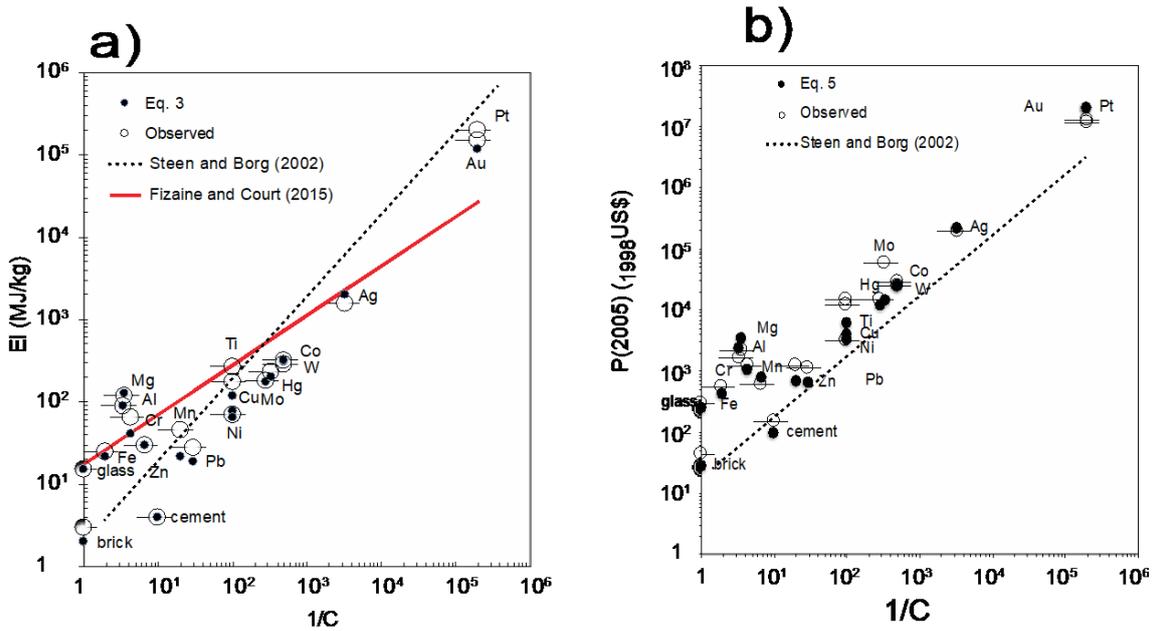


FIGURE 3.2: Observed and calculated production energy (a) and price (b) in 2005 as a function of the inverse of average ore grade.

Equation 3.4 offers a logical explanation of the empirical power law relationships between production energy and ore grade, observed for single metals for ore grades below 1%, where  $E_c$  is the primary contributor to  $E$ . At concentrations greater than 1%, the empirical power-law relationship between energy and dilution is no longer valid because the contribution from metallurgy is of the same order as  $E_c$ . This is exemplified by the big differences in production energy between the estimates in year 2005 ( $\bar{\eta}(2005) = 3$ ) using Eq. 3.4 and those of F. Fizaïne et al., 2015. The slope of the  $E_i = f(1/C)$  line for the metals considered by Florian Fizaïne et al., 2015, results in an overestimation of production energies for Zn, Pb, Ni, Cu, Mo, Hg, Co, and W by a factor of 5 to 10 compared to the values used in our analysis, and an underestimation of production energies for Au and Pt by a factor of 10. The slope of the  $E_i = f(1/C)$  line obtained using the equation of Steen and Borg (2002) is similar to that of Equation 3.4 at concentrations below 1%, but their empirical equation underestimates the production energy of metals at concentrations above 1% by a factor of 10. In contrast, the production energies in 2005 of metals in concentration from 1ppm to 50% in ore deposits can be accurately predicted using Eq. 3.4 with an average  $\eta(2005)$  of 3 (as shown in Fig. 3.2a).

Detailed analysis of the 2005 data (Tab. 3.1) shows that the relationship between the natural logarithms of price and energy is not strictly linear because the fraction of price corresponding to the direct energy consumption decreases with dilution from about 2 at  $C > 10\%$  to 0.5 at  $C < 0.5\%$  (Fig. 3.3a). A correction of this effect leads to the following price-energy relationship:

$$P_{2005} = 0.026 \cdot E_{2005}^{1.1} \cdot \frac{1}{\alpha} \tag{3.11}$$

with  $\alpha = (2/C) - 0.2$ . The fraction of price corresponding to the direct energy consump-

tion  $FP(\%)$  in 2005 reads:

$$FP\% = \frac{P_{\text{energy}} \cdot E_{2005}}{P_{2005}} = \frac{P_{\text{energy}} \cdot E(2005)^{-0.1} \cdot \alpha}{0.026} \quad (3.12)$$

with  $P_{\text{energy}}$  the average price of energy. The deflated prices of metals calculated with Eq. 3.11 are in fair agreement with the values observed in 2005 (Fig. 3.2b).

For  $P_{\text{energy}} = 8_{1998}$  US\$/GJ,  $FP$  decreases with ore grade from 30-40% for steel, Al, Mn, Mg and Cr to 5%-10% for precious metals (Fig. 3.3). These values are broadly consistent with the all-in-cost breakdown of iron (30%: Toktarova 2020), Al (34%: Braga et al., 2016, Ag (12%: Intelligence, 2019a and Au (about 15%: Intelligence, 2019b; Goldcorp, 2015).

### 3.1.3.2. APPLICATION TO BASE AND PRECIOUS METALS ON LONG TIME SCALES

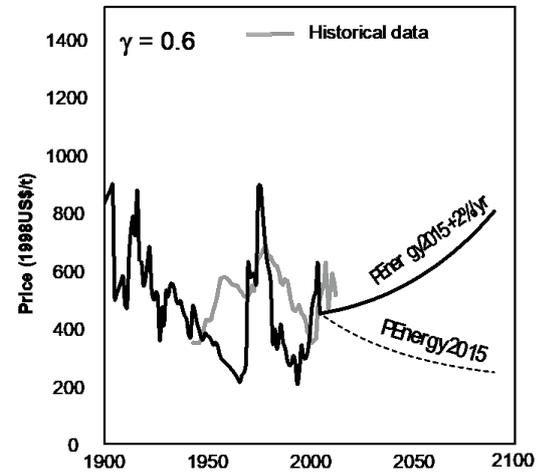
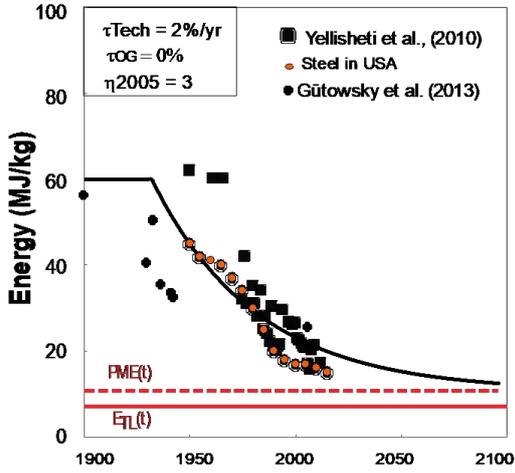
The input data for Eq. 3.4 and 3.11 are the historical evolution of price in constant dollars (1998US\$), and the ore grade and the values of production energy in 2005 (Table 3.1). In absence of data, we assume that the evolution of  $\alpha$  with ore grade, obtained from the analysis of the 2005 data, remains constant over time. For each metal, the following calculation strategy was adopted to constrain the technological improvements and evolution of production energy and price over time:

- The annual rate of average ore grade evolution ( $\tau_{OG_i}$  in Eq. 3.7) is adjusted to reproduce available historical data
- The annual rates of improvements in technological and productivity  $\tau Tech_i$  in Eq. 3.5 and 3.7 are adjusted to reproduce the historical production energies and prices calculated with  $\eta_i(2005)$ . The elasticity coefficient  $\gamma$  in Eq. 3.10 is adjusted to reproduce the metal price variations for the historical changes of  $P_{Oil}$ .
- $\eta_i(t)$  is estimated for  $ETech_i(t)$ ,  $E_{TL,i}(t)$  and  $PME_i(t)$  calculated with the value of  $\tau Tech_i$  derived above.
- Long-term prices are estimated assuming either constant  $P_{\text{energy}}$  or an increase of 2%/yr after 2020, in line with the average growth rate of deflated oil price between 1950 (20 1998US\$) and 2015 (60 1998US\$).

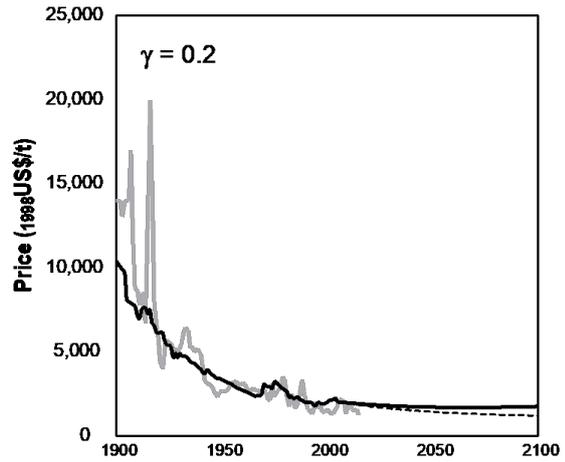
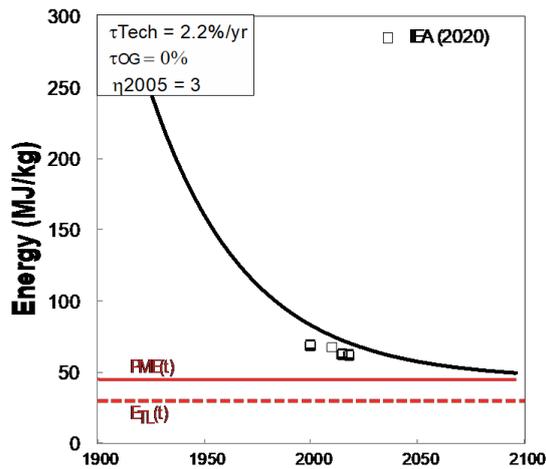
**Ferrous metals at constant ore grade** The production energies of steel, Al, Mn, Mg and Cr calculated in 2005 show good agreement with observed values for  $\bar{\eta}_i(2005) = 3$ . The historical prices of steel, Mn and Cr are fitted with  $\gamma = 0.6$  and those of Mg and Al with  $\gamma = 0.2$ , reflecting the lower share of oil energy in their primary production. The evolution of production energies is reproduced with  $\tau_{Tech} = 1.5\%/yr$  for steel, 2.2% for Al and for 2.5% Mg. The rates of technological improvement of Mn and Cr derived from price data are significantly lower, at 0.3%, and 0.6%/yr, respectively.

While our approach provides a good approximation of historical metal prices, the agreement reported in Fig. 3.3 is not perfect due to economic factors that are not considered in our model

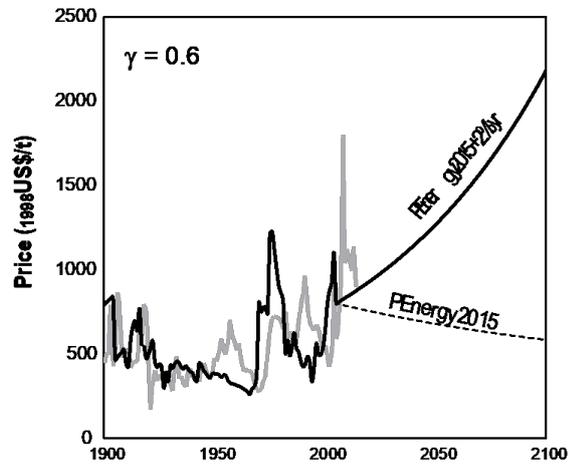
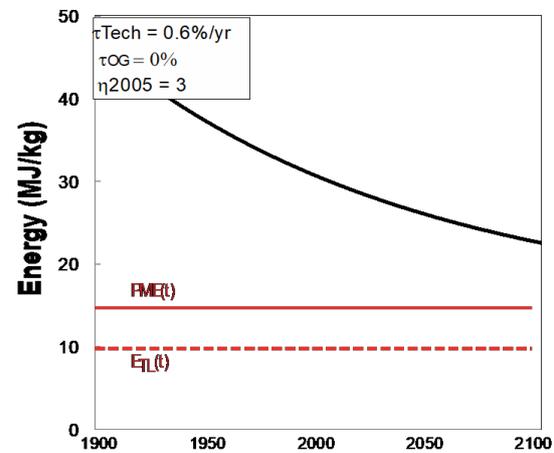
### Steel



### Al



### Mn



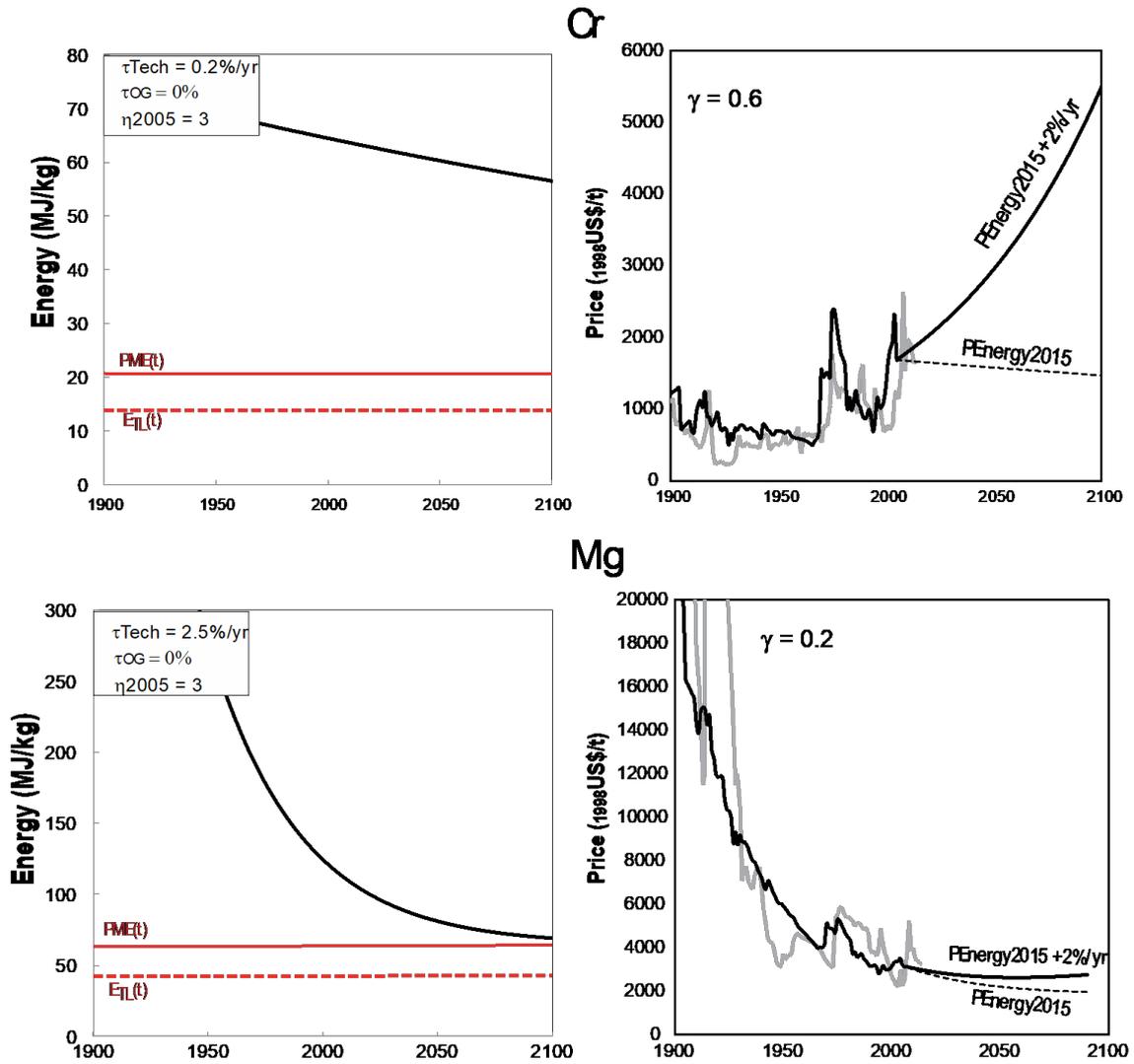


FIGURE 3.3: Production energies (left column) and prices (right column) of base metals. The red lines show the practical minimum energy  $PME$  (continuous) and the thermodynamic limit  $E_{TL,i}(t)$  (dashed). The gray lines in the right column show the observed prices, and the black lines prices calculated for  $P_{energy}(t) = P_{energy}(2015)$  or  $P_{energy}(2015) + 2\%/yr$  after 2015. The symbols show the historical data.

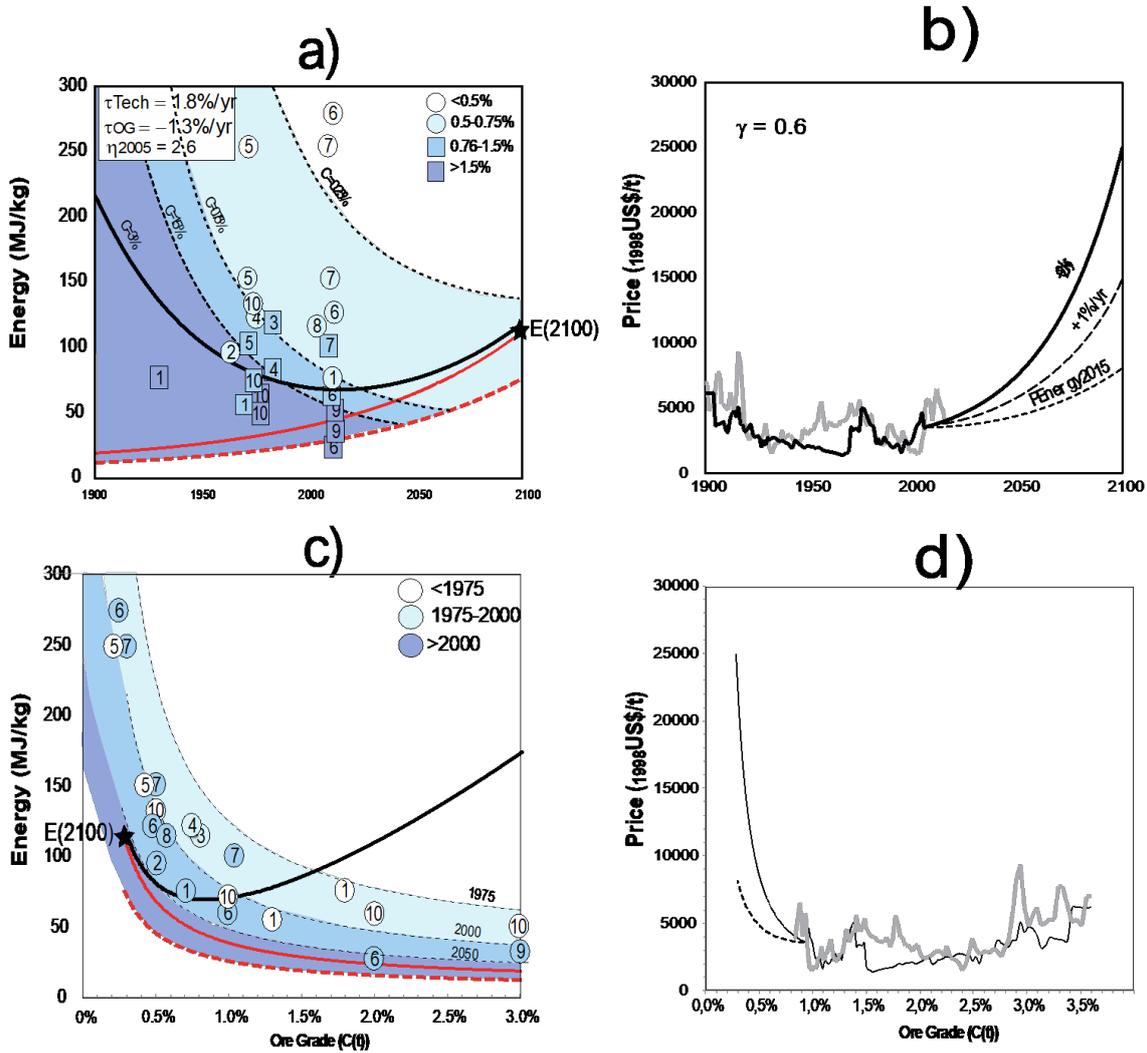


FIGURE 3.4: Energy of copper production (a and c) or price (b and d). The symbols and numbers refer to the literature data with the corresponding ore grades (a) or date of publication (c). The gray line in (b) and (d) show the observed prices, and the black lines prices calculated for  $P_{energy}(t) = P_{energy}(2015) + 0, 1 \text{ or } 2\%/yr$  after 2015. 1) Rötzer and Schmidt. (2020); 2) Rozenkranz(1976); 3) Gaines (1980); 4) Kellogg (1974); 5) Page and Creasey (1972) ; 6) Norgate and Jahanshahi (2010) ; 7) Marsden (2008) ; 8) Office of Energy Efficiency & Renewable Energy (2002); 9) Rankin (2011) ; 10) Chapman (1974)

but can control short-term metal prices. The approach is reliable enough, however, to use for modeling future price evolutions. According to our predictions, the prices of Al, Fe, Mn and Mg are expected to decrease until 2050-2070. After this period, the practical minimum energy (PME) is reached, and further technological improvements become impossible, resulting in constant long-term prices.

**Base metals produced from sulfides: Cu, Ni, Zn** The average copper ore grade decreased from  $\approx 3.5\%$  at 1900 at an average rate ( $\tau_{OG}$ ) of  $1.25\%/yr$  (Northey et al., 2014). For an average annual change of  $\tau_{Tech} = 1.7\%/yr$ , the copper price decreased from 1998US\$7000 in 1900-1920 to 1998US\$3000 in 2005. The assumption of a constant  $\tau_{Tech}$  in our model allows us to reproduce the abrupt drop in copper prices between 1910 and 1930 that was caused by rapid

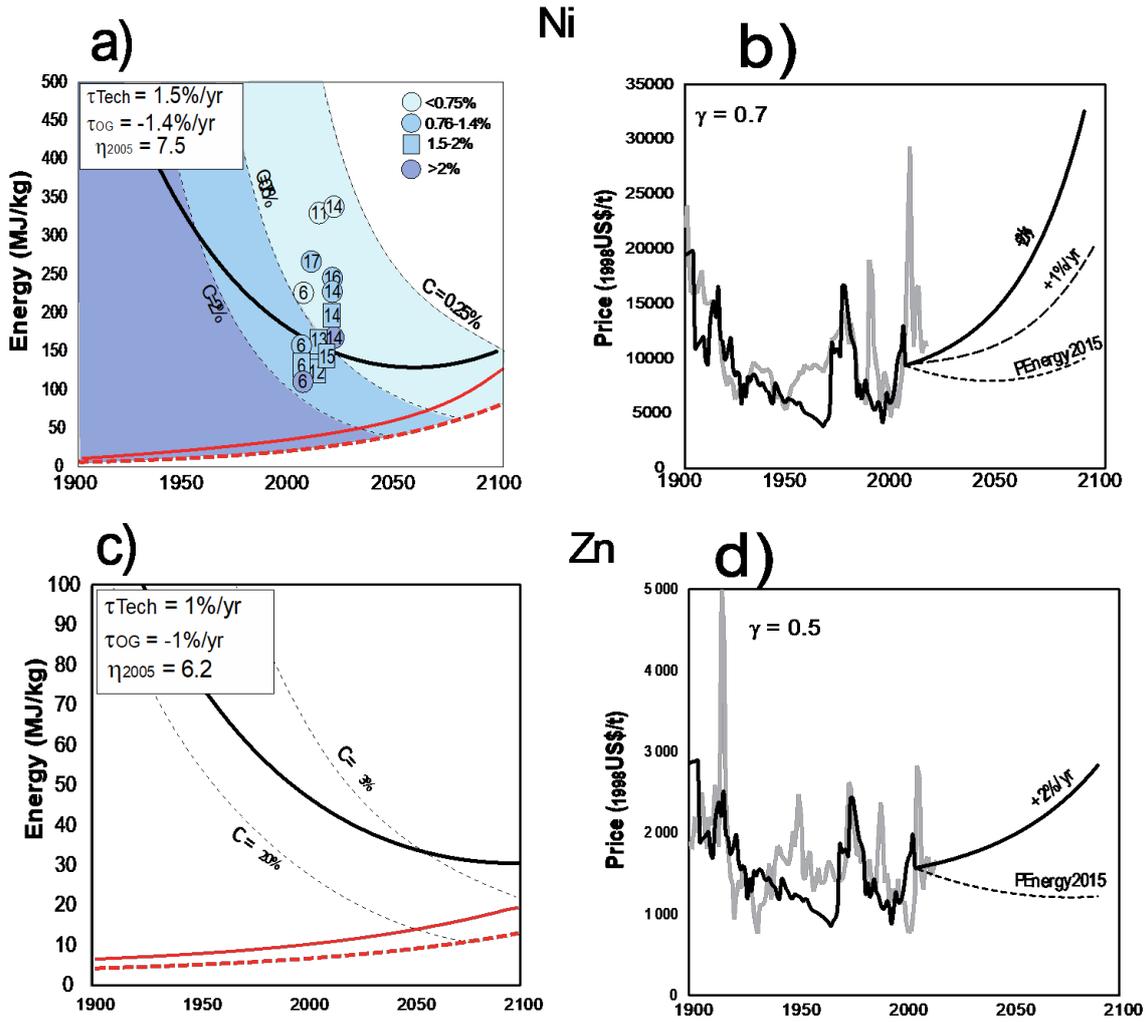


FIGURE 3.5: Production energy and price of nickel and zinc as a function of time or ore grade. Same legend as in Fig. 7. 11) Haque and Norgate (2013); 12) Fukuzawa (2012); 13) Bartzas (2015); 14) Wei et al. (2020); 15) Mistry et al (2016); 16) Nickel institute (2020); 17) Eckelman (2010)

improvements in energy efficiency linked to the introduction of flotation technology (Fuerstenaue et al., 2007) and the electrification of mines (Leong et al., 1940). The production energy at constant ore grade and improving technology (dashed lines in Fig. 3.4a) is in reasonable agreement with literature values for various ore grades between 1963 and 2020 (circled and squared numbers in Fig. 3.4a). The production energy at constant technology (dashed lines in Fig. 3.4c) shows an exponential increase with lowering ore grade, and as expected, most literature values plot between the  $E(t)$  at constant technology of 1975 and  $PME(t)$ . Our estimated value of copper production energy in 1930 is twice the value estimated by (Rötzer et al., 2020). The explanation for this discrepancy is unclear because uncertainties and gaps in historical data on copper production in 1930 preclude further analysis. However, the calculated production energy decreases between 1930 and 2000, in agreement with the results of (Rötzer et al., 2020). From 2000 onwards,  $E(t)$  no longer decreases because it approaches the practical minimum energy PME. The energy gain resulting from technological improvements no longer compensates the additional costs resulting from the decline of ore grade, and  $E(t)$  becomes parallel to PME. However, the increase of production energy after 2000 is much lower than predicted in many previous studies because these studies neglect improvements in technology. The embodied energy, calculated in 2100 at  $C = 0.3\%$ , is about 130 MJ/kg, two times lower than the literature values reported in Fig. 3.4c. Similar results were obtained by (O. Vidal, Rostom, et al., 2019) using an independent dynamic model linking resource quantity, reserves, annual production, industrial capital, production costs and prices.

The thermodynamic price, calculated at constant  $P_{\text{energy}}$ , is U-shaped and is predicted in 2100 to reach the same value as in 1900 (Fig. 3.4). The price in 2100 is three times higher than the price in 1900 if energy increases by 2% per year. The average nickel grade of sulfide ores decreased at a rate of  $\tau_{\text{OG}} = -1.4\%/yr$  from its 1900 value of  $\approx 4\%$ . The evolutions of price and energy shown in Fig. 5a and b were calculated with  $\tau_{\text{Tech}} = -1.5\%/yr$ , similar to copper, as are the rates of technological improvement. However, the energy of nickel production from sulfides is two times that of copper at the same average grade, which suggests a lower production efficiency of ( $\eta_{\text{Ni}}(2005) = 7.7 = 2.6 \cdot \bar{\eta}_i(2005)$ ). The gap to  $PME_{\text{TL}}$  is thus larger, and there is more room for improvement. In the optimistic scenario where breakthrough changes in the production process allow  $E(t)$  to approach PME (Fig. 3.5a), the future long-term price of nickel is expected to remain stable. However, if these changes are not achieved, the future PME will be higher and the price and production energy of nickel will increase significantly from 2015 to 2100 (Fig. 3.5b).

As with nickel, the production efficiency of zinc is lower than for copper. In Fig. 3.5c and d, the estimated price and energy evolutions were based on  $\eta_{\text{Zn}}(2005) = 2.1\eta$  and  $\tau_{\text{OG}} = -1.2\%/yr$ .

**Precious metals** A 1.5% annual decrease was used to fit the historical evolutions of ore grades of silver, platinum, and gold. A common feature for the precious metals is that  $E(t)$  is already constrained by the proximity of PME (Fig. 3.6). Future production energies and prices are thus expected to increase more rapidly than for base metals.

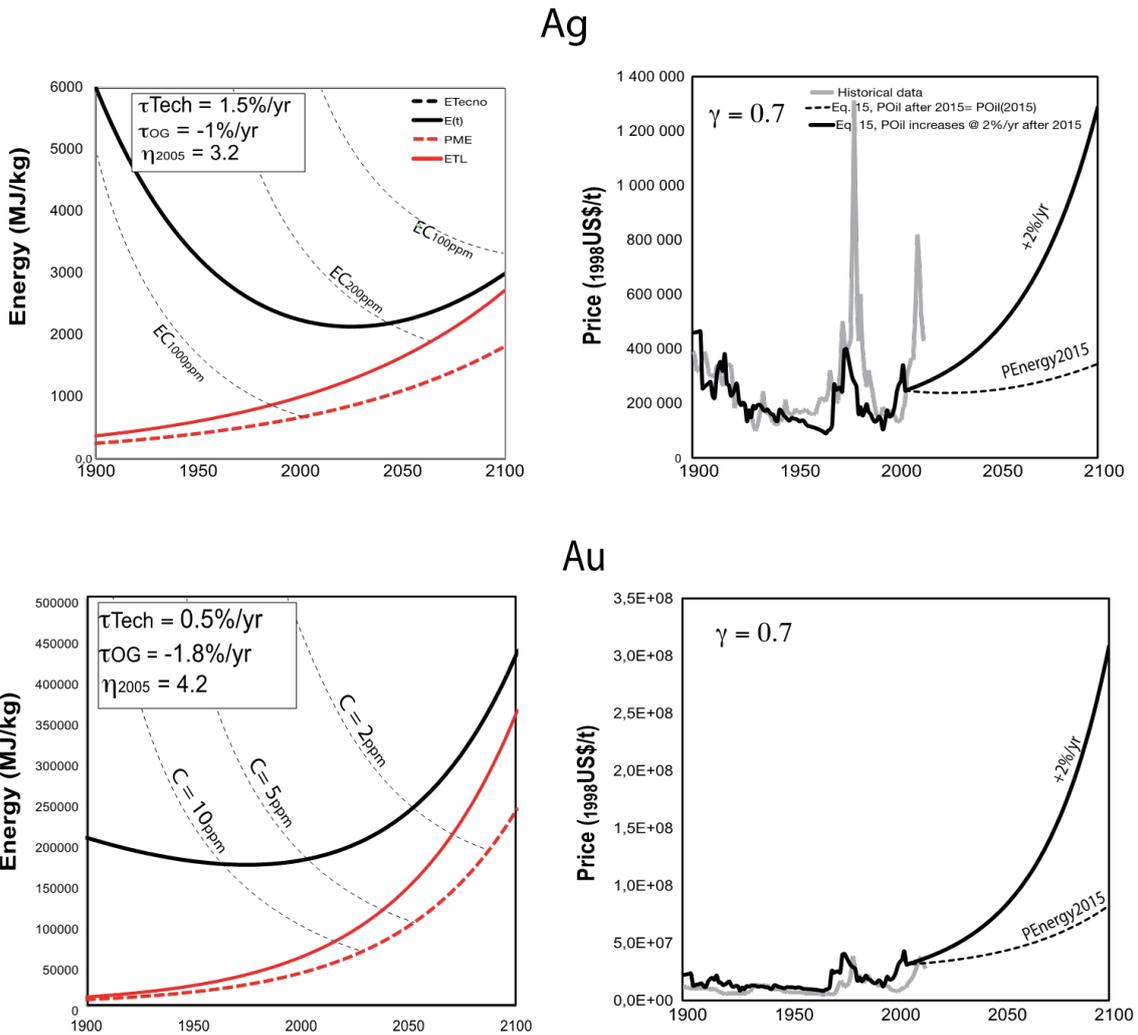


FIGURE 3.6: Production energy and price of precious metals as a function of time

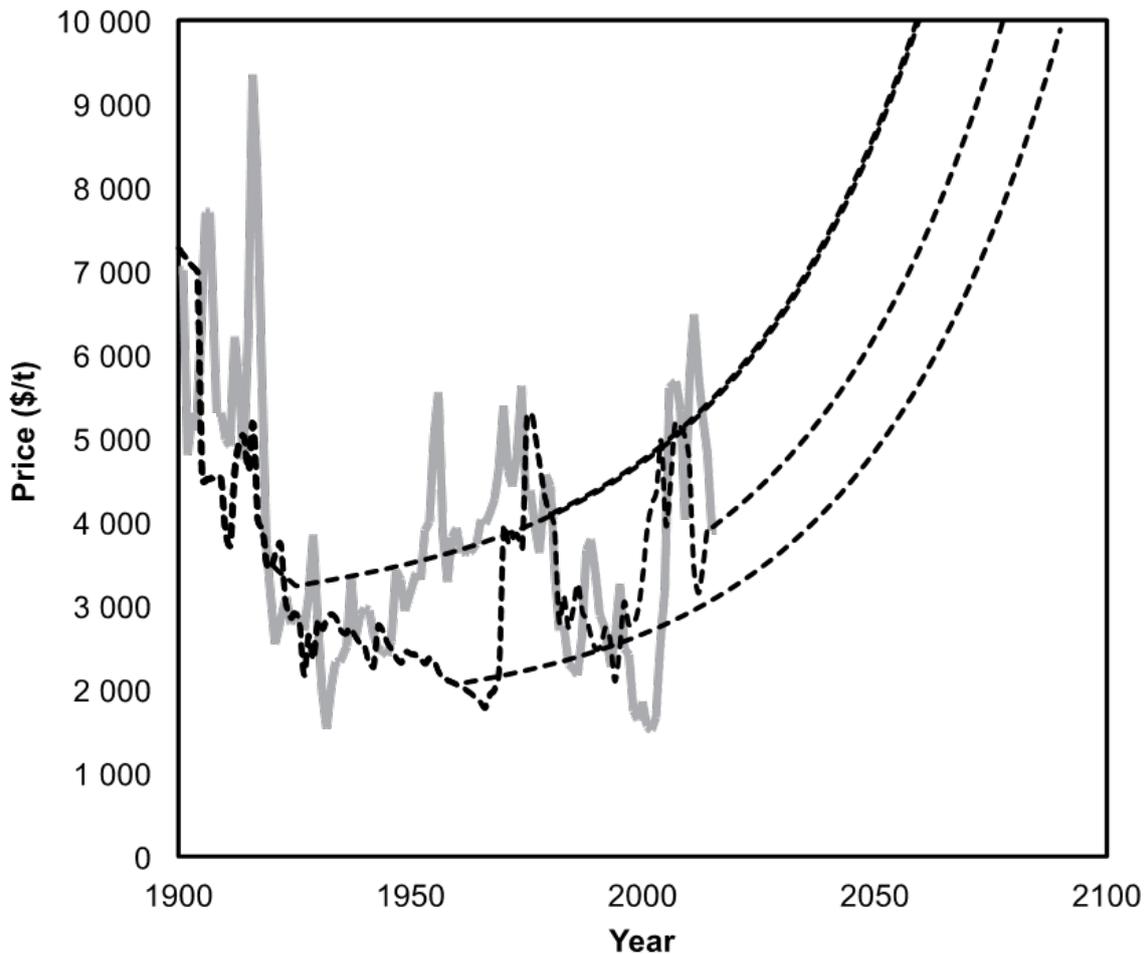


FIGURE 3.7: Calculated copper prices starting from 1920, 1960, 2000 and 2015 (dashed lines) and observed price in 1998US\$ (grey line)

### 3.1.4. DISCUSSION: UNCERTAINTIES ON THE FUTURE ENERGY AND PRICE OF METALS

Assessing the uncertainties in estimated future energy and long-term prices is a challenging task. One approach is to model the system starting from different past dates and comparing the results to the observed evolution. Figure 3.7 illustrates the calculated evolution of copper prices assuming a constant price of energy after the initial date and modeling the system starting from different observed prices in the years 1920, 1960, 2000, and 2015. Although the starting values of ore grades, production energies, and prices are different in each case, the evolutions are similar to those obtained when starting in 2015, with a difference of about +20%. This suggests that the evolution of production energy was predetermined decades ago, and that the long-term evolution of copper prices, corrected for fluctuations in energy prices over the last 60 years, was predictable as early as 1960. Of course, this retroactive modeling is only possible because we have a century-long record of ore grade reduction. Estimating this rate from historical data in 1960 would be highly uncertain, as it is today for future estimates.

The long-term prices presented in Figures 3.3 to 3.6 were calculated assuming a constant rate of change in ore grade but its evolution will depend on how consumption changes in the

future; a higher rate of consumption would increase the decline in average ore grade. For a future decrease of copper ore grade at  $-1.4\%/yr$ , the reserves added to the cumulative production calculated using the ore grade-tonnage relationship of (O. Vidal, Rostom, et al., 2019) would have to increase from 1.4 billion tonnes in 2015 to 3.5 billion tonnes in 2050, with primary production increasing from 19 Mt/year in 2015 to 37.5 Mt/year in 2050.

### 3.1.5. CONCLUSION

The proposed energy-based method satisfactorily reproduces the historical evolution of metal prices since 1900. There is a systematic mismatch between historical and calculated prices for the period 1950-1970, due mainly to economic drivers that controlled the short-term metal price.

Our model accurately describes the competing effects of ore grade decline and technical progress and explains the drop in deflated prices between 1900 and 2000. This pattern is unsustainable in the long term, as the production energy approaches the thermodynamic limit. Our analysis predicts that mineral resource prices will follow a U-shaped curve. It also reconciles two classically opposed views; an unaffordable increase in costs due to depletion of high-quality non-renewable resources versus a compensation by technological improvements. Low-quality resources are more abundant than high-quality resources and this creates a false perception of perpetual abundance. In reality, we are approaching thermodynamic limits when the energy gain from technological and productivity improvements no longer compensates for the decrease in resource quality. This will lead to increasing production energy and higher prices for several metals. To reduce this increase in price, affordable, grinding technologies based on non-mechanical processes will have to be found. Another possibility is to reduce the price of energy. Once the infrastructure of production is built, renewable energies are cheap. If we could use renewable energy sources at a low and stable price in the future, the increasing weight of energy price in the cost of metal production would no longer be an issue.

#### CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

**Olivier Vidal:** Funding acquisition, Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Baptiste Andrieu:** Writing – original draft, Formal analysis, Validation. **Hugo Le Boulzec:** Formal analysis, Validation **Francois Verzier:** review & editing, **Nicholas Arndt:** Writing – review & editing

#### DECLARATION OF COMPETING INTEREST

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

#### DATA AVAILABILITY

Data will be made available on request.

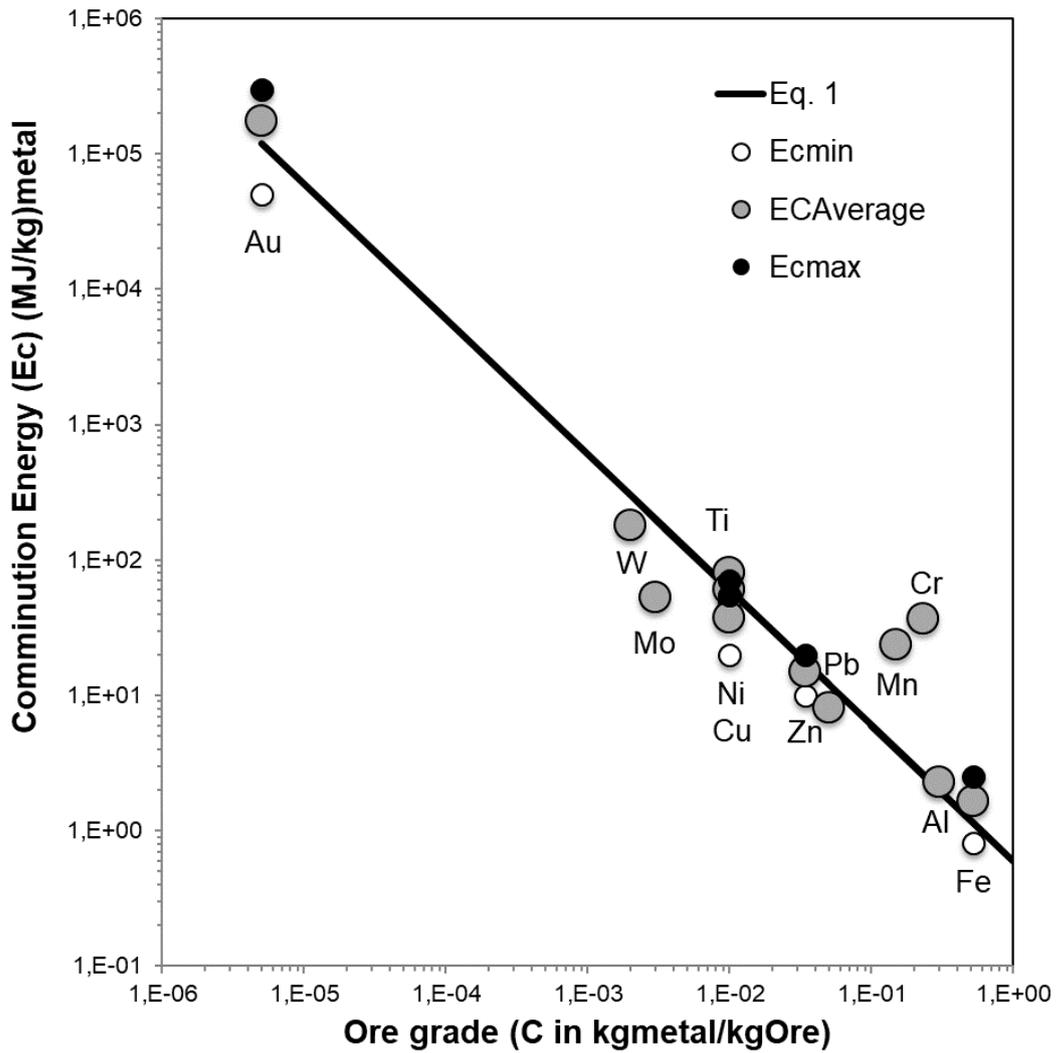


FIGURE 3.8: Observed mining + grinding + comminution energy as a function of ore grade (data in Table 1).

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3.1.6. APPENDIX

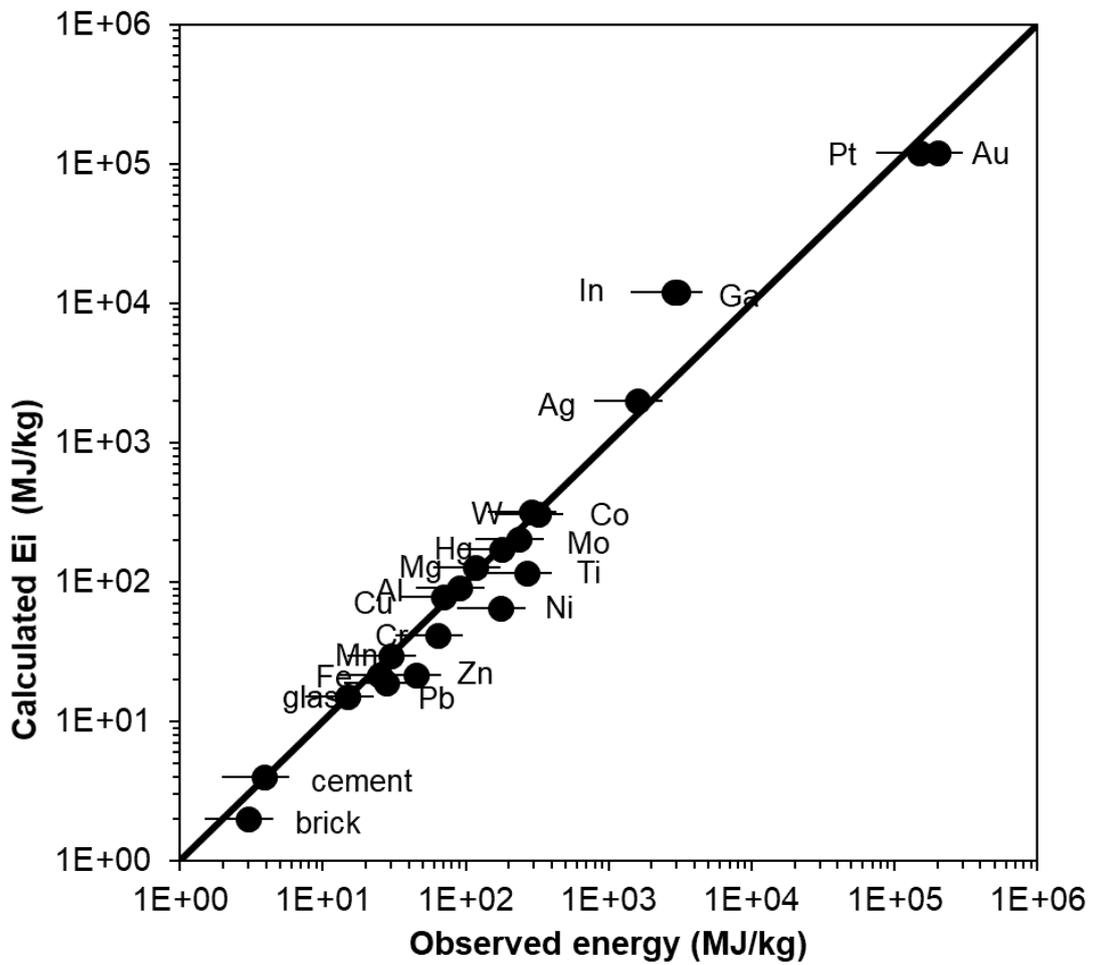


FIGURE 3.9: Production energy calculated with Eq. 5 and  $\bar{\eta} = 3$  as a function of observed values. The error bars show a +50% variation of the observed energy. The plotted values are listed in Tab. 1.

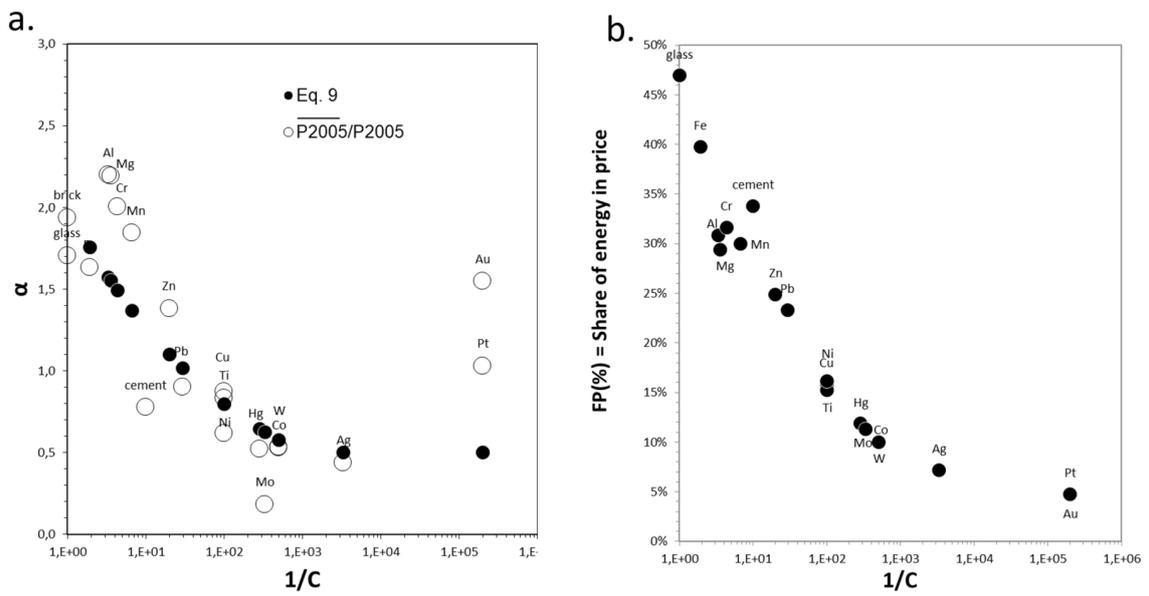


FIGURE 3.10: **a.** Ratio of prices in 2005 estimated with Eq. 5 divided by observed prices (open circles) and  $\alpha$  (filled circles) calculated with Eq. 8. **b.** FP(%) calculated with Eq. 11.

## 3.2. ENERGY INTENSITY OF FINAL CONSUMPTION: THE RICHER, THE POORER THE EFFICIENCY

**Authors** Baptiste Andrieu, Olivier Vidal, Hugo Le Boulzec, Louis Delannoy and François Verzier

### ABSTRACT

To maintain perpetual economic growth, most energy transition scenarios bet on a break in the historical relationship between energy use and gross domestic product (GDP). Practical limits to energy efficiency are overlooked by such scenarios, in particular the fact that high-income individuals tend to buy goods and services that are more energy intensive. Detailed assessments of the energy embodied in regional final consumption are needed to better understand the relationship between energy and GDP. Here, we calculate the energy necessary to produce households and governments' final consumption in 49 world regions in 2017. We correct prices at the sector level and account for the energy embodied in the whole value chain, including capital goods. We find that high-income regions use more energy per unit of final consumption than low-income ones. This result contradicts the common belief that a higher GDP is correlated with a better efficiency and questions the feasibility of mainstream energy transition scenarios based on universal GDP growth.

### KEYWORDS

energy efficiency, input–output, capital, gross domestic product (GDP), purchasing power parity (PPP)

### 3.2.1. INTRODUCTION

International treaties on climate change aim to hold global average temperature to well below 2°C above pre-industrial levels (UNFCCC, 2015) while taking into account “the need to maintain strong and sustainable economic growth” (UNFCCC, 1992), eluding the possibility of these imperatives being contradictory. Meeting climate mitigation targets requires to limit global energy demand, as the deployment of decarbonization technologies alone is not sufficient to reduce emissions at an adequate rate (Gambhir et al., 2017). To allow continuous GDP (Gross Domestic Product) growth, scenarios thus rely on important energy intensity (energy use per unit of GDP) cuts. For the next decade, a yearly decrease of primary energy intensity from 2.4 to 6.8% is assumed (Gambhir et al., 2017), breaking from historical trends of 1.5% for the 1990-2017 time period (Ahmad et al., 2020). Not only does this hypothesis raise feasibility queries (Brockway et al., 2021; Semieniuk et al., 2021), but it also threatens some low-income regions to lack the energy required to maintain decent living standards (Semieniuk et al., 2021;

Hickel and Slamersak, 2022). In a context where resources of the global South are drained by the global North (Hickel, Dorninger, et al., 2022) and environmental impacts are displaced through trade (Wood, Stadler, et al., 2018), understanding precisely current differences in energy intensities is essential to assess the risks associated with scenarios.

Energy allows the production and exchange of services or goods. Its consumption increases together with income, which in turns provides wellbeing (Kalt et al., 2019), within certain limits (Easterlin, 1974). Although the emergence of ecological economics can be traced back to the 1970's (Georgescu-Roegen, 1971; Cleveland, 1987), most studies fail to consider energy as a central factor of production (Wiedenhofer et al., 2020). For example, most research on the energy-GDP interrelationship still do not account for energy embodied in trade (Wiedenhofer et al., 2020; Haberl et al., 2020). Many focus on the causality between both factors (Wiedenhofer et al., 2020) while some advocate that economic value will be decoupled from energy consumption. An edifying example is a study assuming the existence of a Kuznet's curve between energy and GDP—an inverted U-shaped curve implying that total energy use tends to zero in an infinite economy—and predicting a peak of energy demand at US\$107,000 per capita (Bogmans et al., 2020). Yet, to analyse energy intensities, it is essential to see energy neither as a cause or consequence of GDP, nor as an indicator independent of GDP, but as a provider of energy services (Fell, 2017) which are subsequently estimated through the GDP prism. Energy intensity must therefore be understood as the ratio of all the energy necessary to produce a good or service divided by its associated value. This approach makes it necessary to study sector-level energy intensities as a function of affluence, to better pinpoint how different consumption patterns lead to unequal energy use (Galvin et al., 2018; Shove et al., 2014; Chen, X.D. Wu, et al., 2019).

So far, only three studies (Chen and X.F. Wu, 2017; Yannick Oswald et al., 2020; Vita et al., 2021) have carried out multi-sectoral and multi-regional comparisons of footprint energy intensities of goods and services. Yannick Oswald et al., 2020 have calculated sectoral final energy intensities and concluded that higher-income individuals tend to buy goods that are more energy intensive. Vita et al., 2021 have established that energy footprints were mostly driven by durables (goods that are not purchased frequently). Chen and X.F. Wu, 2017 have calculated energy intensities in 26 sectors of 186 regions and showed that intensities vary greatly between sectors. All three analyses account for the energy embodied in intermediate consumption but do not consider the capital goods used in the production process. If the footprint of a strawberry pie is thereby calculated, the energy embodied in the flour and in the strawberries will be accounted for, but not that necessary for the production of the bakery. It is significant because capital goods have a key role in footprint reallocation (Xudong Wu et al., 2021), representing up to two-thirds of the carbon footprint of specific sectors (C.-J. H. Södersten et al., 2018). Furthermore, as factories producing goods bought abroad are not accounted for, the footprints of regions that have delocalized their production are underestimated. Another limit to these studies is that they rely on country-level Purchasing Power Parity (PPP) (Yannick Oswald et al., 2020; Vita et al., 2021) to eliminate national price level differences but not on sector-level PPP, hindering precise comparisons between product categories as different sectors in a given country have different PPPs (World Bank, 2020b). For example, the PPP of the clothing sec-

tor in China is 77% above that of the Chinese average PPP, which in turn is 80% above that of the health sector (World Bank, 2020b). Using the GDP-level PPP for China would thus underestimate the energy intensity of the clothing sector and overestimate that of the health sector. Finally, neither study reports the variations of energy intensity per category of product as a function of affluence (hereby defined as GDP per capita). This hampers to quantify the relationship between regional GDP and regional energy-intensity.

This study aims to calculate footprint energy intensities of households and governments' final consumption over 12 sectors in 49 world regions and compare them to affluence. To do so, we combine price level indexes with a Multi-Regional Input-Output (MRIO) database in which we endogenize capital.

### 3.2.2. MATERIALS AND METHODS

We calculate energy intensities according to three different definitions: Production-Based Account (PBA), Consumption-Based Account (CBA) and final consumption account. We focus on final energy as it is closer to useful energy than primary energy (Haberl et al., 2020; Mastrucci et al., 2020). In the following, “energy” will thus refer to “final energy”.

The pba energy intensity is the ratio of the energy used in a region by the households ( $E_{hh}$ ) and by the local industries, ( $E_{pba}$ ) divided by the GDP ( $Y$ ) of that region calculated in \$PPP:

$$I_{pba} = \frac{E_{hh} + E_{pba}}{Y} \quad (3.13)$$

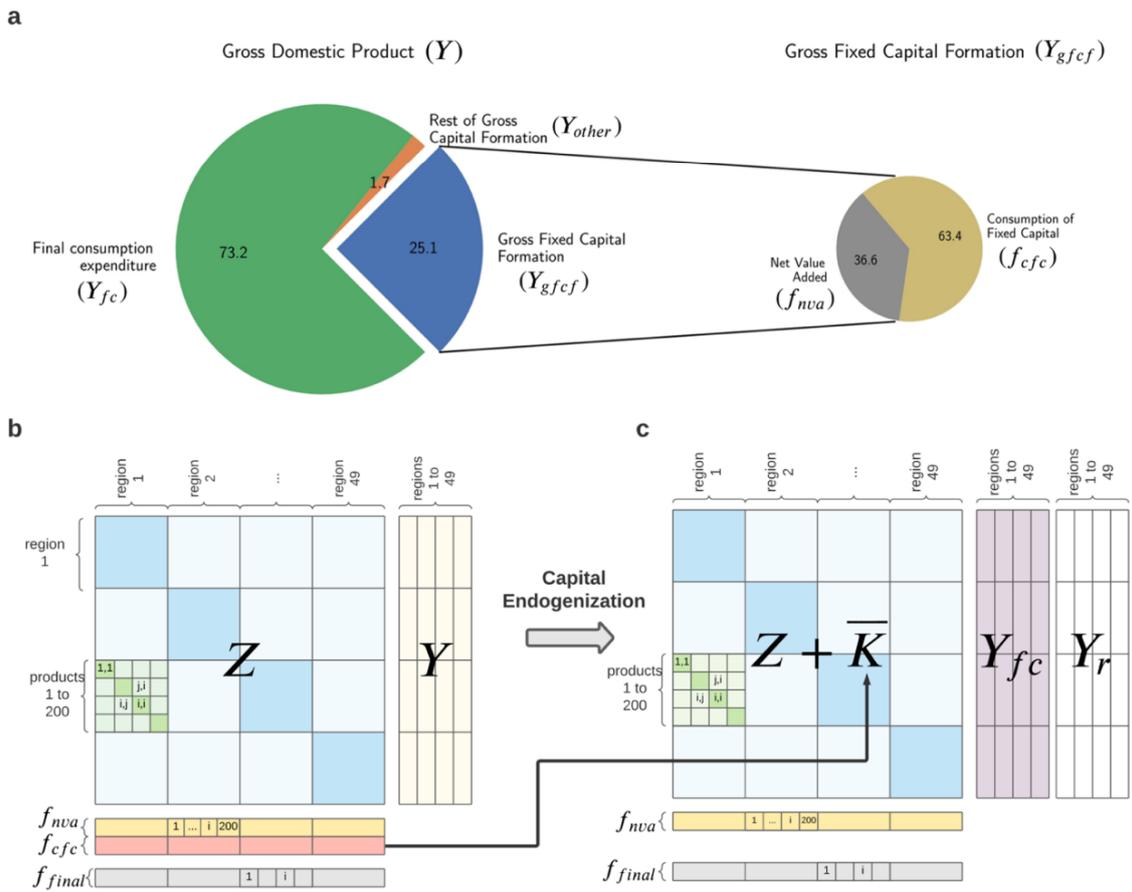
The cba energy use ( $E_{cba}$ ) (Miller et al., 2009; Owen et al., 2017) is defined as the global energy used by industries to produce the GDP of a given region. The cba energy intensity ( $I_{cba}$ ) is a better indicator of efficiency than ( $I_{pba}$ ) as it accounts for the offshored energy use:

$$I_{cba} = \frac{E_{hh} + E_{cba}}{Y} \quad (3.14)$$

However, two limits are associated with  $I_{cba}$ 's calculation convention. First, in the classic input-output formalism, the energy used to produce capital goods is not imputed to the footprint of final consumption but to the gross fixed capital formation (GFCF), a measure of investment (Fig. 3.11 a). If a factory is built in China to produce goods bought in the United States, the embodied energy of the factory is allocated to China's investments and not to the United-Sates. It follows that the energy necessary to produce the factory is omitted in the US footprint of final consumption expenditures. Second,  $E_{hh}$  is included in the calculation process of  $I_{cba}$ . However,  $E_{hh}$  is not in the input-output value chain and may have a different dynamic than  $E_{cba}$ .

To overcome these limits, we define the final consumption energy intensity ( $I_{fc}^K$ ) as the ratio of the energy footprint of final consumption with capital endogenized ( $E_{fc}^K$ )—without accounting for  $E_{hh}$ — and the final consumption expenditures corrected for PPP ( $Y_{fc}$ ):

$$I_{fc}^K = \frac{E_{fc}^K}{Y_{fc}} \quad (3.15)$$



**FIGURE 3.11:** Input–output framework. (a) GDP and GFCF decomposition. (b) Input–output framework.  $Z$  is the transaction matrix,  $Y$  is the final demand matrix,  $f_{nva}$  is the net value-added vector,  $f_{cfc}$  is the CFC vector and  $f_{final}$  is the final energy extension. (c) Input–output with capital endogenized. The CFC ( $f_{cfc}$ ) is transformed into matrix  $\bar{K}$  and added to matrix  $Z$ .  $Y_{fc}$  is the final consumption by households and governments, and  $Y_r$  is the residual final demand.

The superscript K means that capital is endogenized. Capital endogenization consists in adding the consumption of fixed capital (CFC)–investments to replace end-of-life capital goods–to the input-output framework (Fig.3.11 b,c), thereby allocating the energy necessary to produce infrastructures to final consumption.

As a case example, results for these three types of energy intensities are compared for the two regions with extreme levels of affluence in EXIOBASE (Luxembourg and “Rest of Africa”, defined as the African continent without South Africa and Egypt). The choice to include or exclude  $E_{hh}$  in the calculation is then discussed based on regressions of  $E_{hh}$  per capita as a function of affluence and the share of  $E_{hh}$  in  $I_{cba}$  as a function of affluence.

As a case example, results for these three types of energy intensities are compared for the two regions with extreme levels of affluence in EXIOBASE (Luxembourg and “Rest of Africa”, defined as the African continent without South Africa and Egypt). The choice to include or exclude  $E_{hh}$  in the calculation is then discussed based on regressions of  $E_{hh}$  per capita as a function of affluence and the share of  $E_{hh}$  in  $I_{cba}$  as a function of affluence.

We then test the results for correlations between energy intensities and affluence at an aggregated level (GDP level for  $I_{pba}$  and aggregated final consumption for  $I_{fc}^K$ ). If there is a correlation, it can be explained either by a sector-level energy intensity and affluence correlation or by a change in final consumption composition with affluence. We evaluate how much each of the 12 sectors studied contribute to the change in energy intensity by calculating elasticities. Finally, we combine the dynamics of  $E_{hh}$  and  $I_{fc}^K$  as a function of affluence to estimate how much energy is associated with 1% of economic growth in each of the 49 regions.

### 3.2.2.1. INPUT-OUTPUT

Input-output modelling allows to calculate the total industrial output ( $x$ ) necessary to produce final demand  $Y$ .  $Z$  is the transaction matrix, representing the inter-industry transactions between sectors and regions (for a detailed explanation of how  $Z$  is compiled, see Miller et al., 2009 and supplementary information of Stadler et al., 2018).  $Z$  can be subdivided into 49\*49 submatrices of dimensions 200\*200 representing the flows of intermediate products between each pair of regions (Fig. 3.11 b).  $Y$  contains vectors of final demand for each region. This final demand is disaggregated by sector and region of origin. The sum of a row of  $Z$  and  $Y$  gives the total output for a given sector in a given region.  $x$  thus writes:

$$x = Ze + Ye \quad (3.16)$$

with  $e$  a summation vector of appropriate dimension. The direct requirement matrix  $A$  is defined as:

$$A = Z\hat{x}^{-1} \quad (3.17)$$

with  $\hat{x}^{-1}$  meaning that the vector is diagonalized. We therefore have:

$$x = Ax + Ye \quad (3.18)$$

The Leontief inverse ( $L$ ) is the inverse of matrix ( $I - A$ ), obtained when solving for  $x$ :

$$x = LYe \quad (3.19)$$

The production-based factors of production are given by matrix  $F$ . A row of  $F$ , called an extension, represents a given environmental or social impact associated with production. EXIOBASE3 provides several types of energy extensions. We build a final energy extension ( $f_{\text{final}}$ ) by subtracting the extension "Energy Carrier Net LOSS" to the extension "Energy Carrier Net Total". For a discussion of the implications of different energy extension choices, see Owen et al., 2017. The regional aggregation of  $f_{\text{final}}$  gives us  $E_{\text{pba}}$ .

The associated coefficients of production are given by:

$$s_{\text{final}} = f_{\text{final}} \hat{x}^{-1} \quad (3.20)$$

To obtain a region's consumption-based energy use ( $E_{(\text{cba}, \text{region})}$ ), we trace the total output associated to that region's GDP ( $Y_{\text{region}}$ ) and multiply it by the coefficients of production. From the last two equations:

$$E_{(\text{cba}, \text{region})} = s_{\text{final}} LY_{\text{region}} e \quad (3.21)$$

### 3.2.2.2. CAPITAL ENDOGENIZATION

$E_{\text{fc}}^{\text{K}}$  must be calculated using an input-output table with capital endogenized. Capital endogenization consists in allocating a share of the production of capital goods to final consumption expenditures. This share must be representative of how much capital goods are depreciated a given year due to the production of intermediate consumption. To do so, we choose to endogenize the consumption of fixed capital (CFC), defined as the decline in value of the capital stock due to normal wear and tear and obsolescence or normal accident damage (Glossary, 2022).

C.-J. Södersten et al., 2020 built a capital transaction matrix  $\bar{K}_{15}$  with the same dimensions as  $Z$ , from the vector  $f_{\text{cfc}}$  of year 2015 (C.-J. Södersten, 2020). Once added to  $Z$ , this matrix allows to consider CFC not as a sub-share of  $Y_{\text{gfcf}}$  (Fig. 3.11) but as intermediate consumption. A column total of  $\bar{K}_{15}$  equals  $\text{CFC}_{15}$ . To nowcast  $\bar{K}_{15}$  to 2017 using  $\text{CFC}_{17}$ , we transform it into a matrix of coefficients  $\bar{K}'_{15}$  with:

$$\bar{k}'_{i,j,15} = \frac{\bar{k}_{i,j,15}}{\sum_i \bar{k}_{i,j,15}} \quad (3.22)$$

where  $i$  is a row index and  $j$  a column index.  $\bar{K}_{15}$  is obtained by multiplying  $\bar{K}'_{15}$  by the  $f_{\text{cfc}}$  vector of year 2017 ( $f_{(\text{cfc}, 17)}$ ). EXIOBASE provides this extension. However, as pointed out by C.-J. Södersten et al., 2020, inconsistencies exist between EXIOBASE and World Bank data for the ratio  $f_{\text{cfc}}/Y_{\text{gfcf}}$ . The World Bank gives an aggregate value per region of CFC ( $\text{cfc}^{\text{WB}}$ ) and GFCF ( $\text{gfcf}^{\text{WB}}$ ) which is deemed more reliable than EXIOBASE data (C.-J. Södersten et al., 2020). We therefore scale up  $f_{(\text{cfc}, 17)}$  by a scalar  $\beta$  for every region so that:

$$\frac{\sum_{\text{products}} Y_{\text{gfc, region}}}{\beta_{\text{region}} \sum_{\text{products}} f_{\text{cfc, region}}} = \frac{\text{gfc}_{\text{region}}^{\text{WB}}}{\text{cfc}_{\text{region}}^{\text{WB}}} \quad (3.23)$$

We thus obtain  $\bar{K}_{17}$  is the from coefficients  $\bar{k}_{17,i,j}$ :

$$\bar{k}_{17,i,j} = \bar{k}'_{15,i,j} \beta_j f_{\text{cfc},17,j} \quad (3.24)$$

The mean of  $\beta$  values obtained is 0.99 but regional values range from 0.31 to 2.2, confirming the inconsistencies between both sources.  $\bar{K}$  is added to  $Z$  to have a total transaction matrix with capital endogenized. The direct requirement matrix with capital endogenized ( $A^K$ ) is thus:

$$A^K = (Z + \bar{K} \hat{x}^{-1}) \quad (3.25)$$

And the Leontief inverse with capital endogenized becomes:

$$L^K = (I - A^K)^{-1} \quad (3.26)$$

The total energy necessary to produce final consumption in a given region is thus:

$$E_{\text{fc}}^K = s_{\text{final}} L^K Y_{\text{fc}} \quad (3.27)$$

### 3.2.2.3. PURCHASING POWER PARITIES

Energy intensities are calculated using  $E_{\text{pba}}$ ,  $E_{\text{cba}}$ ,  $E_{\text{fc}}^K$  and economic data corrected for purchasing power parity. As  $I_{\text{pba}}$  and  $I_{\text{cba}}$  are calculated at an aggregated regional-level and not at the sector level, we directly use GDP data from World Bank, 2020b. For the EXIOBASE rest of the world regions, country-level data is aggregated using the python module `country_converter` (Stadler, 2017).

However,  $I_{\text{fc}}^K$  is calculated at the sector level. We aggregate the 200 EXIOBASE products into the 12 sectors of the Classification of Individual Consumption According to Purpose (COICOP) as they are the ones used by the ICP. To do so, we modified the table of concordance built in Castellani et al., 2019 in order to include all 200 EXIOBASE products. As differences exist between data in current dollars from EXIOBASE and ICP, we do not directly use ICP data in constant dollars but apply ICP price index to the EXIOBASE data. This prevents outliers to appear due to different sector allocations between EXIOBASE and ICP.

### 3.2.2.4. ELASTICITIES

Elasticity is defined as the percentage change of a variable due to a percentage change of another variable. It can be calculated as the slope of a log-log regression, see Yannick Oswald et al., 2020 for proof. We consider an elasticity only if the coefficient of regression is higher than 0.2. In this section we give the equations used to calculate the contribution of each of the 12 sectors studied to the change in  $I_{\text{fc}}^K$ , both due to the change of  $I_{\text{sect}}^K$  ( $I_{\text{fc}}^K$  for a given sector) and to the change of this sector's share in final consumption expenditures ( $\theta_{\text{sect}}$ ).

Let  $\epsilon_{\text{sect}}^I$  be the elasticity of  $I_{\text{sect}}^K$  as a function of affluence. It is obtained by the following regression, with a constant:

$$\log(I_{\text{sect}}^K) = \epsilon_{\text{sect}}^I \log\left(\frac{Y}{\text{pop}}\right) + a \quad (3.28)$$

A variation of  $I_{\text{sect}}^K$  implies a variation of  $I_{\text{fc}}^K$ . We define  $\eta_{\text{sect}}^I$  as the percentage change of  $I_{\text{fc}}^K$  resulting from the variation of  $I_{\text{sect}}^K$  due to an increase of 1% of affluence. By definition of  $\epsilon_{\text{sect}}^I$  and  $\theta_{\text{sect}}$ :

$$\eta_{\text{sect}}^I = \frac{\epsilon_{\text{sect}}^I I_{\text{sect}}^K \theta_{\text{sect}}}{I_{\text{fc}}^K} \quad (3.29)$$

Let  $\epsilon_{\text{sect}}^\theta$  be the elasticity of  $\theta_{\text{sect}}$  as a function of affluence. It is obtained by the following regression, with b constant:

$$\log(\theta_{\text{sect}}) = \epsilon_{\text{sect}}^\theta \log\left(\frac{Y}{\text{pop}}\right) + b \quad (3.30)$$

A variation of  $\theta_{\text{sect}}$  also implies a variation of  $I_{\text{fc}}^K$ . We define  $\eta_{\text{sect}}^\theta$  as the percentage change of  $I_{\text{fc}}^K$  resulting from the variation of  $\theta_{\text{sect}}$  due to an increase of 1% of affluence. By definition of  $\epsilon_{\text{sect}}^\theta$  and  $\theta_{\text{sect}}$ :

$$\eta_{\text{sect}}^\theta = \frac{\epsilon_{\text{sect}}^\theta \theta_{\text{sect}} (I_{\text{sect}}^K - I_{\text{fc}}^K)}{I_{\text{fc}}^K} \quad (3.31)$$

Changes in  $I_{\text{sect}}^K$  for the 12 ICP sectors could be explained by changes of consumption patters in sub-sectors or changes in energy intensities in sub-sectors. To find out is such is the case, we apply the consumer price indexes to the 255 sub-sectors of the ICP sectors (some of the 200 EX-IOWBASE sectors are disaggregated between several ICP sectors). We then look for correlations between sub sectors' share of expenditures and energy intensities as a function of GDP.

### 3.2.2.5. ENERGY ASSOCIATED WITH ECONOMIC GROWTH

Energy per capita ( $E_{\text{cap}}$ ) is obtained by combining the regressions of  $E_{\text{hh}}$  and  $I_{\text{fc}}^K$  as a function of affluence multiplied by final consumption expenditures per capita:

$$E_{\text{cap}} = \exp\left(a \log\frac{Y}{\text{pop}} + b\right) + \frac{Y_{\text{fc}}}{\text{pop}} \left(c \frac{Y}{\text{pop}} + d\right) \quad (3.32)$$

With  $a$ ,  $b$ ,  $c$  and  $d$ , the coefficients obtained from the regressions. To calculate the impact of economic growth, we modify the intercepts of the regressions of the previous equation for each region. Otherwise, the results would not account for the dispersion of the data around the regression line. For each given region, we define  $b'$  and  $d'$  the modified intercepts of the regressions of  $E_{\text{hh}}$  and  $I_{\text{fc}}^K$  so that the lines with slopes  $a$  and  $c$  pass by that region's data point. Solving for the increase of  $E_{\text{cap}}$  due to 1% increase of  $Y$  and  $Y_{\text{fc}}$  gives:

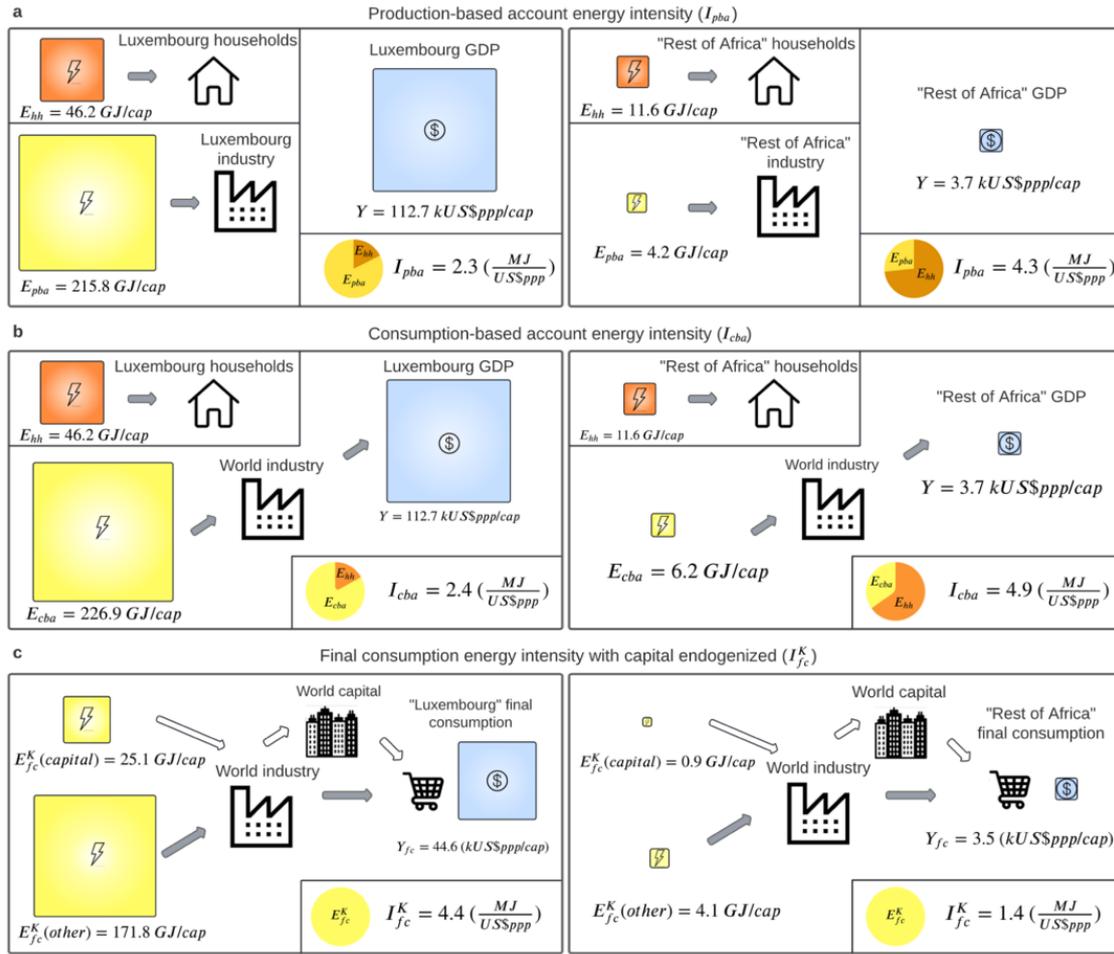
$$\Delta E_{\text{cap}} = (1.01^a - 1)e^{b'} \left( \frac{Y}{\text{pop}} \right)^a + 0.01 \frac{Y_{\text{fc}}}{\text{pop}} \left( 2.01c \frac{Y}{\text{pop}} + d' \right) \quad (3.33)$$

### 3.2.2.6. DATA

Our calculations are based on EXIOBASE v3.8.2 (Stadler et al., 2018), an open-access MRIO database which represents the world economy divided between 200 products in 44 countries and 5 rest of the world regions. It contains many environmental extensions, including primary energy and energy loss, which allows to calculate a final energy environmental extension. As of this version, the energy data for year 2017 is a nowcast based on 2015 International Energy Agency (IEA) world energy balances (IEA, 2022). The trade and macroeconomic data for year 2017 has been estimated by EXIOBASE authors based on the original EXIOBASE3 data series for year 2011 and United Nations macroeconomic data for year 2017 (Stadler et al., 2018). The data for capital endogenization is based on matrixes built by Södersten and colleagues (C.-J. H. Södersten et al., 2018) for year 2015 and was nowcasted to year 2017 using World Bank data (World Bank, 2022). The sectoral PPPs come from the International Comparison Panel (ICP) 2017 cycle (World Bank, 2020c).

### 3.2.2.7. LIMITATIONS

The main limitations to this study are those inherent to input-output calculation (Rodrigues et al., 2018). We chose EXIOBASE3 for this study in order to endogenize capital using existing matrixes. Existing input-output databases have been extensively compared and differ in their methodology, thus yielding differences in the results (Owen, 2017). However, these differences are limited—1-3% of difference for most regions and up to 20% for outlier countries—when comparing carbon emission accounts for the same base year (Wood, Moran, et al., 2019). Uncertainties are also associated with the year of reference of our data. ICP data is compiled for year 2017 but EXIOBASE tables were compiled for year 2011 and updated using macro-economic data for year 2017. The reference year for the inter-industry capital requirement matrix is 2015 (C.-J. Södersten, 2020) and we updated it using World Bank and EXIOBASE data for year 2017. Important differences existed between EXIOBASE and World Bank CFC data ( $\beta$  values). Energy data is a now-cast from 2015 IEA data (IEA, 2022). Uncertainties are also associated with sector aggregation in input-output (Steen-Olsen et al., 2014; Koning et al., 2015). However, we aggregate sectors only after calculating the footprint so matrix  $L$  is not impacted. Uncertainties do exist due to the conversion of EXIOBASE sectors to COICOP sectors as it is not possible to have an exact correspondence.



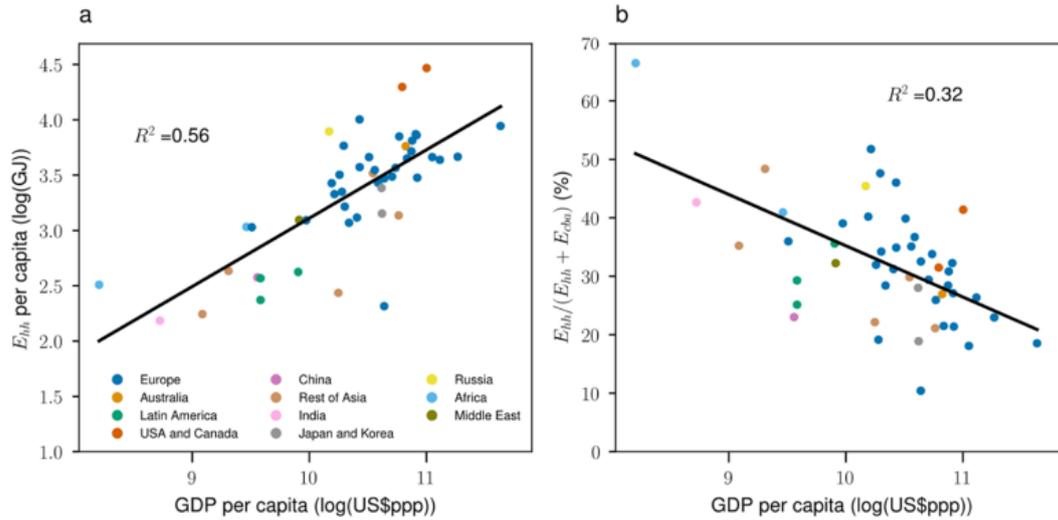
**FIGURE 3.12:** Energy intensity scopes. (a) Production-based energy intensity ( $I_{pba}$ ). (b) Consumption-based energy intensity ( $I_{cba}$ ). (c) Final consumption energy intensity with capital endogenized ( $I_{fc}^K$ ). (a-c), Comparisons between richest and poorest EXIOBASE regions. "Rest of Africa" is the African continent less South Africa and Egypt. Open access pictograms from svgrepo.com.

### 3.2.3. RESULTS AND DISCUSSION

#### 3.2.3.1. CHOOSING THE RIGHT INDICATOR

Differences in energy intensities calculation methods are illustrated in Figure 3.12 for the two EXIOBASE regions with extreme levels of affluence: Luxembourg and "Rest of Africa" (Africa excluding Egypt and South Africa).  $I_{pba}$  (Fig. 3.12 a),  $I_{cba}$  (Fig. 3.12 b) and  $I_{fc}^K$  (Fig. 3.12 c) have respective values of 2.3, 2.4 and 4.4 MJ/US\$ppp in Luxembourg and 4.3, 4.9 and 1.4 MJ/US\$ppp in "Rest of Africa". For these regions, the consumption-based and production-based approaches yield similar results, with the energy intensity of "Rest of Africa" being twice higher than that of Luxembourg. However,  $I_{fc}^K$  is two times higher than  $I_{cba}$  in Luxembourg and three times lower than  $I_{cba}$  in "Rest of Africa". This difference is mostly due to  $E_{hh}$  which is accounted for in  $I_{cba}$  but not in  $I_{fc}^K$ —another difference being the share of final consumption in GDP—.  $E_{hh}$  represents 65% of  $I_{cba}$  in "Rest of Africa" but only 17% in Luxembourg, although  $E_{hh}$  per capita is four times lower in "Rest of Africa" than in Luxembourg.

This finding can be generalized to all EXIOBASE regions. Even though  $E_{hh}$  increases with



**FIGURE 3.13:** Households direct energy use ( $E_{hh}$ ). (a) Households direct energy use per capita ( $E_{hh}$  per capita). (b) Share of households' direct energy use in consumption-based footprint ( $E_{hh}/(E_{hh} + E_{cba})$ ). (a-b) Richer regions have higher per capita  $E_{hh}$  but the share of  $E_{hh}$  in the footprint decreases with affluence.

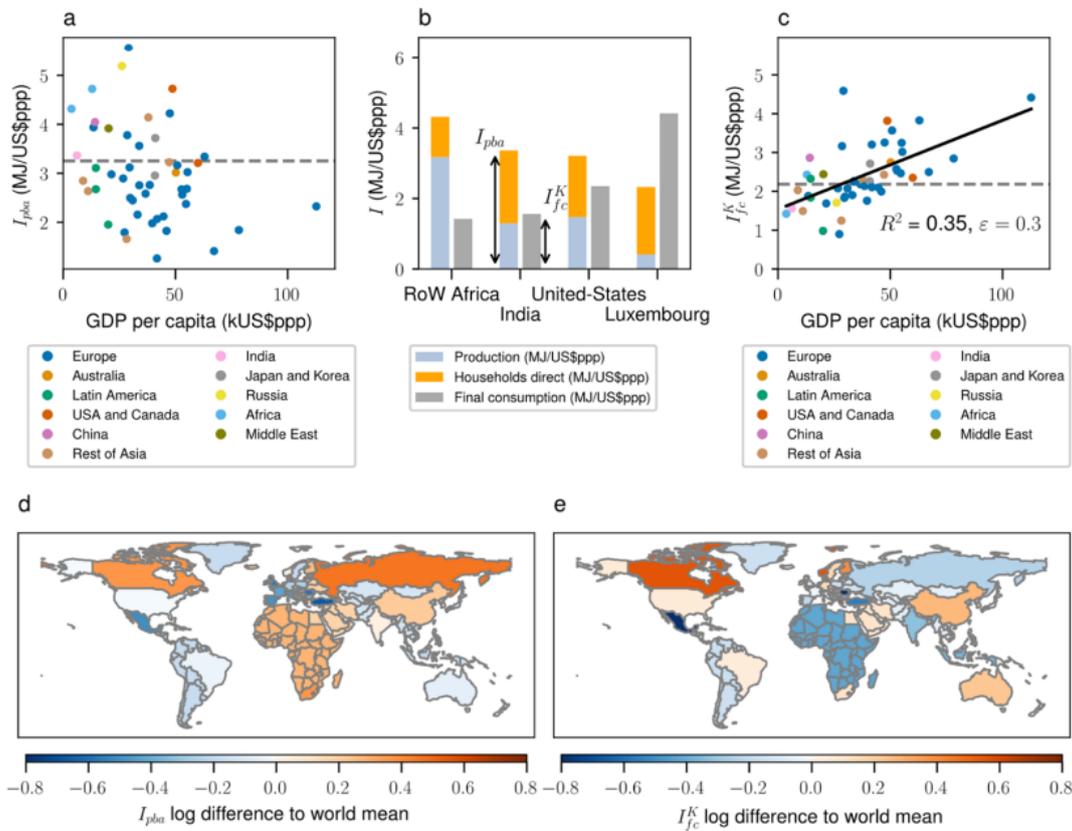
affluence (Fig. 3.13 a), its share in the total footprint of regions decreases with affluence (Fig. 3.13 b). This change is due to the fact that even at very low levels of affluence (thus very low levels of final consumption energy footprint), direct energy is still used by individuals for survival or every day needs.

We argue that  $E_{hh}$  must be calculated separately from the energy intensity of GDP because it has a different dynamic. Oswald and colleagues (Yannick Oswald et al., 2020) also found that “Heat and electricity”, the direct energy sector with the highest energy intensity, behaved fundamentally differently from others. Including  $E_{hh}$  in energy intensity calculation biases the results by inflating the energy intensity of poor regions more than that of wealthy ones. Energy intensities should therefore be analysed using  $I_{fc}^K$  and not  $I_{cba}$ . Using  $I_{cba}$  instead of  $I_{fc}^K$  could lead to major misinterpretations, such as concluding that Luxembourg is two times more efficient than “Rest of Africa” (Fig. 3.12 b) whereas it is actually 3 times less efficient (Fig. 3.12 c).

### 3.2.3.2. INTERNATIONAL ENERGY INTENSITY DISPARITIES

Regional values of  $I_{pba}$  are scattered but no trend is observed as a function of affluence ( $R^2 < 0.2$ ) (Figure 3.14 a, d). In contrast,  $I_{fc}^K$  is higher in wealthier regions, with an elasticity of 0.27 ( $I_{fc}^K$  increases by 0.27% for every 1% increase of affluence) (Figure 3.14 c, e).  $I_{pba}$  and  $I_{fc}^K$  are disaggregated for regions with extreme levels of affluence on Figure 3.14 b.  $I_{pba}$  is made of household direct energy use (in orange) and domestic production energy (in blue), whereas  $I_{fc}^K$  is only made of the footprint of final consumption (in gray).

Our results show that when calculating the energy intensity with capital endogenized, the energy intensity is higher in richer regions, while Oswald and colleagues (Yannick Oswald et al., 2020) found that it decreases slightly in richer regions. Three factors explain these differences: we consider the footprint of capital goods and of government final consumption expenditures, we do not consider households direct energy use, and we study year 2017 and not 2011. Our



**FIGURE 3.14:** Energy intensity disparities. (a) Production-based account energy intensity ( $I_{pba}$ ) as a function of affluence. The dashed gray line represents the world value. Regional data (scattered dots) do not fit affluence ( $R^2 < 0.2$ ). (b) Energy intensity examples ( $I_{pba}$  and  $I_{fc}^K$ ). (c) Final consumption energy intensity with capital endogenized ( $I_{fc}^K$ ) as a function of affluence. The dashed gray line represents the world value and the black line the linear fit. An elasticity ( $\epsilon$ ) of 0.27 is calculated. (d) Log difference of  $I_{pba}$  to the world mean. (e) Log difference of  $I_{fc}^K$  to the world mean. 20 of the 49 regions switch colors between the two maps.

|  | World value | $I_{\text{sect}}^{\text{K}}$<br>$R^2$ | $\epsilon_{\text{sect}}^{\text{I}}$ | $\eta_{\text{sect}}^{\text{I}}$ | World value | $\theta_{\text{sect}}$<br>$R^2$ | $\epsilon_{\text{sect}}^{\text{I}}$ | $\eta_{\text{sect}}^{\text{I}}$ |
|--|-------------|---------------------------------------|-------------------------------------|---------------------------------|-------------|---------------------------------|-------------------------------------|---------------------------------|
| CPI: 01 - Food and non-Alcoholic beverages                                   | 4           | 0.02                                  | 0.14                                | 0.02                            | 0.07        | 0.02                            | -0.16                               | -0.01                           |
| CPI: 02 - Alcoholic beverages, tobacco and narcotics                         | 6.4         | 0.05                                  | -0.15                               | 0                               | 0.01        | 0.01                            | -0.19                               | 0                               |
| CPI: 03 - Clothing and footwear  | 5.2         | 0.08                                  | 0.19                                | 0.01                            | 0.02        | 0                               | -0.19                               | -0.01                           |
| CPI: 04 - Housing, water, electricity, gas and other fuels                   | 1.8         | 0.46                                  | 0.48                                | 0.08                            | 0.19        | 0.17                            | -0.17                               | 0.01                            |
| CPI: 05 - Furnishings, household equipment and routine household maintenance | 4.6         | 0.18                                  | 0.17                                | 0.01                            | 0.02        | 0.04                            | -0.01                               | 0                               |
| CPI: 06 - Health   | 1.5         | 0.25                                  | 0.3                                 | 0.02                            | 0.07        | 0.07                            | 0.15                                | 0                               |
| CPI: 07 - Transport  | 4.6         | 0.02                                  | 0.27                                | 0.04                            | 0.07        | 0.36                            | 0.34                                | 0.02                            |
| CPI: 08 - Communication  | 1.4         | 0.01                                  | -0.02                               | 0                               | 0.04        | 0.08                            | 0.41                                | -0.01                           |
| CPI: 09 - Recreation and culture   | 3.1         | 0.04                                  | 0.09                                | 0.01                            | 0.06        | 0.01                            | 0.1                                 | 0                               |
| CPI: 10 - Education  | 0.7         | 0.26                                  | 0.47                                | 0.02                            | 0.15        | 0.11                            | -0.12                               | 0.01                            |
| CPI: 11 - Restaurants and hotels   | 1.3         | 0.02                                  | 0.15                                | 0.01                            | 0.06        | 0                               | -0.53                               | 0.01                            |
| CPI: 12 - Miscellaneous goods and services                                   | 2           | 0.04                                  | 0.15                                | 0.03                            | 0.25        | 0.04                            | 0.14                                | 0                               |

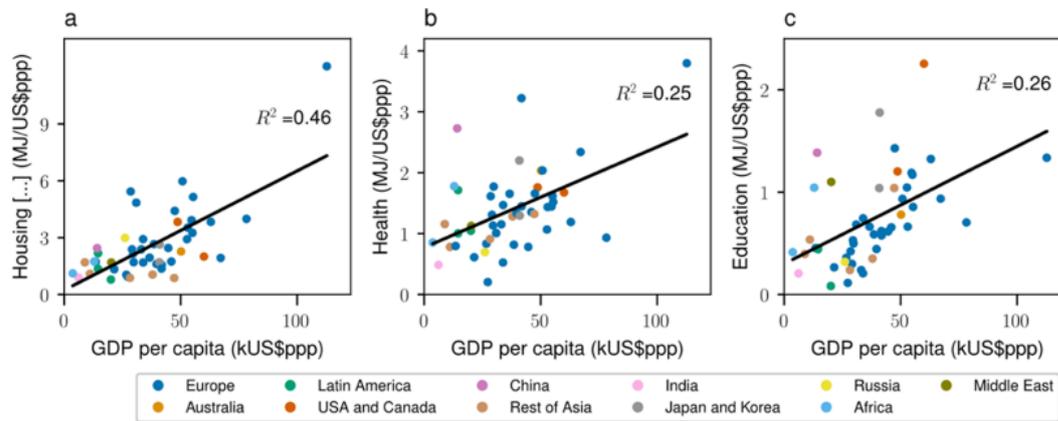
**TABLE 3.2:** Elasticities.  $R^2$  refers to the coefficient of regression of  $I_{\text{sect}}^{\text{K}}$  and  $\theta_{\text{sect}}$  as a function of affluence. The associated  $\epsilon$  and  $\eta$  are used in the paper only if  $R^2 > 0.2$  (colored lines).

results challenge the belief that richer regions are more efficient. One explanation is that economywide rebound effects can cut half of the gains from improved energy efficiency (Brockway et al., 2021). Another explanation could be that the energy efficiency gains in a region affects other regions in a globalized world economy. Indeed, if technologies are transferred, they can improve energy intensity of all regions at the same time and not only that of the wealthy ones. This is consistent with the fact that absolute decoupling of energy consumption and GDP (growth of GDP and degrowth of energy consumption) though experienced in a limited number of regions has been observed in regions with extremely low human development index and not only in high-income regions (Akizu-Gardoki et al., 2018). Vita et al., 2021 also found that over the period 1995–2011, energy efficiency was observed in 47 out of 49 studied regions with very different affluence levels.

### 3.2.3.3. SECTOR-LEVEL ENERGY INTENSITIES

The fact that  $I_{\text{fc}}^{\text{K}}$  scales with affluence can either be explained by increases of sector-level energy intensities  $I_{\text{sect}}^{\text{K}}$  with affluence or by a change of composition of final consumption across regions. Only the housing, education, and health sectors representing, respectively, 19, 15 and 7% of world final consumption show a correlation between  $I_{\text{sect}}^{\text{K}}$  and affluence ( $R^2 > 0.2$ ) (Table 3.2, Figure 3.15). Their elasticities,  $\epsilon_{\text{sect}}^{\text{I}}$ , defined as the percentage change of  $I_{\text{fc}}^{\text{K}}$  due to a change of  $I_{\text{sect}}^{\text{K}}$  resulting from an increase of affluence by 1%, are 0.08, 0.02, and 0.02%. The increase in the energy intensity of these three sectors thus explains 45% of the total elasticity of  $I_{\text{fc}}^{\text{K}}$ , equal to 0.27% (Figure 3.14 c).

The transport sector's share in the final consumption ( $\theta_{\text{transport}}$ ) is the only one correlated with affluence ( $R^2 > 0.2$ ) (Extended Data Table 3.2, Figure 3.16). For each 1% increase of affluence,  $\theta_{\text{transport}}$  increases by 0.34%. As the energy intensity of the transport sector is higher than that of the world mean (Table 3.2, Figure 3.14 e), an increase in  $\theta_{\text{transport}}$  translates by an increase of  $I_{\text{fc}}^{\text{K}}$ . The increase of  $I_{\text{fc}}^{\text{K}}$  due to an increase of  $\theta_{\text{transport}}$  resulting from an increase of 1% of affluence is of 0.02%. This value represents 8% of the total elasticity of  $I_{\text{fc}}^{\text{K}}$ . The four dynamics above-mentioned are significant as they explain 53% of the total elasticity, the 20 other dynamics (Table 3.2) explaining the other 47% but with  $R^2$  under 0.2. Four sectors play a specific role in this energy intensity evolution. The first contribution comes from the transport



**FIGURE 3.15:** Sector-level energy intensities. (a) Housing, water, electricity, gas, and other fuel sectors. (b) Health sector. (c) Education sector. (a–c) The black lines represent linear fits. The nine other sectors are not displayed as we obtained  $R^2 < 0.2$ .

sector, whose share in final consumption expenditures increases with affluence. As the energy intensity of this sector is twice higher than that of total final consumption, a higher share of transport sector implies a higher energy intensity. The energy intensity elasticities of housing, education, and health sectors are positive, meaning that richer regions use more energy per dollar of final consumption. However, the contribution to the increase of  $I_{fc}^K$  due to the housing sector is 4 times higher than that of the education and health sectors.

These sectors can be further disaggregated into EXIOBASE subsectors. Out of 255 possible EXIOBASE subsectors, only 12 had their expenditure shares of the CPI sector total which fitted as a function of GDP with  $R^2 > 0.2$ . Among these, none represented more than 4% of a CPI sector's total expenditures. Moreover, 40 subsectors had their energy intensity which fitted as a function of GDP with  $R^2 > 0.2$ . Among these, only 7 represented more than 4% of a CPI sector's total expenditures, all fitting positively as a function of GDP. These included vegetables, fruit, nuts (14% of CPI 01), wearing apparel, furs (18% of CPI 03 total), real estate services (55% of CPI 04 total), public administration and defense services, compulsory social security services (15% of CPI 06 total), air transport services (7% of CPI 07 total), education services (65% of CPI 10 total), and retail trade services, except of motor vehicles and motorcycles and repair services of personal and household goods (15% of CPI 10 total).

### 3.2.3.4. TOTAL ENERGY FOOTPRINT

The total footprint energy per capita (Figure 3.17) is obtained by combining the regression of  $E_{hh}$  per capita (Figure 3.13 a) and the regression of  $I_{fc}^K$  (Figure 3.14 c), multiplied by final consumption per capita. The black line of Figure 3.17 is not linear because regions have a different share of final consumption in their GDP. Together, these two dynamics explain the differences in the total footprint per capita between regions with a  $R^2$  of 0.88 (Figure 3.17).

Economic growth is sometimes considered useful to reduce energy use as it could drive technological progress, thereby reducing overall energy use (Bogmans et al., 2020). However, the first consequence of economic growth is to produce more goods and services. We quantify the

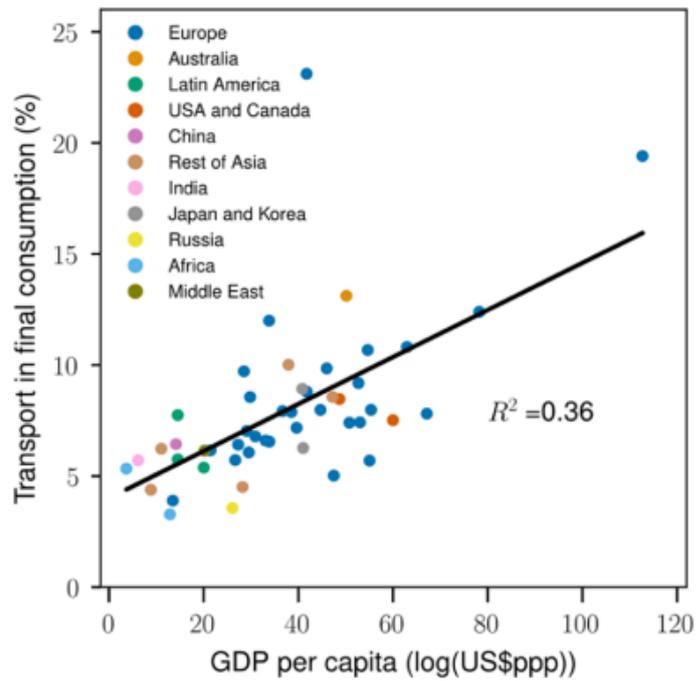


FIGURE 3.16: Share of transport sector in final consumption expenditures versus affluence. The black line represents the linear fit. The 11 other sectors are not displayed as we obtained  $R^2 < 0.2$ .

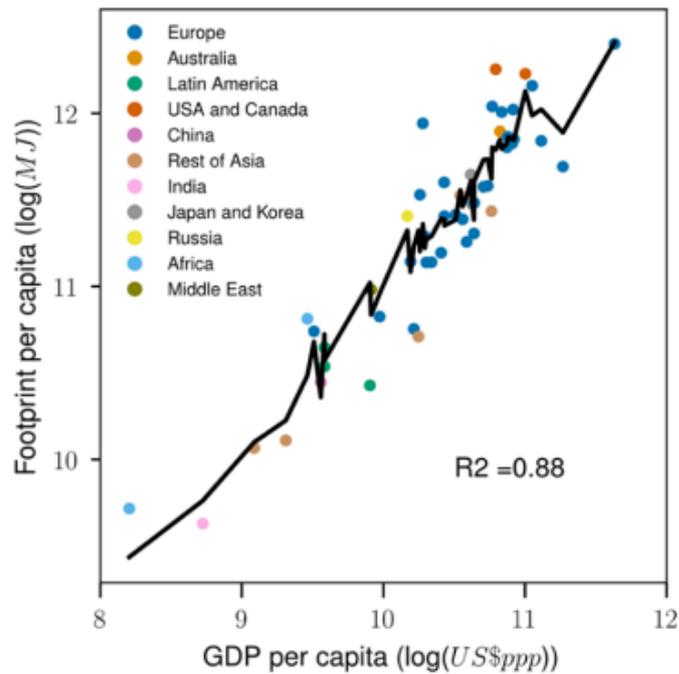
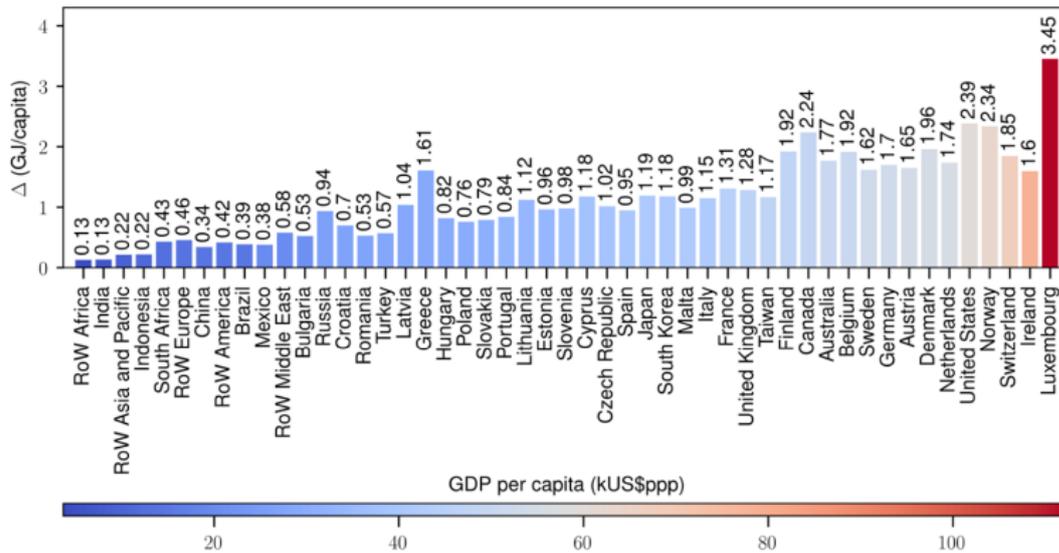


FIGURE 3.17: Total energy footprint per capita. Total energy footprint per capita scales with affluence ( $R^2 = 0.88$ ). The black line is obtained by summing  $E_{hh}$  per capita from the regression of Figure 3.14 a and  $E_{fc}^K$  from the regression of Figure 3.14 e multiplied by the final consumption expenditure per capita.



**FIGURE 3.18:** Energy per capita associated with 1% of economic growth. Bars represent the increase of energy footprint per capita if a region's GDP increases by 1% for year 2017, that is, without technological progress associated with time.

regional increase in energy footprint per capita due to 1% of economic growth for the year 2017, independently of technological progress (Figure 3.18). In 2017, 9.2% of global population still lived in extreme poverty (World Bank, 2020a). We show that the energy associated with 1% of economic growth is 27 times higher in the richest region studied than in the poorest, meaning that supplementary energy use would have much more impact if used for the Global South than for the Global North. This corroborates similar work on carbon emissions which has shown that eradicating world poverty would increase global carbon emissions by less than 2.1% (Bruckner et al., 2022) or that a recomposition of consumption could reduce by 16% overall emissions while allowing a rise in consumption for those earning the less (Millward-Hopkins et al., 2020). Equity in energy use would reduce poverty and shift energy use from luxury and transport to subsistence and necessities (Y. Oswald et al., 2021).

### 3.2.3.5. IMPLICATIONS FOR ENERGY TRANSITION SCENARIOS

Conceptually, the energy intensity of final consumption calculated by using sectoral PPPs and considering capital goods is the most interesting definition of energy intensity as it is the closest to the thermodynamic meaning of embodied energy. This indicator increases with GDP per capita, meaning that richer regions are less efficient than poorer ones. This contradicts the common belief that a higher GDP is correlated with a better efficiency and corroborates the existing research questioning the plausibility of a break in the historical energy intensity trend (Brockway et al., 2021; Semieniuk et al., 2021; Andrieu et al., 2022). Though the potential of improvement is still considerable (Nakićenović et al., 1996; Cullen et al., 2011), economy-wide rebound effects (Sorrell et al., 2008; Brockway et al., 2021), costly investments (Fowlie et al., 2018; Gillingham et al., 2018), and adaptation to climate change (Ruijven et al., 2019) may limit our ability to reduce energy intensity as fast as it is planned in reference scenarios

(Semieniuk et al., 2021).

We call for the authoritative scenario makers to stop speculating on energy intensity reduction and to produce prudential scenarios in which environmental and social targets are met, no matter the energy intensity. Mathematically, it means that some regions must be prepared to limit their economic growth. Energy scenarios must focus on sufficiency (Millward-Hopkins et al., 2020) in order to meet everyone's basic needs (Grubler et al., 2016; Rao et al., 2019), even if this implies limiting the luxury consumption of a rich minority (Yannick Oswald et al., 2020). The choice of the regions whose economic growth must be limited should take place in the context of common but differentiated responsibilities to tackle climate change (UNFCCC, 1992) and within a specific framework of energy justice (Sovacool et al., 2016). A solution could be to achieve absolute convergence between Global South and Global North energy use per capita (Hickel, Dorninger, et al., 2022). We go even further and argue that the Global South must temporarily have more access to energy per capita to build the infrastructure already built in the Global North (Olivier Vidal et al., 2021). If there is a break in the historical data due to breakthrough technologies, then growth in every region could become an option again but climate action would not have been jeopardized by exogenously fixed economic growth.

### 3.3. REFERENCES

- Ahmad, Tanveer and Dongdong Zhang (2020). “A critical review of comparative global historical energy consumption and future demand: The story told so far”. en. In: *Energy Reports* 6, pp. 1973–1991. ISSN: 2352-4847. DOI: 10.1016/j.egyr.2020.07.020. URL: <https://www.sciencedirect.com/science/article/pii/S2352484720312385> (visited on 02/24/2022).
- Akizu-Gardoki, Ortzi, Gorka Bueno, Thomas Wiedmann, Jose Manuel Lopez-Guede, Iñaki Arto, Patxi Hernandez, and Daniel Moran (2018). “Decoupling between human development and energy consumption within footprint accounts”. In: *Journal of Cleaner Production* 202, pp. 1145–1157. DOI: 10.1016/j.jclepro.2018.08.235.
- Andrieu, Baptiste, Laurie Marraud, Olivier Vidal, Mathis Egnell, Laurent Boyer, and Guillaume Fond (2022). “The Exponential Relationship between Healthcare Systems’ Resource Footprints and Their Access and Quality: A Study of 49 Regions between 1995 and 2015”. In: *SSRN Electronic Journal*. DOI: 10.2139/ssrn.4182423.
- Birat, J.-P., M. Chiappini, and C. et al. Ryman (2014). “Cooperation and Competition Among Structural Materials”. In: *Revue de Métallurgie* 110, pp. 97–131.
- Bogmans, C., L. Kiyasseh, A. Matsumoto, A. Pescatori, and G. M. M. Ferretti (2020). “Energy, Efficiency Gains and Economic Development: When Will Global Energy Demand Saturate?” In: *IMF Working Papers*.
- Braga, C.A.P. and J.V. da Fonseca Netto (2016). “A Dynamic State Observer to Control the Energy Consumption in Aluminium Production Cells”. In: *Systems Science Control Engineering* 4.1, pp. 307–319. DOI: 10.1080/21642583.2016.1238325.
- Brockway, Paul E., Steve Sorrell, Gregor Semieniuk, Matthew Kuperus Heun, and Victor Court (2021). “Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications”. In: *Renewable and Sustainable Energy Reviews* 141, p. 110781. DOI: 10.1016/j.rser.2021.110781.
- Bruckner, Benedikt, Klaus Hubacek, Yuli Shan, Honglin Zhong, and Kuishuang Feng (2022). “Impacts of poverty alleviation on national and global carbon emissions”. In: *Nature Sustainability* 5.4, pp. 311–320. DOI: 10.1038/s41893-021-00842-z.
- Castellani, Valentina, Antoine Beylot, and Serenella Sala (2019). “Environmental impacts of household consumption in Europe: Comparing process-based LCA and environmentally extended input-output analysis”. In: *Journal of Cleaner Production* 240, p. 117966. DOI: 10.1016/j.jclepro.2019.117966.
- Chen, G.Q., X.D. Wu, Jinlan Guo, Jing Meng, and Chaohui Li (2019). “Global overview for energy use of the world economy: Household-consumption-based accounting based on the world input-output database (WIOD)”. In: *Energy Economics* 81, pp. 835–847. DOI: 10.1016/j.eneco.2019.05.019.
- Chen, G.Q. and X.F. Wu (2017). “Energy overview for globalized world economy: Source, supply chain and sink”. In: *Renewable and Sustainable Energy Reviews* 69, pp. 735–749. DOI: 10.1016/j.rser.2016.11.151.
- Cleveland, Cutler J. (1987). “Biophysical economics: Historical perspective and current research trends”. In: *Ecological Modelling* 38.1-2, pp. 47–73. DOI: 10.1016/0304-3800(87)90044-5.
- Cullen, Jonathan M., Julian M. Allwood, and Edward H. Borgstein (2011). “Reducing Energy Demand: What Are the Practical Limits?” In: *Environmental Science & Technology* 45.4. Publisher: American Chemical Society, pp. 1711–1718. ISSN: 0013-936X. DOI: 10.1021/es102641n. (Visited on 03/03/2022).
- Deverajan, S. and A. C. Fisher (1981). “Hotelling’s Economics of Exhaustible Resources: Fifty Years Later”. In: *Journal of Economic Literature* 19.1, pp. 65–73.
- Easterlin, R.A. (1974). “Does Economic Growth Improve the Human Lot? Some Empirical Evidence”. In: *Nations and Households in Economic Growth*. Elsevier, pp. 89–125. DOI: 10.1016/b978-0-12-205050-3.50008-7.
- Farzin, Y. H. (1995). “Technological Change and the Dynamics of Resource Scarcity Measures”. In: *Journal of Environmental Economics and Management* 29, pp. 105–120.

- Fell, Michael James (2017). “Energy services: A conceptual review”. In: *Energy Research & Social Science* 27, pp. 129–140. DOI: 10.1016/j.erss.2017.02.010.
- Ferreira da Cunha, R. and A. Missemmer (2020). “The Hotelling Rule in Non-Renewable Resource Economics: A Reassessment”. In: *Canadian Journal of Economics*. DOI: 10.1111/caje.12444.
- Fizaine, F. and V. Court (2015). “Renewable electricity producing technologies and metal depletion: A sensitivity analysis using the EROI”. In: *Ecological Economics* 110, pp. 106–118.
- Fizaine, Florian and Victor Court (2015). “Renewable electricity producing technologies and metal depletion: A sensitivity analysis using the EROI”. In: *Ecological Economics* 110, pp. 106–118. DOI: 10.1016/j.ecolecon.2014.12.001.
- Fowlie, Meredith, Michael Greenstone, and Catherine Wolfram (2018). “Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program”. In: *The Quarterly Journal of Economics* 133.3, pp. 1597–1644. DOI: 10.1093/qje/qjy005.
- Fuerstenau, M.C., G.J. Jameson, and R-H. Yoon (2007). *Froth Flotation: A Century of Innovation*. Littleton: Society for Mining, Metallurgy, and Exploration.
- Galvin, Ray and Minna Sunikka-Blank (2018). “Economic Inequality and Household Energy Consumption in High-income Countries: A Challenge for Social Science Based Energy Research”. In: *Ecological Economics* 153, pp. 78–88. DOI: 10.1016/j.ecolecon.2018.07.003.
- Gambhir, Ajay, Laurent Drouet, David McCollum, Tamaryn Napp, Dan Bernie, Adam Hawkes, Oliver Fricko, Petr Havlik, Keywan Riahi, Valentina Bosetti, and Jason Lowe (2017). “Assessing the Feasibility of Global Long-Term Mitigation Scenarios”. In: *Energies* 10.1, p. 89. DOI: 10.3390/en10010089.
- Georgescu-Roegen, Nicholas (1971). *The Entropy Law and the Economic Process*. Cambridge, Mass: Harvard University Press. ISBN: 9780674281653.
- Gillingham, Kenneth and James H. Stock (2018). “The Cost of Reducing Greenhouse Gas Emissions”. In: *Journal of Economic Perspectives* 32.4, pp. 53–72. DOI: 10.1257/jep.32.4.53.
- Giurco, D., B. McLellan, D.M. Franks, K. Nansai, and T. Prior (2014). “Responsible mineral and energy futures: views at the nexus”. In: *J. Clean. Prod.* 84, pp. 322–338.
- Glossary (2022). “DataBank”. In: *World Bank*. URL: <https://databank.worldbank.org/>.
- Goldcorp (2015). *The Real Cost of Mining Gold*. URL: <https://www.kitco.com/ind/fulp/2015-02-04-The-Real-Cost-of-Mining-Gold.html>.
- Grubler, Arnulf, Charlie Wilson, and Gregory Nemet (2016). “Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions”. In: *Energy Research & Social Science* 22, pp. 18–25. DOI: 10.1016/j.erss.2016.08.015.
- Gutowski, T. G., S. Sahni, J. M. Allwood, M. F. Ashby, and E. Worrell (2013). “The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand”. en. In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 371.1986, pp. 20120003–20120003. ISSN: 1364-503X, 1471-2962. DOI: 10.1098/rsta.2012.0003. URL: <http://rsta.royalsocietypublishing.org/cgi/doi/10.1098/rsta.2012.0003> (visited on 06/06/2019).
- Haberl, Helmut, Dominik Wiedenhofer, Doris Virág, Gerald Kalt, Barbara Plank, Paul Brockway, Tomer Fishman, Daniel Hausknost, Fridolin Krausmann, Bartholomäus Leon-Gruchalski, Andreas Mayer, Melanie Pichler, Anke Schaffartzik, Tânia Sousa, Jan Streeck, and Felix Creutzig (2020). “A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights”. In: *Environmental Research Letters* 15.6, p. 065003. DOI: 10.1088/1748-9326/ab842a.
- Hickel, Jason, Christian Dorninger, Hanspeter Wieland, and Intan Suwandi (2022). “Imperialist appropriation in the world economy: Drain from the global South through unequal exchange, 1990–2015”. In: *Global Environmental Change* 73, p. 102467. DOI: 10.1016/j.gloenvcha.2022.102467.
- Hickel, Jason and Aljosa Slamersak (2022). “Existing climate mitigation scenarios perpetuate colonial inequalities”. In: *The Lancet Planetary Health* 6.7, e628–e631. DOI: 10.1016/s2542-5196(22)00092-4.
- Hotelling, H. (1931). “The economics of exhaustible resources”. In: *Journal of Political Economy* 39, pp. 137–175.

- Hund, K., D. La Porta, T.P. Fabregas, T. Laing, and J. Drexhage (2020). *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition*. URL: <https://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf>.
- IEA (2022). *World Energy Balances*. International Energy Agency. URL: <https://www.iea.org/reports/world-energy-balances-overview>.
- Intelligence, SP Global Market (2019a). <https://www.spglobal.com/marketintelligence/en/news-insights/research/silver-all-in-sustaining-costs-to-fall-again-in-2019-as-silver-price-struggles>.
- (2019b). <https://www.spglobal.com/marketintelligence/en/news-insights/research/gold-all-in-sustaining-cost-up-25-yoy-in-2018-but-forecast-lower-in-2019>.
- Jones, A.G. (2023). “Mining for netzero: The impossible task”. In: *The Leading Edge* 42.4, pp. 266–276. DOI: 10.1190/tle42040266.1.
- Kalt, Gerald, Dominik Wiedenhofer, Christoph Görg, and Helmut Haberl (2019). “Conceptualizing energy services: A review of energy and well-being along the Energy Service Cascade”. In: *Energy Research Social Science* 53, pp. 47–58. DOI: 10.1016/j.erss.2019.02.026.
- Kelley, K.D., D.L. Huston, and J.M. Peter (2021). “Toward an effective green economy: the Critical Minerals Mapping Initiative (CMMI)”. In: *SGA News* 48, pp. 1–5.
- Koning, Arjan de, Martin Bruckner, Stephan Lutter, Richard Wood, Konstantin Stadler, and Arnold Tukker (2015). “Effect of aggregation and disaggregation on embodied material use of products in input–output analysis”. In: *Ecological Economics* 116, pp. 289–299. DOI: 10.1016/j.ecolecon.2015.05.008.
- Lee, J., J. A. List, and M. C. Strazicich (2006). “Non Renewable Resource prices: Deterministic or Stochastic trends?” In: *Journal of Environmental Economics and Management* 51, pp. 354–370.
- Leong, Y.S., E. Erdreich, J.C. Burrit, O.E. Kiessling, C.E. Nighman, and G.C. Heikes (1940). *Technology, Employment and Output Per Man in Copper Mining*. Tech. rep. Philadelphia, PA, USA: Work Projects Administration in cooperation with Dept. of the Interior, Bureau of Mines.
- Levhari, D. and N. Liviatan (1977). “Notes on Hotelling’s economics of exhaustible resources”. In: *The Canadian Journal of Economics* 10.2, pp. 177–192.
- Mastrucci, Alessio, Jihoon Min, Arkaitz Usubiaga-Liaño, and Narasimha D. Rao (2020). “A Framework for Modelling Consumption-Based Energy Demand and Emission Pathways”. In: *Environmental Science & Technology* 54.3, pp. 1799–1807. DOI: 10.1021/acs.est.9b05968.
- McLellan, B.C., E. Yamasue, T. Tezuka, G. Corder, A. Golev, and D. Giurco (2016). “Critical minerals and energy-impacts and limitations of moving to unconventional metal-energy nexus”. In: *Fund. Res.* 2, pp. 392–395.
- Miller, Ronald E. and Peter D. Blair (2009). *Input-Output Analysis Foundations and Extensions. Foundations and Extensions*. Cambridge University Press, p. 784. ISBN: 9780521739023.
- Millward-Hopkins, Joel, Julia K. Steinberger, Narasimha D. Rao, and Yannick Oswald (2020). “Providing decent living with minimum energy: A global scenario”. In: *Global Environmental Change* 65, p. 102168. DOI: 10.1016/j.gloenvcha.2020.102168.
- Morrison, W.M. (2019). “China’s economic rise: History, trends, challenges, and implications for the United States”. In: *Curr. Polit. Econ. Northern and Western Asia* 28.2/3, pp. 189–242.
- Mudd, G, Z Weng, and SM Jowitt (2013). “A detailed assessment of global Cu reserve and resource trends and worldwide Cu endowments”. In: *Economic Geology* 108.5, pp. 1163–83.
- Mudd, G M (2009). *The Sustainability of Mining in Australia: Key Production Trends and Their Environmental Implications for the Future*. Tech. rep. Department of Civil Engineering, Monash University and Mineral Policy Institute.
- Nakićenović, Nebojsa, Paul Viktor Gilli, and Rainer Kurz (1996). “Regional and global exergy and energy efficiencies”. In: *Energy* 21.3, pp. 223–237. DOI: 10.1016/0360-5442(96)00001-1.

- Oswald, Y., J.K. Steinberger, D. Ivanova, and J. Millward-Hopkins (2021). “Global redistribution of income and household energy footprints: a computational thought experiment”. In: *Global Sustainability* 4. DOI: 10.1017/sus.2021.1.
- Oswald, Yannick, Anne Owen, and Julia K. Steinberger (2020). “Large inequality in international and intranational energy footprints between income groups and across consumption categories”. In: *Nature Energy* 5.3, pp. 231–239. DOI: 10.1038/s41560-020-0579-8.
- Owen, Anne (2017). “Discussion”. In: *Developments in Input-Output Analysis*. Springer International Publishing, pp. 167–184. DOI: 10.1007/978-3-319-51556-4\_6.
- Owen, Anne, Paul Brockway, Lina Brand-Correa, Lukas Bunse, Marco Sakai, and John Barrett (2017). “Energy consumption-based accounts: A comparison of results using different energy extension vectors”. In: *Applied Energy* 190, pp. 464–473. DOI: 10.1016/j.apenergy.2016.12.089.
- Ozdemiroglu, E. (1993). “Measuring Natural Resource scarcity: A study of The Price Indicator”. CSERGE, Working Paper GEC 93-14, ISSN 0967-8875, 28p.
- Popp, David, Richard G. Newell, and Adam B. Jaffe (Jan. 2010). “Chapter 21 - Energy, the Environment, and Technological Change”. en. In: *Handbook of the Economics of Innovation*. Ed. by Bronwyn H. Hall and Nathan Rosenberg. Vol. 2. Handbook of the Economics of Innovation, Volume 2. North-Holland, pp. 873–937. DOI: 10.1016/S0169-7218(10)02005-8. URL: <https://www.sciencedirect.com/science/article/pii/S0169721810020058> (visited on 07/17/2023).
- Rao, Narasimha D., Jihoon Min, and Alessio Mastrucci (2019). “Energy requirements for decent living in India, Brazil and South Africa”. In: *Nature Energy* 4.12, pp. 1025–1032. DOI: 10.1038/s41560-019-0497-9.
- Rodrigues, João F. D., Daniel Moran, Richard Wood, and Paul Behrens (2018). “Uncertainty of Consumption-Based Carbon Accounts”. In: *Environmental Science & Technology* 52.13, pp. 7577–7586. DOI: 10.1021/acs.est.8b00632.
- Rötzer, N. and M. Schmidt (2020). “Historical, Current, and Future Energy Demand from Global Copper Production and Its Impact on Climate Change”. In: *Resources* 9.44. DOI: 10.3390/resources9040044.
- Ruijven, Bas J. van, Enrica De Cian, and Ian Sue Wing (2019). “Amplification of future energy demand growth due to climate change”. In: *Nature Communications* 10.1. DOI: 10.1038/s41467-019-10399-3.
- Semieniuk, Gregor, Lance Taylor, Armon Rezai, and Duncan K. Foley (2021). “Plausible energy demand patterns in a growing global economy with climate policy”. In: *Nature Climate Change* 11.4, pp. 313–318. DOI: 10.1038/s41558-020-00975-7.
- Shove, Elizabeth and Gordon Walker (2014). “What Is Energy For? Social Practice and Energy Demand”. In: *Theory, Culture & Society* 31.5, pp. 41–58. DOI: 10.1177/0263276414536746.
- Slade, M. E. (1982). “Trends in Natural-Resource Commodity Prices: an Analysis of the Time Domain”. In: *Journal of environmental economics and management* 9, pp. 122–137.
- Södersten, Carl-Johan (2020). *Capital use matrices*. DOI: 10.5281/ZENODO.3874309.
- Södersten, Carl-Johan, Richard Wood, and Thomas Wiedmann (2020). “The capital load of global material footprints”. In: *Resources, Conservation and Recycling* 158, p. 104811. DOI: 10.1016/j.resconrec.2020.104811.
- Södersten, Carl-Johan H., Richard Wood, and Edgar G. Hertwich (2018). “Endogenizing Capital in MRIO Models: The Implications for Consumption-Based Accounting”. In: *Environmental Science & Technology* 52.22, pp. 13250–13259. DOI: 10.1021/acs.est.8b02791.
- Sorrell, Steve and John Dimitropoulos (2008). “The rebound effect: Microeconomic definitions, limitations and extensions”. In: *Ecological Economics* 65.3, pp. 636–649. DOI: 10.1016/j.ecolecon.2007.08.013.
- Sovacool, Benjamin K., Raphael J. Heffron, Darren McCauley, and Andreas Goldthau (2016). “Energy decisions reframed as justice and ethical concerns”. In: *Nature Energy* 1.5. DOI: 10.1038/nenergy.2016.24.
- Stadler, Konstantin (2017). “The country converter coco - a Python package for converting country names between different classification schemes”. In: *The Journal of Open Source Software* 2.16, p. 332. DOI: 10.21105/joss.00332.

- Stadler, Konstantin, Richard Wood, Tatyana Bulavskaya, Carl-Johan Södersten, Moana Simas, Sarah Schmidt, Arkaitz Usubiaga, José Acosta-Fernández, Jeroen Kuenen, Martin Bruckner, Stefan Giljum, Stephan Lutter, Stefano Merciai, Jannick H. Schmidt, Michaela C. Theurl, Christoph Plutzer, Thomas Kastner, Nina Eisenmenger, Karl-Heinz Erb, Arjan de Koning, and Arnold Tukker (2018). “EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables: EXIOBASE 3”. en. In: *Journal of Industrial Ecology* 22.3, pp. 502–515. ISSN: 1088-1980. DOI: 10.1111/jiec.12715. (Visited on 11/05/2020).
- Steen-Olsen, Kjartan, Anne Owen, Edgar G. Hertwich, and Manfred Lenzen (2014). “Effects of Sector Aggregation on CO<sub>2</sub> Multipliers in Multiregional Input–Output Analyses”. In: *Economic Systems Research* 26.3, pp. 284–302. DOI: 10.1080/09535314.2014.934325.
- Tokimatsu, Koji, Henrik Wachtmeister, Benjamin McLellan, Simon Davidsson, Shinsuke Murakami, Mikael Höök, Rieko Yasuoka, and Masahiro Nishio (2017). “Energy modeling approach to the global energy-mineral nexus: A first look at metal requirements and the 2 °C target”. en. In: *Applied Energy* 207, pp. 494–509. ISSN: 03062619. DOI: 10.1016/j.apenergy.2017.05.151. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0306261917307055> (visited on 09/16/2020).
- Tromans (2008). “Mineral comminution: Energy efficiency considerations”. In: *Mineral Engineering* 21 (8), pp. 613–620.
- UNFCCC (1992). *United Nations Framework Convention on Climate Change*. Tech. rep. UNFCCC.
- (2015). *Paris Agreement*. Tech. rep. UNFCCC.
- Uri, N. D. (1995). “A Reconsideration of Effect of Energy Scarcity on Economic Growth”. In: *Energy* 20.1, pp. 1–12.
- Vidal, O., B. Goffé, and N. Arndt (2013). “Metals for a low-carbon society”. In: *Nat. Geosci.* 6, pp. 894–896.
- Vidal, O., F.Z. Rostom, C. François, and G. Giraud (2019). “Prey–Predator Long-Term Modeling of Copper Reserves, Production, Recycling, Price, and Cost of Production”. In: *Environ. Sci. Technol.* 53, pp. 11323–11336. DOI: 10.1021/acs.est.9b03883.
- Vidal, Olivier, Hugo Le Boulzec, Baptiste Andrieu, and François Verzier (2021). “Modelling the Demand and Access of Mineral Resources in a Changing World”. en. In: *Sustainability* 14.1, p. 11. ISSN: 2071-1050. DOI: 10.3390/su14010011. URL: <https://www.mdpi.com/2071-1050/14/1/11> (visited on 01/28/2022).
- Vita, Gibran, Narasimha D. Rao, Arkaitz Usubiaga-Liaño, Jihoon Min, and Richard Wood (2021). “Durable Goods Drive Two-Thirds of Global Households’ Final Energy Footprints”. en. In: *Environmental Science & Technology* 55.5, pp. 3175–3187. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/acs.est.0c03890. (Visited on 02/27/2022).
- Wang, P., H. Wang, W-Q. Chen, and S. Pauliuk (2022). “Carbon neutrality needs a circular metal-energy nexus”. In: *Fundam. Res.* 2, pp. 1–6.
- Watarai, T., B.C. McLellan, S. Ogata, and T. Tezuka (2018). “Analysis for potential for criti-”. In.
- Wiedenhofer, Dominik, Doris Virág, Gerald Kalt, Barbara Plank, Jan Streeck, Melanie Pichler, Andreas Mayer, Fridolin Krausmann, Paul Brockway, Anke Schaffartzik, Tomer Fishman, Daniel Hausknost, Bartholomäus Leon-Gruchalski, Tânia Sousa, Felix Creutzig, and Helmut Haberl (2020). “A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping”. In: *Environmental Research Letters* 15.6, p. 063002. DOI: 10.1088/1748-9326/ab8429.
- Wood, Richard, Daniel D. Moran, João F. D. Rodrigues, and Konstantin Stadler (2019). “Variation in trends of consumption based carbon accounts”. In: *Scientific Data* 6.1. DOI: 10.1038/s41597-019-0102-x.
- Wood, Richard, Konstantin Stadler, Moana Simas, Tatyana Bulavskaya, Stefan Giljum, Stephan Lutter, and Arnold Tukker (2018). “Growth in Environmental Footprints and Environmental Impacts Embodied in Trade: Resource Efficiency Indicators from EXIOBASE3”. In: *Journal of Industrial Ecology* 22.3, pp. 553–564. DOI: 10.1111/jiec.12735.
- World Bank (2020a). *Poverty and Shared Prosperity: Reversals of Fortune*. The World Bank, Washington, DC. DOI: 10.1596/978-1-4648-1602-4.

- (2020b). *Purchasing Power Parities and the Size of World Economies*. en. Tech. rep. WorldBank, p. 227.
  - (2020c). *Purchasing Power Parities and the Size of World Economies: Results from the 2017 International Comparison Program*. The World Bank, Washington, DC. DOI: 10.1596/978-1-4648-1530-0.
  - (2022). *World Development Indicators*. The World Bank, Washington, DC. URL: <https://databank.worldbank.org/reports.aspx?source=2&series=NY.ADJ.DKAP.CD&country=>.
- Wu, Xudong, Chaohui Li, Jinlan Guo, Xiaofang Wu, Jing Meng, and Guoqian Chen (2021). “Extended carbon footprint and emission transfer of world regions: With both primary and intermediate inputs into account”. In: *Science of The Total Environment* 775, p. 145578. DOI: 10.1016/j.scitotenv.2021.145578.
- Yellishetty, Mohan, P.G. Ranjith, and A. Tharumarajah (2010). “Iron ore and steel production trends and material flows in the world: Is this really sustainable?” en. In: *Resources, Conservation and Recycling* 54.12, pp. 1084–1094. ISSN: 09213449. DOI: 10.1016/j.resconrec.2010.03.003. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344910000674> (visited on 02/01/2019).



## CHAPTER 4 | REGIONALIZING IMPACTS USING INPUT-OUTPUT

In the first version of MATER, we considered that there were no exchanges in between regions, which is an obvious limitation. The first part of this chapter presents how input-output databases can be used to analyze economic and ecological exchanges in between regions. The second part of this chapter explains how an input-output database was used to regionalize impacts in MATER.

- Sankey diagrams are a type of flow diagram where the thickness of a flow is proportional to its value. They are powerful visual representation tools that would allow to shed light on the various ways to calculate carbon footprints and on the implications of choosing one method over another. Although several multi-regional input-output databases allow for the calculation of footprints, none of them has been systematically represented as Sankey diagrams. To fill this gap, we build an open access web application to represent carbon footprints for 49 world regions between 1995 and 2019 based on EXIOBASE data.
- Based on the insights and the experience gained by building these sankey diagrams, we use EXIOBASE data to regionalize impacts in MATER.

## 4.1. MAPPING GLOBAL GREENHOUSE GASES EMISSIONS

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### ABSTRACT

Consumption-based carbon assessments are essential for evaluating climate change responsibility. However, the results vary greatly depending on the calculation perimeter chosen, making them confusing to non-expert readers and hindering their use for policymaking. Sankey diagrams are a type of flow diagram where the thickness of a flow is proportional to its value. They are powerful visual representation tools that would allow to shed light on the various ways to calculate carbon footprints and on the implications of choosing one method over another. Although several multi-regional input-output databases allow for the calculation of footprints, none of them has been systematically represented as Sankey diagrams. To fill this gap, we build an open access web application to represent carbon footprints for 49 world regions between 1995 and 2019 based on EXIOBASE data. We include production-based, consumption-based and consumption-based with capital endogenized accounts. We then provide examples of the insights gained with such diagrams.

### 4.1.1. INTRODUCTION

International climate negotiations rely on the concept of common but differentiated responsibility (UNFCCC, 1992). Currently, these negotiations are mostly based on territorial greenhouse gases (GHG) emissions. As emissions in one country can enable the consumption of goods and services in another (Hertwich et al., 2009), a fair distribution of responsibility for emissions is essential to halt climate change. The development of global multi-regional input-output databases, tracking global economic exchanges, has made it possible to include offshored emissions in what is known as the Consumption-Based (CB) account, as opposed to the Production-Based (PB) account which is limited to local emissions (Miller et al., 2009). CB accounting is not sufficient to assess responsibilities (Kander et al., 2015; Dietzenbacher et al., 2020) but provides a useful complementary metric which could be used in climate negotiations.

In the CB approach, emissions associated with the production of capital goods remain in the country where the infrastructure was built (C.-J. Södersten et al., 2020). For example, if a car is manufactured in China but purchased in Europe, the emissions during the car's production process will be imputed to Europe but the car factory's production footprint will be imputed to China. An emerging body of literature addresses this problem by endogenizing capital in input-output databases (C.-J. H. Södersten et al., 2018a). With this approach, for each car sold by a Chinese factory to a European consumer, part of the factory's footprint is imputed to the European consumer. This method brings footprint calculations closer to life cycle assessments and thereby makes them more accurate. However, the task is complex and calculating footprints

with endogenous capital is not yet as straightforward as calculating traditional CB footprint. Including capital in footprint calculations may change the results dramatically. For example, the GHG footprint of final consumption in some regions can increase by as much as 57% when capital goods are added to the value chain (C.-J. H. Södersten et al., 2018a). The way capital is accounted for also affects temporal responsibility (Chen et al., 2018): a factory built today is expected to produce goods for the next 50 years.

Footprint results are usually given in tons of CO<sub>2</sub> equivalent per person. However, the perimeter of the studies is rarely specified and a certain level of expertise is needed to understand the implications of the different choices (Heinonen, Ottelin, Ala-Mantila, et al., 2020). The study may stop at final household consumption, or add government expenditures in addition, or add capital creation either directly or by endogenizing it (Heinonen, Ottelin, Ala-Mantila, et al., 2020). In the end, depending on the perimeter chosen, the results can vary by up to a factor of 4 (Heinonen, Ottelin, Ala-Mantila, et al., 2020). This can lead to confusion about the different rankings between countries and the mitigation measures to be taken.

A visual representation of the differences in input-output results depending on the perimeter chosen would thus be useful for policy makers commissioning studies or new users of input-output tables. Sankey diagrams –a type of flow diagram where the thickness of the flows is proportional to the flow’s value– are an appropriate visualisation tool for this as they allow to follow every step of the calculation. Sankey diagrams have been used to represent the world’s GHG emissions in 2009 (Chen et al., 2018), but not for several regions and years at the same time.

Here, we develop a methodology to visually represent several possible perimeters for calculating GHG footprints as Sankey diagrams. These diagrams are constructed based on EXIOBASE data for 49 regions of the world over period 1995-2019 and are accessible on a web application.

#### 4.1.2. STEPS

We use EXIOBASE3 (Stadler et al., 2018) –a global multi-regional input-output database– to calculate GHG footprints using the PB approach, the CB approach and the CB approach with capital endogenized (CBk). Each approach can be disaggregated in several visualisation ‘steps’. For example, the PB account can be disaggregated between production sectors and production regions. In a trade-off between completeness and readability, we choose to represent 10 steps, shown as vertical dotted lines on Figure 4.1 (the Sankey diagram of France in 2019). These 10 steps are described thereafter. Diagrams for all other regions and years are available at <https://sankey.theshiftproject.org>.

The first step allows the reader to see which GHGs are being studied, namely carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and sulfur hexafluoride (SF<sub>6</sub>). It is the sum of the GHGs involved in all three approaches, ie. territorial emissions plus imports. It is therefore not specific to a single approach but can be interpreted as all the GHGs over which a given region has direct or indirect responsibilities.

Steps 2, 3 and 4 correspond to PB accounts disaggregated between: regions (step 2), territorial or import (step 3) and emission sector (step 4). In step 2, the 431Mt of French territorial emissions correspond to the node “France (431)”. The 48 other EXIOBASE regions are aggregated in Africa, Asia, Europe, Middle East, North America, Oceania and South America. Step 3 is similar to step 2 but facilitates readability by aggregating all imports together. Step 4 disaggregates PB emissions by sector. A first sector corresponds to direct emissions by households, governments and Non-Profit Institutions Serving Households (NPISHS) (mainly in personal transport and heating). Then, the 200 EXIOBASE sectors are disaggregated into six major industrial categories: agriculture-food, energy industry, heavy industry, manufacturing industry, services and transport services. The colours in the overall diagram correspond to the seven different sectors of step 4. For example, any blue flow on the diagram corresponds to GHGs emitted by the agriculture and food industries.

Step 5 corresponds to the CB account disaggregated across final demand categories (who buys final goods, services and infrastructure): households, governments, NPISHS and Gross Capital Formation (GCF). Direct emissions in the region studied is disaggregated between households, governments and NPISHS. The transition from step 4 to step 5 thus corresponds to the classical use of input-output tables to transition from PB accounting to CB accounting.

GCF is made up of expenditures for the acquisition of fixed assets in the economy, plus net changes in the level of inventories (Glossary, 2022). It is a measure of investments in the infrastructure used to produce goods and services. In an approach aiming to assess the responsibility of final consumption, GCF should not be treated as a separate category but rather incorporated in the footprint of other sectors. However, not all GCF should be attributed to other sectors. For example, if a region’s investments grow rapidly over a short period of time, attributing all of these investments to that period would lead to an overestimation of the footprint of final consumption (C.-J. H. Södersten et al., 2018b). On the other hand, a region experiencing an economic crisis may be underinvesting but still benefit from the infrastructure built in previous years. To overcome these issues, we follow Södersten’s methodology (C.-J. H. Södersten et al., 2018b) to endogenize (ie. add capital to the input-output framework so that its emissions are imputed to final consumption) only the Consumption of Fixed Capital (CFC). The CFC represents the replacement value of capital used up in the process of production and is deemed to be a better proxy for the capital currently used by industries than GCF (C.-J. H. Södersten et al., 2018b). This choice implies that only the capital which reaches its end of life during the study year is considered. Net Capital Formation (NCF) is the difference between GCF and CFC. If NCF is positive (GCF superior to CFC), it corresponds to investments which will be used in subsequent years. If it is negative, it means that not all end-of-life capital goods are replaced by new ones.

To ensure continuity of the flows in the Sankey diagrams, it is necessary to distinguish between cases where NCF is positive and negative. When NCF is positive, GCF is divided between CFC (step 5 to step 6) and a node called ‘Positive capital formation’ (step 5 to 8). The node ‘Positive capital formation’ corresponds to the expansion of capital stock and is not included in the footprint with capital endogenized (the flows stop at step 8). When NCF is negative, CFC is the

sum of the flows from GCF (step 5 to step 6) and the flows from a node called ‘Negative capital formation’ (step 5 to step 6). The node ‘Negative capital formation’ corresponds to the use of stocks from previous years that have not been replaced. It is possible for NCF to be positive for some sectors and negative for others. In some diagrams (such as Figure 4.1), the node ‘Positive capital formation’ and ‘Negative capital formation’ both appear. In that case, NCF is equal to the positive node minus the negative node.

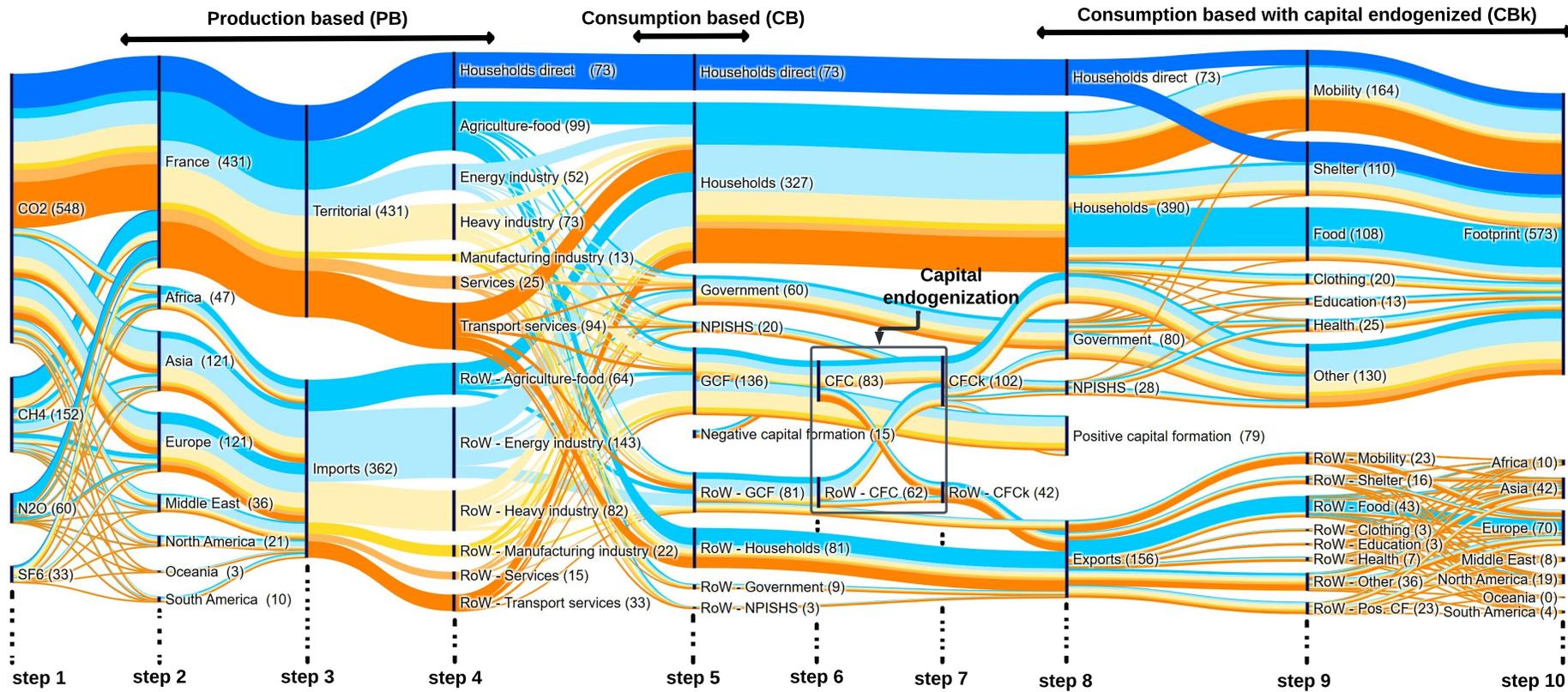


FIGURE 4.1: Sankey diagram of French greenhouse gas emissions in 2019. RoW stands for Rest of the World.

To summarize, GCF is disaggregated into CFC (steps 5 to 6) and positive capital formation (steps 5 to 8). Negative capital formation is added to CFC (steps 5 to 6). CFC is then endogenized (steps 6 to 7). The endogenized capital is added to final consumption (steps 7 to 8).

Step 8 presents the same disaggregation as step 5, but this time with endogenized capital. The “Households”, “Government” and “NPISHS” nodes are thus larger at step 8 than at step 5 while the GCF node does not appear on step 8. The “Positive capital formation” node is added, corresponding to the increase in capital stock. The footprint with endogenous capital is then disaggregated by service (Fell, 2017) on step 10: mobility, shelter, food, clothing, education, health and other goods and services. The emissions all along the value chain ultimately enable the realization of these services. Exports are aggregated on step 8 and disaggregated on steps 9 and 10, respectively by service and region of destination.

The three calculation methods -production based, consumption based and consumption based with capital endogenized- are represented by black horizontal arrows on figure 4.1. The sankey diagrams allow to easily understand the differences between them. They also allow to see that for a given calculation method, several disaggregations exist. For example, the CB footprint can be disaggregated by type of consumer (step 8) or by service (step 9).

In a recent review of consumption-based carbon assessments, Heinonen and colleagues showed that for a selected location, carbon footprint estimates varied widely (between 10 and 28 tons of CO<sub>2</sub>eq per capita in the United-States, between 1.8 and 7.6 tons in China, and between 6.7 and 13 tons in the European Union) (Heinonen, Ottelin, Ala-Mantila, et al., 2020). When comparing regional results from different studies, the Sankey diagrams built here may help understand where the differences come from. Any group of nodes on any step of Figure 4.1 could represent a calculation perimeter. Some perimeters are included in others (e.g., the CB footprint of households’ final consumption is part of the total CB footprint) so choosing one over the other will increase the footprint for every region. The same is true when capital endogenization is added to households, government and NPISHS.

However, the relative differences between regions can change greatly depending on the calculation hypothesis, even when choosing the same perimeter. For example, in 2019, the per capita footprint of the United-States was 2.1 times higher than that of China under the PB approach, 2.5 times higher under the CB approach and 4.4 times higher in the CB approach with capital endogenized. Choosing one perimeter rather than another significantly impacts the responsibilities in emissions.

Regional rankings can also change depending on the calculation perimeter. For example, out of the 49 regions studied, Japan is the 20th region with the highest per capita PB footprint, the 19th highest per capita CB footprint but the 5th highest per capita CB footprint with endogenous capital. On the other hand, China is the 22nd region with the highest per capita PB footprint, the 32nd when using CB accounting and the 42nd when using CB with endogenous capital.

### 4.1.3. DETECTING REGIONAL DIFFERENCES

Exploring the sankey diagrams on the application allows to understand easily why footprints differ between regions. Comparing the size of the ‘Territorial’ (step 3), ‘Imports’ (step 3), ‘Exports’ (step 8) and ‘Footprint’ (step 10) nodes is the simplest way to understand the overall structure of a region’s imports and exports. The reader can then dive into the details, such as the regions from where the imports come from (step 2), the regions where the exports go to (step 10) or the production (step 4) or consumption sectors (step 9).

The colours of the flows correspond to the production-based sector (step 4). All the direct emissions by households, governments and NPISHS correspond to dark blue. The production-based emissions in the agriculture-food, energy industry, heavy industry, manufacturing industry, services and transport services sectors correspond respectively to the blue, light blue, light yellow, yellow, light orange and orange colours. Three diagrams for which a colour is predominant are given as examples in figures 4.2 to 4.5. The light blue colour of the diagram of Australia in 2019 (Figure 4.2) shows that an important part of its PB emissions come from the energy industry. Following these light-blue flows show that over a third of that sector’s emissions are exported (in part corresponding to the exports of Australian coal). Second, the blue colour of the diagram of Brazil in 2019 (Figure 4.4) shows that the agriculture-food sector is responsible for over 50% of Brazilian emissions. Tracing back this blue colour shows that most of these emissions are CH<sub>4</sub> emissions (second node of step 1). Third, the diagram of Cyprus in 2019 is mostly orange, showing that over 50% of its PB emissions are related to the transport sector (Figure 4.4). It is important to note that the flows appear smaller on Fig. 4.2 than on Fig. 4.4 even though the total is higher in Australia than in Brazil in 2019. This is due to the fact that the flow sizes are normalized as a function of time and not in between regions so that one can see their size change with time for every region on the web application. Another colour code could have been chosen (ie. by making the colours correspond to any other step than step 4). Allowing the user to choose the colour code is thus a possible improvement for the next versions of the application.

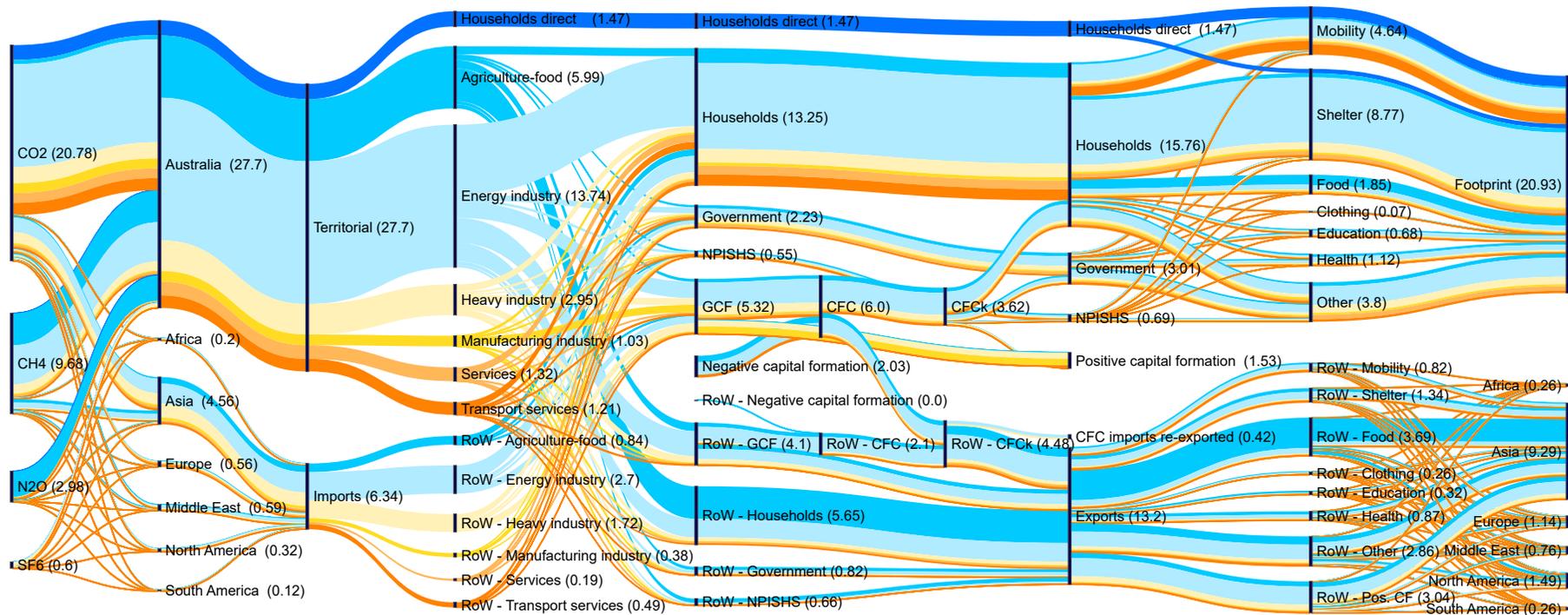


FIGURE 4.2: Sankey diagram of per capita greenhouse gases emissions in Australia in 2019.

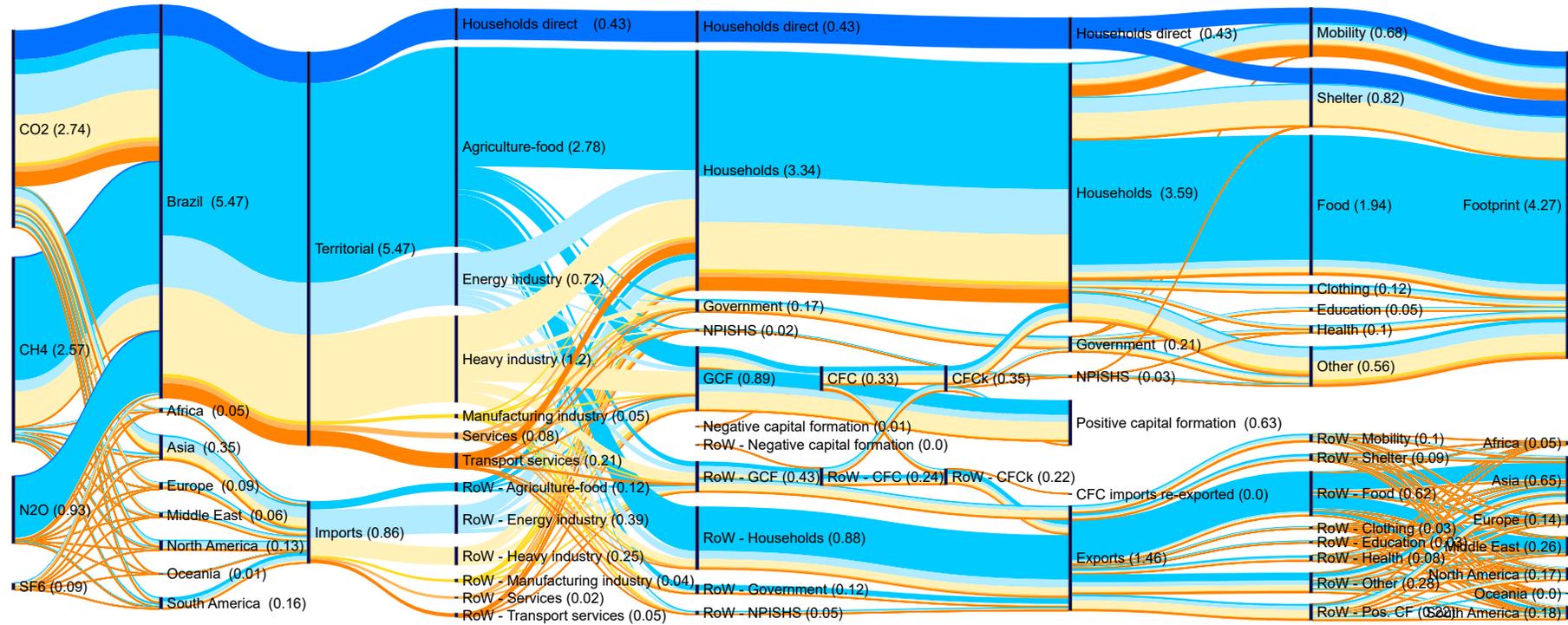


FIGURE 4.3: Sankey diagram of per capita greenhouse gases emissions in Brazil in 2019.

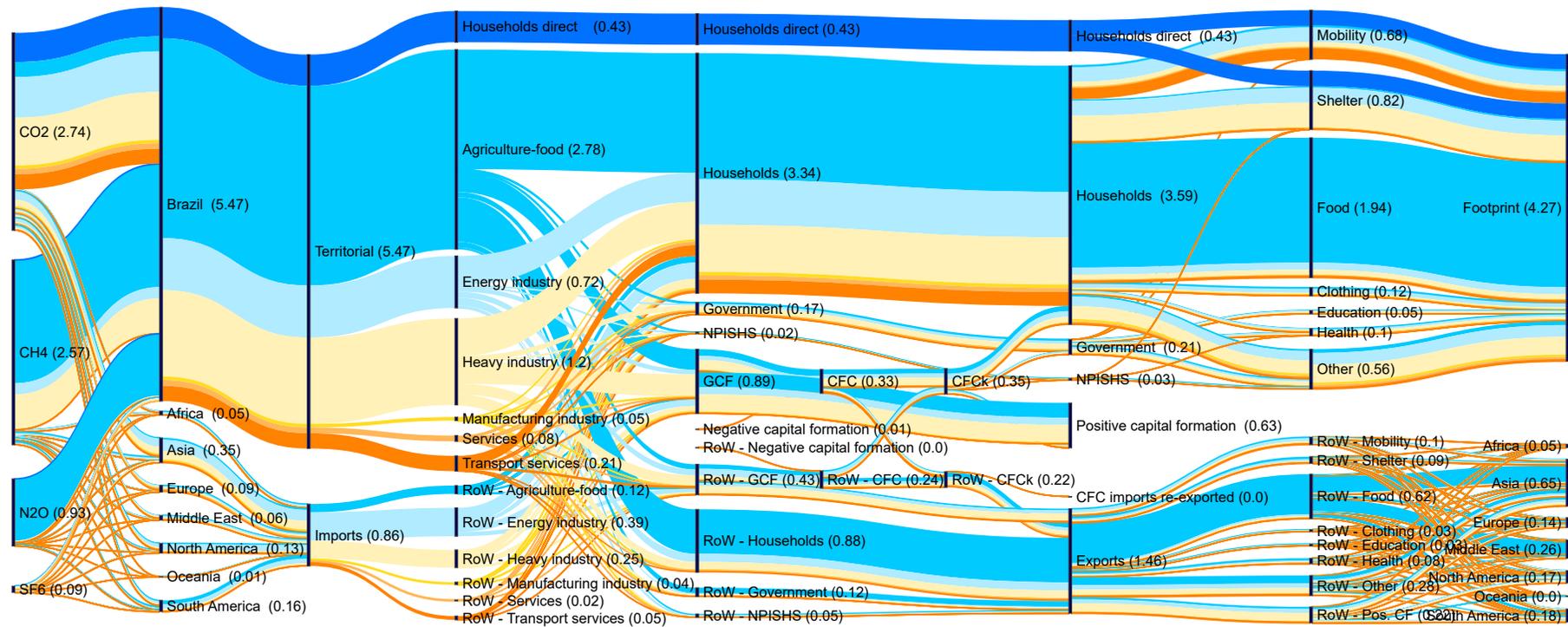


FIGURE 4.4: Sankey diagram of per capita greenhouse gases emissions in Cyprus in 2019.

#### 4.1.4. CAPITAL DYNAMICS: THE EXAMPLES OF RUSSIA AND CHINA

The sensitivity of results to capital endogenization is particularly important in times of crisis or strong economic growth. Following the collapse of the Soviet Union, Russia suffered from a total lack of investments (Bracho et al., 2005). Its gross fixed capital formation was divided by 4 between 1990 and 1995 (Bracho et al., 2005). In 1995, Russia's consumption of fixed capital was estimated at 188 billion US\$, over two times above that year's gross fixed capital formation level, estimated at 83 billion US\$ (World Bank, 2022). It means that the existing capital stock was depreciated at a faster rate than it was replaced. In other words, one can consider Russia in 1995 as a net "importer" of 105 billion US\$ of capital from previous years, equivalent to 27% of the 1995 GDP. The red box of Figure 4.5 highlights the associated imports of 895 Mt CO<sub>2</sub>eq from previous years. It represents 56% of the traditional CB footprint. The CB footprint with capital endogenized yields a result 32% above the traditional CB footprint.

On the other hand, China's consumption of fixed capital in 1995 was only of 83 billion US\$ while its creation of fixed capital was of 238 billion US\$. Net capital formation was thus of 155 billion US\$ which corresponded to 21% of its GDP. The box of Figure 4.6 shows that 1565 tons of GHG have been emitted in 1995 for the capital that will be depreciated in the future. It represents 39% of the traditional CB footprint. The CB footprint with capital endogenized yields a result 40% lower than the traditional CB footprint.

When neither in crisis nor in important growth phase, economies have a constant share of net capital formation in their gross fixed capital formation and a constant share of gross fixed capital formation in their GDP. In 2019, the consumption of fixed capital represented respectively 77% and 82% of the United-States and France's gross fixed capital formation. As a share of gross fixed capital formation in GDP, it respectively represented 21% and 23%. The emissions associated with the net capital formation (positive capital formation, minus negative capital formation) represent respectively 6 and 10% of the traditional CB footprint in the United States and France. In a steady state economy, there would be a balance between capital depreciation and construction, and GHG emissions associated net capital formation would be at zero.

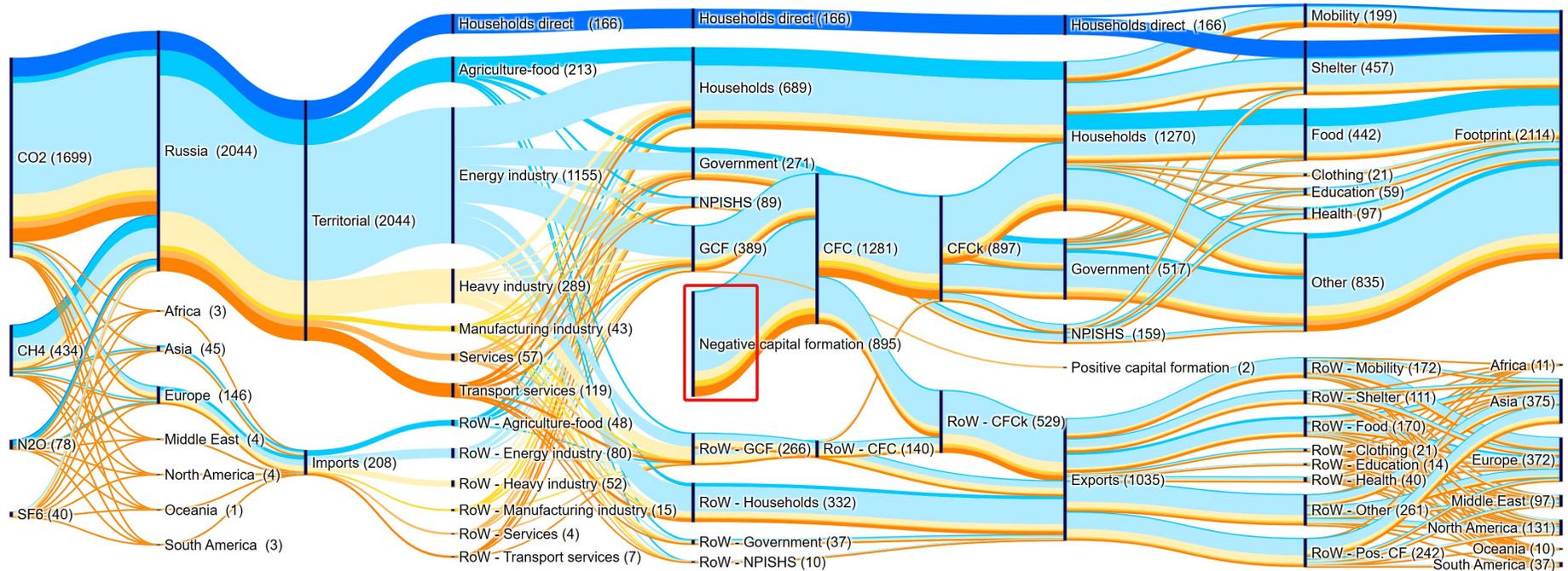


FIGURE 4.5: Sankey diagram of Russian greenhouse gases emissions in 1995

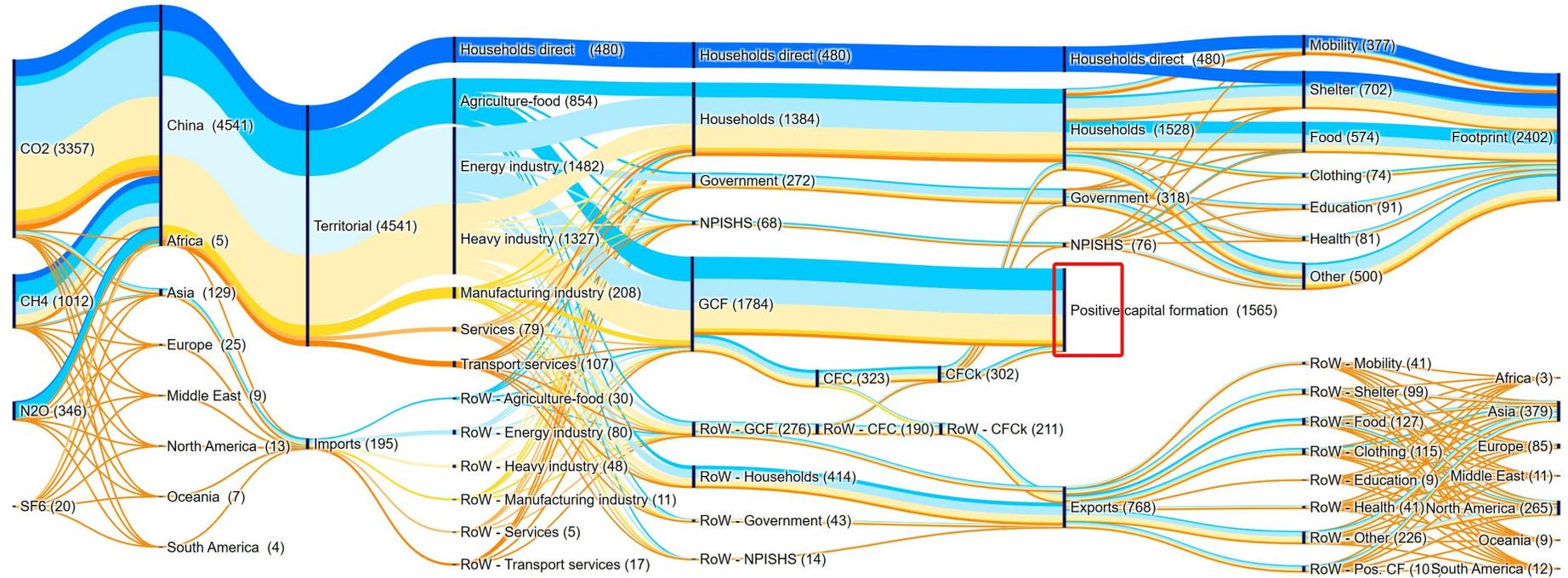


FIGURE 4.6: Sankey diagram of Chinese greenhouse gases emissions in 1995

#### 4.1.5. CONCLUSION

To easily understand the implications of choosing a production-based, consumption-based or consumption-based with endogenized capital approach when calculating carbon footprints, we built a web application containing 1225 sankey diagrams of regional carbon footprints using EXIOBASE v3.8.2. The diagrams provide first order explanations of regional variations in carbon footprints. They will be useful to policymakers and to scholars interested in learning input-output analysis.

#### 4.1.6. METHODS

##### 4.1.6.1. INPUT OUTPUT

We use the product by product version of EXIOBASE v3.8.2 to calculate emission accounts. The production-based account is obtained by adding the direct emissions of region  $i$  ( $f_{direct}$ ) to the factor of production emissions of region  $i$ .

The consumption-based account of region  $i$  for a given gas and final demand category ( $f_{d,cat}$ ) is obtained by multiplying the factor of production coefficients ( $s^{gas}$ ) by the Leontief inverse ( $L$ ) itself multiplied by a vector of final demand ( $y_{fd,cat}^i$ ):

$$d_{cba,fd,cat}^{i,gas} = s^{gas} L y_{fd,cat}^i \quad (4.1)$$

With  $L = (I - A)^{-1}$ ,  $I$  being the identity and  $A$  the direct requirement matrix. The total consumption-based account footprint is thus obtained by summing over the gases and final demand categories, and adding the direct emissions by households:

$$d_{cba}^{i,ghg} = \sum_{gas} \left( \sum_{fd,cat} s^{gas} L y_{fd,cat}^i + f_{direct}^{gas} \right) \quad (4.2)$$

We adopt C.-J. H. Södersten et al., 2018a methodology for capital endogenization. The capital endogenization process consists in modifying the direct requirements matrix to consider the CFC as intermediate production and not as a final demand category. Matrix  $\bar{K}$  is the capital transaction matrix, such that the sum of its lines ( $i$ ) equals cfc:

$$\sum_i \bar{k}_{i,j} = cfc \quad (4.3)$$

One line of  $\bar{K}$  provides the information of what the CFC of a given sector in a given region is used for. A column of  $\bar{K}$  corresponds to the CFC needed from all sectors and all regions to produce a given product in a given region. We use the  $\bar{K}$  matrices built by C.-J. Södersten, 2020 for years 1995-2015. These matrices have been updated by Wood et al., 2021 for years 2016-2019 but they appear to use a different methodology, as the totals seem not to have been rescaled to WorldBank data as done in the original study by C.-J. Södersten, 2020. We thus choose to now-cast the matrix of year 2015, using WorldBank and EXIOBASE data for years 2016-2019, as done by Andrieu et al., 2022 for year 2017.

The direct requirement matrix with capital endogenized writes:

$$A^K = (Z + \bar{K})\hat{x}^{-1} \quad (4.4)$$

with  $Z$  the transaction matrix and  $\hat{x}^{-1}$  the diagonalized and inverted total industry output  $x$ .

The associated Leontief inverse is thus:

$$L^K = (I - A^K)^{-1} \quad (4.5)$$

The consumption-based account footprint with capital endogenized is calculated by summing over the gases and final demand categories apart from GCF ( $fd, k, cat$ ):

$$d_{cba,K}^{i,ghg} = \sum_{gas} \left( \sum_{fd,k,cat} s^{gas} L^K y_{fd,k,cat}^i + f_{hh,i}^{gas} \right) \quad (4.6)$$

#### 4.1.6.2. FLOWS PER DIAGRAM

The strategy for constructing the Sankey diagram consists of (i) calculating the footprints with all possible methods (ii) selecting only the relevant flows for the region under consideration, without duplicates (iii) assigning to each flow a node of passage to the different stages (iv) color coding the flows and aggregating them so that the diagram is readable (v) plotting the diagram. The different steps are developed below and are available in the source code provided with the paper.

To select the relevant flows for a region (France for example), we start by taking the CB footprint of France (partly from France, partly from other regions), we add the emissions in France which are allocated to the CB footprint of other regions (allowing to build the export nodes and to complete the part of the CB footprint of France). We then add the imports and exports related to the endogenization of capital. In particular, some of the flows imported to create GFCF in France are re-exported during capital endogenization, which includes the additional node "re-exported imports".

Once all the flows have been selected, they are grouped in a table where each flow corresponds to a row and each column to the different steps. The information contained in  $d_{cba, fd\_cat}^{i,gas}$  is used to complete levels 1 to 5 (Fig. 4.1). The main difficulty appears at the junction between levels 6 and 7 (Fig. 4.1) because input-output formalism allows to go from PB to CB or from PB to CBk but not from CB to CBk. In particular, net fixed capital formation can be negative. We therefore start by adding these negative emissions - considering them as imports from previous years - in order to ensure the continuity of the flows throughout the diagram (there cannot be any negative flows). The transition between levels 6 and 7 is then made by an algorithm that ensures the continuity of flows and colors despite a lack of information to trace exactly the flows from CB to CBk. From level 8 to level 10, the definition of the different crossing points simply depends on that of  $s^{gas} L^K y_{fd,k,cat}^i$ .

EXIOBASE does not provide end uses of direct household emissions. To split them between

housing and mobility, we use the IPCC data available for 36 regions (UNFCCC, 2022). For the remaining regions, housing and mobility are each assumed to represent 50% of the total, in line with what is observed for countries with data. 14 of the 900 values obtained in the IPCC database are incompatible with EXIOBASE (residential emissions represent more than 90% of total direct household emissions). We therefore saturate these values at 90%.

The column corresponding to level 4 of the created table allows to define a color code so that the color of each flow corresponds to its emission sector in the PB approach. The flows are then aggregated by color to avoid duplicating flows of the same color between the same nodes. The diagram is then built with the python plotly library. The code to build and put online the application to visualize the results is available with this article.

#### 4.1.6.3. LIMITATIONS

The sankey diagrams built here allow to visually represent the production-based, consumption-based and consumption-based with endogenized capital accounts but several other responsibility allocation schemes exist. Examples include the downstream responsibility (in which the responsibility of emissions is enabled by purchases and not sales) (Lenzen et al., 2020), income-based responsibility (the downstream emissions enabled by primary inputs of individual nations or sectors) (Liang et al., 2017), the labor and capital based footprint (the emissions that individuals enable by providing labor and capital to companies) (Pottier et al., 2023), the emission responsibility allotment (a regional metric which credits actions contributing to reduce global emissions and penalizes actions increasing them) (Dietzenbacher et al., 2020), the value-added based responsibility (which allocates emissions responsibility according to the share of value-added they generate) (Piñero et al., 2019), or mixes of the above (Tukker et al., 2020; Steining et al., 2016).

Input-output calculations can allocate emissions based on either the place of consumption (territory principle) or the place of residence of consumers (residential principle) (Heinonen, Ottelin, Guddisardottir, et al., 2022). EXIOBASE3 is built using the residence principle (Owen et al., 2016; Heinonen, Ottelin, Ala-Mantila, et al., 2020). Another limitation of these diagrams is that they do not represent the differences between the residential or territory principle.

As for the method used to endogenize capital, its main limit is that it is not dynamic. It considers that the capital depreciated a given year was built using the technologies of this same year whereas it actually stems from different age cohorts. Södersten and colleagues carried out sensitivity analysis about this steady state assumption and showed that the results for some regions could change substantially if environmental extensions from previous years were used rather than that of the current year (C.-J. H. Södersten et al., 2018a).

#### 4.1.6.4. DATA AVAILABILITY

All the sankey diagrams are available on an open-access web application: [sankey.theshiftproject.org](https://sankey.theshiftproject.org). EXIOBASE3 is available at EXIOBASE 3 - Zenodo. The capital use matrices are available at Capital use matrices - Zenodo. Population data is available at Population, total - Data (world-

bank.org). WorldBank CFC and GFCF data are available at Gross fixed capital formation (current US\$) - Data (worldbank.org)..

#### 4.1.6.5. CODE AVAILABILITY

The code used to calculate the footprints is available on github: <https://github.com/baptiste-an/Mapping-global-ghg-emissions>. The code to build the application is available on github: <https://github.com/baptiste-an/Application-mapping-GHG>.

## 4.2. REGIONALIZING IMPACTS IN MATER

In the first version of MATER, we considered that there were no exchanges in between regions (ie. that metals were extracted, transformed into a final product and consumed in a given region). This is obviously a limitation. A way to improve this is to use input-output data to add flows in between regions.

### 4.2.1. MRIO AND IAM COUPLINGS

Researchers from both the IAM and the MRIO fields have leveraged findings from each other (Budzinski et al., 2023).

First, IAM assumptions and results have been used to support MRIO analyses, as shown by studies from Wiebe et al., 2018 and De Koning et al., 2016. These studies incorporated external scenarios into the MRIOs to adjust final demand structures and use coefficients. The findings indicate that substantial changes in consumption patterns and potential environmental impacts from new low carbon technologies are to be expected.

Secondly, MRIO results have been used to enhance IAM assessments. For example, Daly et al., 2015 investigated indirect emissions of a national energy system by coupling IAMs with MRIO models. Other studies have determined environmental stressors using LCA-IO models to include additional impact categories in integrated assessment modelling.

Budzinski and colleagues tried to go beyond this by building a method to merge an IAM with an MRIO based on the Make and Use framework. This approach aims to enhance both MRIO and IAM models simultaneously. It also aspires to include changing consumption patterns (degrowth scenarios) in future climate change mitigation scenario studies. Their method utilizes the energy system model of MESSAGEix-GLOBIOM and EXIOBASE (Budzinski et al., 2023). Such a strong coupling presents many advantages but is not possible in MATER for two reasons.

The first reason is that to use the Make and Use framework, both systems need to be represented in monetary units but there are no prices in MATER. The second reason is that MATER is a stock-driven model and not a flow-driven model. This means that we need an iterative process to calculate stocks (for example the number of cars, then the number of wind turbines to produce the energy to produce the cars, etc.), which cannot be done in an input-output framework which is only based on flows.

We therefore choose to use MRIO results to improve MATER rather than carrying a strong coupling between the two.

### 4.2.2. EXIOBASE DATA IN MATER

The accounting part (construction phase) of MATER starts with a reference stock of goods, which can be used to dimension a flow of goods to be produced ('goods in-flow (gd/yr)') (Fig 4.7 to control sequence). This makes it possible to dimension a manufacturing industry. Material

intensity data are then used to dimension a flow of raw materials entering the manufacturing industry ('Materials demand (ton/yr)'). These raw materials come from a market ('Raw materials aggregated market (ton)'), itself fed by a flow of recycled raw materials and a flow of primary raw materials from the 'Primary RM industry'. This 'Primary RM industry' extracts the 'Primary minerals supply (ton/yr)' flow from the environment (the cloud in figure 4.7).

A simplification of figure 4.7 is shown in figure 4.8, which depicts the chain used to produce the cars needed to build and maintain the fleet in France. In the non-regionalized version of MATER, the chain leading to the construction of these cars is linear and assumed to be in France all along: iron ore extraction, steel industry, steel market, manufacturing industry and in-use cars (figure 4.8).

The blue arrows in Figure 4.8 represent flows, and therefore run from left to right. However, the logical link between variables runs from right to left: it is the flow of cars that determines the flow of steel, which in turn determines the flow of iron ore. To regionalize the model, we need to go from right to left.

The first step is thus to regionalize the manufacturing industry. To do this, we use EXIOBASE's inverse Leontief matrix. A concordance table is constructed between MATER's 'goods' and EXIOBASE's 200 products. For example, cars in MATER correspond to the 'Motor vehicles, trailers and semi-trailers (34)' sector in EXIOBASE. EXIOBASE makes it possible to trace what had to be produced along the entire value chain (i.e. in each of the 200 sectors of each of the 49 regions) to in the end produce the cars bought in France. But it's not this total we're interested in, as it would imply double counting (for example, steel shouldn't be counted at this stage, as it will be counted via material intensity in the next step). We therefore select only the footprint associated with the manufacturing industry (here we also use 'Motor vehicles, trailers and semi-trailers (34)', but for other goods it may be a combination of sectors).

We use the energy footprint rather than the euro footprint, as this is more easily comparable between countries (euros are not at purchasing power parity in EXIOBASE). This footprint is then transformed into percentages to retain only the relative values, since the absolute values of energy consumption by manufacturing industry are calculated directly in MATER. An example with three regions (France, China, and Rest of the World (RoW)) is shown in figure 4.9 for car demand in France. Using EXIOBASE's Leontief matrix (only mock data on the figure), 20% of the energy used to manufacture cars purchased in France is used in China, 50% in France and 30% in the rest of the world.

The second regionalization step is the regionalization of the raw materials industry. To do so we use the transaction matrix Z of EXIOBASE, which represents the direct exchanges between sectors and regions. Here we do not use the Leontief inverse because we want to know where the raw materials used by a manufacturing industry in a given region come from, no matter who buys the goods in the end. This is represented in figure 4.10 (with mock data). The steel used in China comes at 80% from China, 1% from France and 19% from the rest of the world. Other rates are obtained for the steel used in France (blue lines) and in the rest of the world (green lines).

The third step consists in doing the same calculations as for the second step, but this time

at the mine level rather than at the raw materials industry level. We use the transaction matrix  $Z$  to find out where the iron ore used by the steel industry in a given region comes from. This is illustrated in Figure 4.11 by the red, blue and green lines between the iron ore mines and the steel industries (using mock data again).

#### 4.2.3. SCENARIOS FOR THE FUTURE

MATER underwent a calibration process utilizing data from EXIOBASE spanning the years 1995 to 2015. This enabled us to align the model with historical trade dynamics and economic activities. Looking towards long-term scenario analysis, we can adjust the proportions of import and export components at every stage to suit the conditions under investigation.

This opens the possibility to construct a variety of scenarios such as 'Business as Usual,' where current trends continue unabated, 'Delocalization,' which explores the effects of increased offshoring and outsourcing, and 'Relocalization,' that considers the impacts of bringing production processes closer to the point of consumption.

The adaptability of MATER in accommodating these various scenario constructions provides an exciting avenue for future research, which will enhance our understanding of how these different future trajectories could influence sustainability.

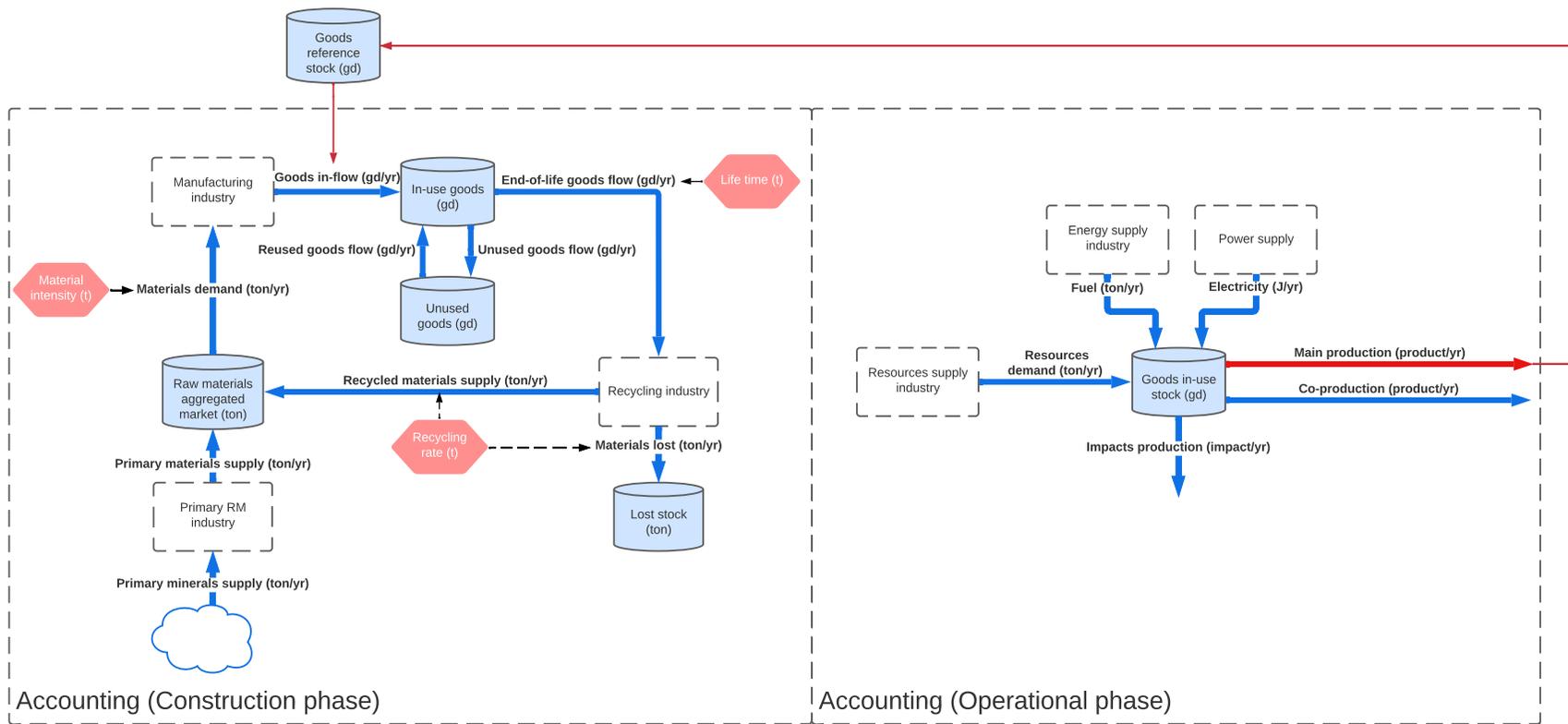


FIGURE 4.7: MATER framework

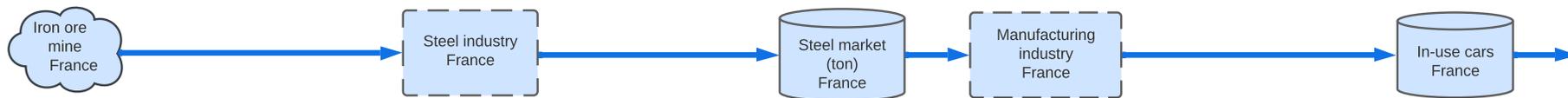


FIGURE 4.8: MATER framework simplification for cars

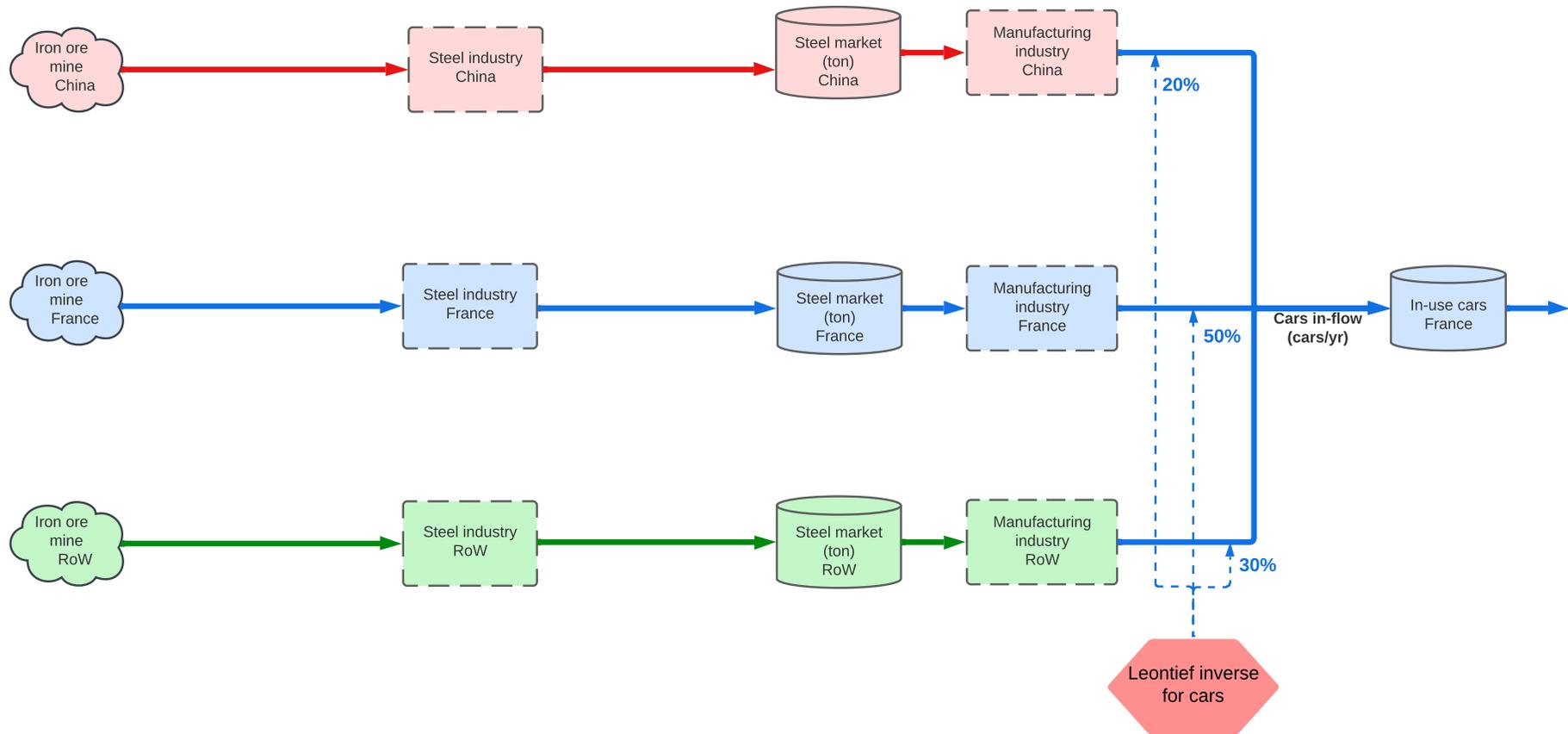


FIGURE 4.9: First regionalization step

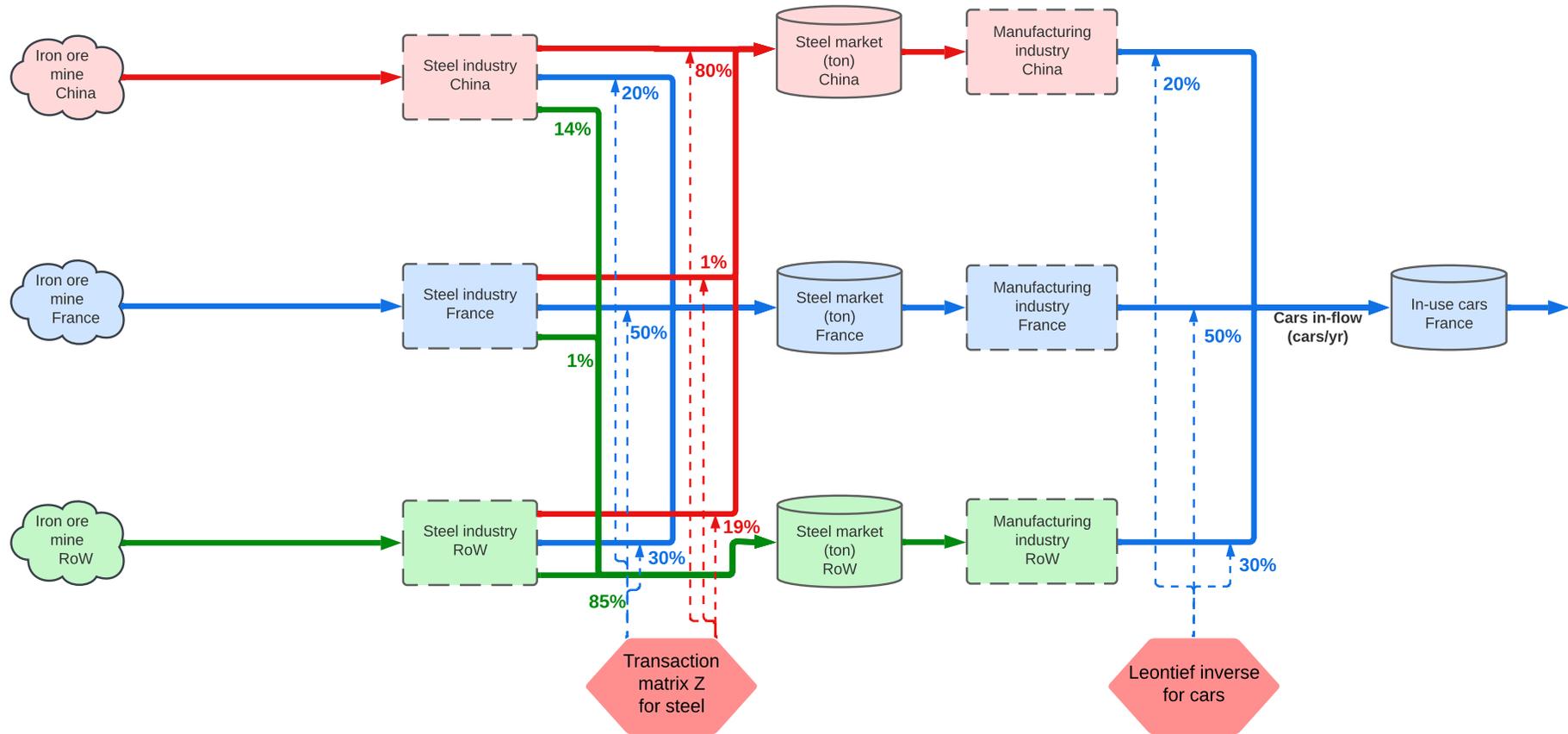


FIGURE 4.10: Second regionalization step

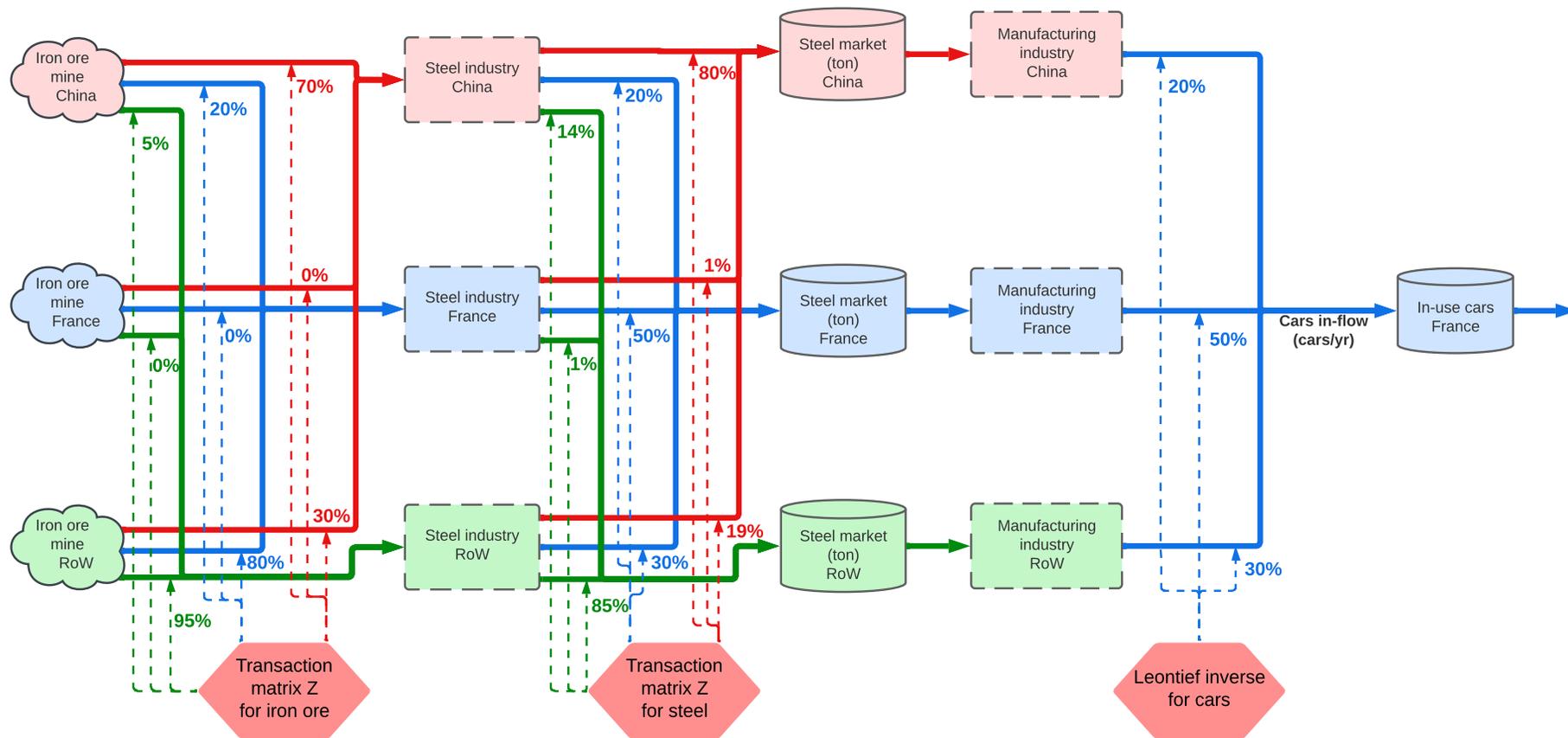


FIGURE 4.11: Third regionalization step

### 4.3. REFERENCES

- Andrieu, Baptiste, Olivier Vidal, Hugo Le Boulzec, Louis Delannoy, and François Verzier (2022). “Energy Intensity of Final Consumption: the Richer, the Poorer the Efficiency”. In: *Environmental Science & Technology* 56.19, pp. 13909–13919. DOI: 10.1021/acs.est.2c03462.
- Bracho, G. and J. L. Lopez (2005). “The Economic Collapse of Russia”. In: *BNL Quarterly Review* 58.232, pp. 53–89.
- Budzinski, Maik, Richard Wood, Behnam Zakeri, Volker Krey, and Anders Strømman (Jan. 2023). “Coupling energy system models with multi-regional input-output models based on the make and use framework – insights from MESSAGEix and EXIOBASE”. In: *Economic Systems Research*, pp. 1–19. DOI: 10.1080/09535314.2022.2158065.
- Chen, Zhan-Ming, Stephanie Ohshita, Manfred Lenzen, Thomas Wiedmann, Magnus Jiborn, Bin Chen, Leo Lester, Dabo Guan, Jing Meng, Shiyun Xu, Guoqian Chen, Xinye Zheng, JinJun Xue, Ahmed Alsaedi, Tasawar Hayat, and Zhu Liu (2018). “Consumption-based greenhouse gas emissions accounting with capital stock change highlights dynamics of fast-developing countries”. In: *Nature Communications* 9.1. DOI: 10.1038/s41467-018-05905-y.
- Daly, Hannah E., Kate Scott, Neil Strachan, and John Barrett (Sept. 2015). “Indirect CO2 Emission Implications of Energy System Pathways: Linking IO and TIMES Models for the UK”. In: *Environmental Science & Technology* 49.17. Publisher: American Chemical Society, pp. 10701–10709. ISSN: 0013-936X. DOI: 10.1021/acs.est.5b01020. URL: <https://doi.org/10.1021/acs.est.5b01020> (visited on 07/20/2023).
- De Koning, Arjan, Gjalte Huppel, Sebastiaan Deetman, and Arnold Tukker (Apr. 2016). “Scenarios for a 2 °C world: a trade-linked input–output model with high sector detail”. In: *Climate Policy* 16.3. Publisher: Taylor & Francis eprint: <https://doi.org/10.1080/14693062.2014.999224>, pp. 301–317. ISSN: 1469-3062. DOI: 10.1080/14693062.2014.999224. URL: <https://doi.org/10.1080/14693062.2014.999224> (visited on 07/20/2023).
- Dietzenbacher, Erik, Ignacio Cazarro, and Iñaki Arto (2020). “Towards a more effective climate policy on international trade”. In: *Nature Communications* 11.1. DOI: 10.1038/s41467-020-14837-5.
- Fell, Michael James (May 2017). “Energy services: A conceptual review”. en. In: *Energy Research & Social Science* 27, pp. 129–140. ISSN: 2214-6296. DOI: 10.1016/j.erss.2017.02.010. URL: <https://www.sciencedirect.com/science/article/pii/S2214629617300518> (visited on 04/21/2022).
- Glossary (2022). “DataBank”. In: *World Bank*. URL: <https://databank.worldbank.org/>.
- Heinonen, Jukka, Juudit Ottelin, Sanna Ala-Mantila, Thomas Wiedmann, Jack Clarke, and Seppo Junnila (2020). “Spatial consumption-based carbon footprint assessments - A review of recent developments in the field”. In: *Journal of Cleaner Production* 256, p. 120335. DOI: 10.1016/j.jclepro.2020.120335.
- Heinonen, Jukka, Juudit Ottelin, Anna Katrin Guddisardottir, and Seppo Junnila (2022). “Spatial consumption-based carbon footprints: two definitions, two different outcomes”. In: *Environmental Research Communications* 4.2, p. 025006. DOI: 10.1088/2515-7620/ac5489.
- Hertwich, Edgar G. and Glen P. Peters (2009). “Carbon Footprint of Nations: A Global, Trade-Linked Analysis”. In: *Environmental Science & Technology* 43.16, pp. 6414–6420. DOI: 10.1021/es803496a.
- Kander, Astrid, Magnus Jiborn, Daniel D. Moran, and Thomas O. Wiedmann (2015). “National greenhouse-gas accounting for effective climate policy on international trade”. In: *Nature Climate Change* 5.5, pp. 431–435. DOI: 10.1038/nclimate2555.
- Lenzen, Manfred, Arunima Malik, Mengyu Li, Jacob Fry, Helga Weisz, Peter-Paul Pichler, Leonardo Suveges Moreira Chaves, Anthony Capon, and David Pencheon (July 2020). “The environmental footprint of health care: a global assessment”. en. In: *The Lancet Planetary Health* 4.7, e271–e279. ISSN: 25425196. DOI: 10.1016/S2542-5196(20)30121-2. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2542519620301212> (visited on 10/05/2021).

- Liang, Sai, Shen Qu, Zeqi Zhu, Dabo Guan, and Ming Xu (Jan. 2017). “Income-Based Greenhouse Gas Emissions of Nations”. In: *Environmental Science & Technology* 51.1. Publisher: American Chemical Society, pp. 346–355. ISSN: 0013-936X. DOI: 10.1021/acs.est.6b02510. URL: <https://doi.org/10.1021/acs.est.6b02510> (visited on 06/07/2023).
- Miller, Ronald E. and Peter D. Blair (2009). *Input-Output Analysis Foundations and Extensions. Foundations and Extensions*. Cambridge University Press, p. 784. ISBN: 9780521739023.
- Owen, Anne, Richard Wood, John Barrett, and Andrew Evans (2016). “Explaining value chain differences in MRIO databases through structural path decomposition”. In: *Economic Systems Research* 28.2, pp. 243–272. DOI: 10.1080/09535314.2015.1135309.
- Piñero, Pablo, Martin Bruckner, Hanspeter Wieland, Eva Pongrácz, and Stefan Giljum (Apr. 2019). “The raw material basis of global value chains: allocating environmental responsibility based on value generation”. In: *Economic Systems Research* 31.2. Publisher: Routledge\_eprint: <https://doi.org/10.1080/09535314.2018.1536038>, pp. 206–227. ISSN: 0953-5314. DOI: 10.1080/09535314.2018.1536038. URL: <https://doi.org/10.1080/09535314.2018.1536038> (visited on 06/07/2023).
- Pottier, Antonin and Gaëlle Le Treut (2023). “Quantifying GHG emissions enabled by capital and labor: Economic and gender inequalities in France”. en. In: *Journal of Industrial Ecology* 27.2. \_eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/jiec.13383>, pp. 624–636. ISSN: 1530-9290. DOI: 10.1111/jiec.13383. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.13383> (visited on 05/08/2023).
- Södersten, Carl-Johan (2020). *Capital use matrices*. DOI: 10.5281/ZENODO.3874309.
- Södersten, Carl-Johan, Richard Wood, and Thomas Wiedmann (2020). “The capital load of global material footprints”. In: *Resources, Conservation and Recycling* 158, p. 104811. DOI: 10.1016/j.resconrec.2020.104811.
- Södersten, Carl-Johan H., Richard Wood, and Edgar G. Hertwich (2018a). “Endogenizing Capital in MRIO Models: The Implications for Consumption-Based Accounting”. In: *Environmental Science & Technology* 52.22, pp. 13250–13259. DOI: 10.1021/acs.est.8b02791.
- (Nov. 2018b). “Endogenizing Capital in MRIO Models: The Implications for Consumption-Based Accounting”. en. In: *Environmental Science & Technology* 52.22, pp. 13250–13259. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/acs.est.8b02791. URL: <https://pubs.acs.org/doi/10.1021/acs.est.8b02791> (visited on 07/07/2021).
- Stadler, Konstantin, Richard Wood, Tatyana Bulavskaya, Carl-Johan Södersten, Moana Simas, Sarah Schmidt, Arkaitz Usubiaga, José Acosta-Fernández, Jeroen Kuenen, Martin Bruckner, Stefan Giljum, Stephan Lutter, Stefano Merciai, Jannick H. Schmidt, Michaela C. Theurl, Christoph Plutzar, Thomas Kastner, Nina Eisenmenger, Karl-Heinz Erb, Arjan de Koning, and Arnold Tukker (2018). “EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables: EXIOBASE 3”. en. In: *Journal of Industrial Ecology* 22.3, pp. 502–515. ISSN: 1088-1980. DOI: 10.1111/jiec.12715. (Visited on 11/05/2020).
- Steininger, Karl W., Christian Lininger, Lukas H. Meyer, Pablo Muñoz, and Thomas Schinko (Jan. 2016). “Multiple carbon accounting to support just and effective climate policies”. en. In: *Nature Climate Change* 6.1. Number: 1 Publisher: Nature Publishing Group, pp. 35–41. ISSN: 1758-6798. DOI: 10.1038/nclimate2867. URL: <https://www.nature.com/articles/nclimate2867> (visited on 06/18/2023).
- Tukker, Arnold, Hector Pollitt, and Maurits Henkemans (Apr. 2020). “Consumption-based carbon accounting: sense and sensibility”. In: *Climate Policy* 20.sup1. Publisher: Taylor & Francis\_eprint: <https://doi.org/10.1080/14693062.2020.1728208>, pp. S1–S13. ISSN: 1469-3062. DOI: 10.1080/14693062.2020.1728208. URL: <https://doi.org/10.1080/14693062.2020.1728208> (visited on 06/07/2023).
- UNFCCC (1992). *United Nations Framework Convention on Climate Change*. Tech. rep. UNFCCC.
- (2022). *Greenhouse Gas Inventory Data - Detailed data by Party*. Tech. rep. UNFCCC. URL: [https://data.unfccc.int/detailed\\_data\\_by\\_party](https://data.unfccc.int/detailed_data_by_party).

Wiebe, Kirsten Svenja, Eivind Lekve Bjelle, Johannes Többen, and Richard Wood (Aug. 2018). “Implementing exogenous scenarios in a global MRIO model for the estimation of future environmental footprints”. In: *Journal of Economic Structures* 7.1, p. 20. ISSN: 2193-2409. DOI: 10.1186/s40008-018-0118-y. URL: <https://doi.org/10.1186/s40008-018-0118-y> (visited on 07/20/2023).

Wood, Richard and Carl-Johan Södersten (2021). *Capital use matrices*. DOI: 10.5281/ZENODO.7073276.

World Bank (2022). “Adjusted savings: consumption of fixed capital (current US\$) - Russian Federation”. In: *WorldBank*. URL: <https://data.worldbank.org/indicator/NY.ADJ.DKAP.CD?locations=RU>.

This chapter presents two studies that advance the understanding of the health-environment nexus:

- The first article advances existing research by assessing over 1000 environmental and social impacts of healthcare systems, across the whole value chain, including infrastructures.
- The second article explores the relationship between energy footprint per capita (a variable considered to be representative of an individual's lifestyle) and the incidence, Years Lived with Disability (YLDs) and Years of Life Lost (YLLs) of 293 diseases in 176 countries over the period 1990-2019.

These studies pave the way for future integration of the healthcare sector in MATER.

The MATER model, presented in chapter 2, allows to map the dynamics of resource use across different sectors of the economy. It is, however, important to note that the modeling process can vary significantly in its complexity, depending on the sector under scrutiny.

Sectors such as transport and building are easier to model due to the relatively straightforward nature of their supply and demand dynamics. For instance, in the transportation sector, the demand for cars can be associated directly with factors like population growth, urbanization, and income levels. Likewise, the infrastructure stock (e.g., cars, roads) and the associated flows (e.g., fuel consumption, emissions) can be quantified relatively easily. Similarly, in the building sector, the demand for housing and associated infrastructure stocks (e.g., buildings) and flows (e.g., energy use, waste generation) can be directly linked to socio-economic indicators such as population, income, and urbanization rate. However, the healthcare sector presents a considerably more complex modelling challenge due to the inherent complexities of the health systems and their multitude of feedback loops and indirect effects. Healthcare systems are multi-faceted, integrating a vast array of services, technologies, and human inter-

actions. These can range from primary care consultations to complex surgical interventions, all of which require diverse inputs and generate different types of outputs. Moreover, the demand for healthcare is influenced not only by demographic and economic factors but also by health status, health behaviours, and policies, among other things. This makes the prediction of demand and the associated resource flows considerably more challenging.

The objective of this chapter is therefore to explore the nexus between health and the environment, through two studies, to pave the way for future integration of the healthcare sector in MATER.

Only two studies assessed the raw materials footprints of healthcare sectors. The healthcare sector was found to be responsible for 13% and 5% of the national material extraction footprint for the Netherlands and Germany, respectively (Steenmeijer et al., 2022; Ostertag et al., 2021). No study has thus far estimated the resource footprint of healthcare systems at a multi-regional level, apart from scarce water use. To fill this gap, the first study of this chapter advances existing research by assessing over 1000 environmental and social impacts of healthcare systems, across the whole value chain, including infrastructures. We find that an exponential link exists between healthcare systems' resources footprint and their healthcare access and quality (HAQ) index. Both prevention and efficiency measures will be needed to change this relationship. If it is not enough, high-income countries will have to choose between further reducing the resource consumption of their healthcare systems or shifting the efforts to other sectors, health being considered an incompressible need. We call for the creation of a "HAQE" (healthcare access, quality, and efficiency) index that would add resource efficiency to access and quality when ranking healthcare systems.

This first study shows the impacts of healthcare sectors on the environment. The second study takes a completely different point of view to examine the relationship between the energy footprint per capita (EFC) (which measures the amount of energy required to sustain an individual's lifestyle) and diseases. We find that high EFC is correlated to low rates of enteric infections, maternal and neonatal disorders, nutritional deficiencies and sexually transmissible infections. However, high EFC is also correlated to high rates of substance use disorders, neoplasms, neurological, mental and musculoskeletal disorders, and diabetes and kidney diseases. These are only correlations and causality is of course not implied. Nevertheless, the fact that high EFC is not correlated to low rates of non-communicable diseases shows that there is no causality between high EFC and low rates of non-communicable diseases. This questions the mainstream narrative that economic growth and technological innovation (which are the source of increased energy use) inherently contribute positively to health. It suggests that while they may provide solutions to certain health problems, they might simultaneously introduce new health challenges, directly or indirectly, through changes in lifestyle and environmental degradation.

Though these two articles provide useful insights to understand the health-environment nexus, they are not yet sufficient to model properly the healthcare sector using the stock-flow approach of MATER. More research is needed using systems thinking to model the dynamics of healthcare.

## 5.1. THE EXPONENTIAL RELATIONSHIP BETWEEN HEALTHCARE SYSTEMS' RESOURCE FOOTPRINTS AND THEIR ACCESS AND QUALITY: A STUDY OF 49 REGIONS BETWEEN 1995 AND 2015

**Authors** Baptiste Andrieu, Laurie Marraud, Olivier Vidal, Mathis Egnell, Laurent Boyer, and Guillaume Fond

### ABSTRACT

**Background** Strategies to reduce the environmental impact of healthcare are often limited to greenhouse gases emissions. To broaden their scope, our aim was to determine the evolution of the resource footprints, dependency and efficiency of healthcare systems and to determine the relationship between this evolution and their Healthcare Access and Quality (HAQ) index.

**Methods** We carried out an input-output analysis of 49 healthcare systems from 1995 to 2015.

**Findings** Healthcare systems' footprint increased over the last two decades, reaching 7% of global non-metallic minerals footprint, 4% of global metal ores footprint and 5% of global fossil fuels footprint in 2013. This increase was mostly due to China, rising from 7% of the non-metallic minerals footprint in 1995 to 45% in 2013. 80% of the healthcare systems studied were dependent at more than 50% on fossil fuel imports. The energy footprint per capita was correlated exponentially with the HAQ index but some countries performed much better than others at a given energy footprint. Healthcare systems have not become more efficient between 2002 and 2015. We measured over 1000 other impacts, available with this paper.

**Interpretation** Healthcare systems' resources footprint are exponentially linked to their HAQ. Both prevention and efficiency measures will be needed to change this relationship. If it is not enough, high-income countries will have to choose between further reducing the resource consumption of their healthcare systems or shifting the efforts to other sectors, health being considered an incompressible need. We call for the creation of a "HAQE" (healthcare access, quality, and efficiency) index that would add resource efficiency to access and quality when ranking healthcare systems.

**Funding** The Shift Project.

### RESEARCH IN CONTEXT

**Evidence before this study** Healthcare, as any economic sector, relies on physical stocks and flows. The carbon emissions associated with healthcare have been assessed both at the regional and the global scale. The PubMed database was explored from inception to June 1st 2022, for

studies in English, using the keywords “healthcare” or “health care” with either “energy footprint”, “raw materials”, “environmental footprint” or “resource footprint”. After reviewing the titles, a single study assessed the scarce water use associated with healthcare globally, together with other environmental impacts. Two studies have assessed the resource footprint of the healthcare sector in the Netherlands and Germany, respectively. To the best of our knowledge, no study has thus far estimated the resource footprint of healthcare systems at a multi-regional level, apart from scarce water use.

**Added value of this study** This study advances existing research by assessing over 1000 environmental and social impacts of healthcare systems, across the whole value chain, including infrastructures. The added value of our methods compared to previous work is (1) the harmonisation of the expenditure data with World Health Organization reference data, (2) the endogenization of capital in input-output calculations (3) the correction of purchasing power parity for the analysis of intensities and (4) the comparison of the results with healthcare access and quality indexes. Among the impacts studied, resource footprints (divided in non-metallic minerals, metal ores, and fossil fuels) and dependencies were assessed for the first time. Energy footprint was used as an indicator representative of all resource footprints. Global North countries and China were responsible for the majority of global healthcare resource footprint. We found an exponential relationship between resource footprint and healthcare access and quality.

**Implications of all the available evidence** Countries of the Global South not only have lower HAQ indexes compared to the Global North, but also suffer from some of the impacts associated with the high HAQ indexes of rich countries. In a world with limited access to low-carbon energy sources, it is crucial to limit the growth of the global healthcare energy demand. The most effective compromise would be to target the reduction of healthcare footprint in high-income countries to insure a fair access to high-quality healthcare systems in the Global South. This objective could be reached by a combination of sociotechnical interventions and prevention.

### 5.1.1. INTRODUCTION

Healthcare systems currently represent one to five percent of the global emissions of greenhouse gas, particulate matter, air pollutants, reactive nitrogen in water and scarce water use (Lenzen, Malik, et al., 2020). These environmental impacts induce negative health effects that further increase the need for healthcare. Individuals should not have to take such considerations into account, which must be addressed by public health policies. However, for policy makers to implement the right strategy, a thorough understanding of the interactions between healthcare and the environment is needed. Healthcare systems’ impacts on climate change have been studied both at the country (Weisz et al., 2020; Nansai et al., 2020; Eckelman and J. Sherman, 2016; Tennison et al., 2021; Eckelman, J. D. Sherman, et al., 2018; Malik et al., 2018; R. Wu, 2019) and multi-regional level (Lenzen, Malik, et al., 2020; Pichler et al., 2019; Harm, 2019), leading over 50 countries to sign the UN commitment to a resilient, low-carbon health system at the Glasgow COP26 (Organisation, 2022). Resource footprints—defined as all resources

used directly and indirectly by an economic sector—are responsible for over 90% of global biodiversity loss and water stress impacts, as well as half of global greenhouse gas emissions (Panel, 2018). Healthcare's resource footprints include non-metallic minerals (use for the construction of buildings, such as hospitals), metal ores (used for the production of buildings and machines) or fossil fuels (used for example to produce drugs, build hospitals or power ambulances). Though they are good proxies of environmental damage (Steinmann et al., 2017), we lack data on these footprints which were therefore missing from the Glasgow agreements. So far, only two studies assessed the raw materials footprints of healthcare sectors. The healthcare sector was found to be responsible for 13% and 5% of the national material extraction footprint for the Netherlands and Germany, respectively (Steenmeijer et al., 2022; Ostertag et al., 2021).

A further concern relates to the inherent reliance of healthcare systems on imported resources, a factor which endows the healthcare sector with a high degree of vulnerability to crises (Hess et al., 2011). For example, if the energy transition is not fast enough, the risks of energy crisis due to decreasing fossil fuels quality –and thus available quantity– may threaten healthcare with shortages (Delannoy et al., 2021; Hess et al., 2011). Furthermore, the Global North countries and China are together responsible for 92% of the global resource use in excess of equitable and sustainable boundaries (Hickel, O'Neill, et al., 2022). Such levels of consumption in high-income countries have been allowed by resource imports from the Global South (Hickel, Dorninger, et al., 2022). To stay within safe and just earth system boundaries (Rockström et al., 2023), it is urgent to examine and repair the structural discriminations that drive resource footprints (Deivanayagam et al., 2023).

Strategies differ on how to address the problem, ranging from green growth to degrowth or post-growth approaches (Wiedenhofer et al., 2020). For green growth to work, decoupling would need to be absolute (ie. growth in GDP and degrowth in impacts) and of adequate magnitude. A recent systematic review showed that a rapid reduction in resource use could not be achieved with the existing decoupling rate (Haberl et al., 2020). Data on the quantity of resources used per unit of health expenditures would help understand whether past technological progress has contributed to a reduction in the footprint of healthcare. Since health expenditures is not an end in itself but a means for citizens to access good quality healthcare, comparing the multi-regional resource footprints of healthcare systems as a function of time and healthcare quality would also help understand possible pathways to achieve both Sustainable Development Goals 3 (good health and well-being) and 13-15 (environmental targets).

Our aim was first to determine the evolution of healthcare systems' resource footprints (in tons) at a multi-regional level –divided between non-metallic minerals, metal ores and fossil fuels– between 1995 and 2013 as well as their resource dependency. Our secondary objectives were (i) to calculate an aggregated energy footprint indicator (in joules of final energy) between 1995 and 2015, representative of all the resources used, (ii) to determine the relationship between this indicator and the evolution of healthcare access and quality, and (iii) to disaggregate the energy footprint along the value chain to better understand variations across countries.

## 5.1.2. METHOD

### 5.1.2.1. STUDY DESIGN

We carried out an input-output analysis of regional healthcare systems using EXIOBASE3 for 44 countries and 5 “rest of the world” regions from 1995 to 2015. EXIOBASE3 is an open-access multi-regional input-output database (Stadler, Wood, Bulavskaya, C.-J. Södersten, Simas, S. Schmidt, Usubiaga, Acosta-Fernández, Kuenen, Bruckner, Giljum, Lutter, Merciai, Jannick H. Schmidt, et al., 2018). Input-output analysis is a top-down approach to trace the worldwide industrial output necessary to produce the final consumption of a given product in a given region (Ronald E Miller et al., 2009a). Environmental extensions link the factors of production, such as resource footprint or environmental impacts, to the industrial output. It is thereby possible to trace the resource footprint of a specific sector of final consumption, such as health. Resource footprints in a given region can be disaggregated by region of production to calculate a share of resource imports.

To have a common and trustworthy source for health expenditure data, we used the World Health Organisation’s (WHO) Global Health Expenditure (GHE) database (Organization, 2022) and completed it with OECD’s health expenditure database (OECD, 2022). Health expenditures were mapped to 6 Exiobase sectors (Supplementary Table 5.2): ‘Health and social work services (85)’, ‘Chemicals nec’, ‘Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (52)’, ‘Insurance and pension funding services, except compulsory social security services (66)’, ‘Public administration and defence services; compulsory social security services (75)’ and ‘Private households with employed persons (95)’ (see Appendix for supplementary method).

A limit of classic input-output databases is that capital formation (investments) is reported as final consumption and not as intermediate consumption. For example, the cement and steel required to build a hospital is not accounted for in “Health and social work services” but in “Construction work”. The GHE database provides capital health expenditure for some years and some regions but data are neither complete nor disaggregated in capital sub-sectors (Organization, 2022). To overcome this limit, we have endogenized capital use in EXIOBASE3 using capital use matrixes (C.-J. H. Södersten et al., 2018a; C.-J. Södersten et al., 2018). Part of the investments was thereby considered as intermediate consumption.

### 5.1.2.2. RESOURCE FOOTPRINTS AND DEPENDENCY

Once EXIOBASE3 was modified to account for capital use, we calculated resource footprints, measured in tons and tons per capita. Non-metallic minerals, metal ores and fossil fuels were distinguished because they are associated with different environmental impacts and supply risks. Tracing footprints also allowed us to assess resources dependencies, defined as the percentage of imported resources. Resources data ended in 2013 (Stadler, Wood, Bulavskaya, C.-J. Södersten, Simas, S. Schmidt, Usubiaga, Acosta-Fernández, Kuenen, Bruckner, Giljum, Lutter, Merciai, Jannick H Schmidt, et al., 2021). Within the three resource categories, only fossil fuel (Delannoy et al., 2021) and some metallic ores (Graedel et al., 2015) are critical, while

other metallic ores and non-metallic minerals are not. The dependencies are still calculated for each category, as it also gives insights to where resources are produced and thus to the offshoring of the associated impacts.

### 5.1.2.3. RELATIONSHIP BETWEEN TOTAL ENERGY FOOTPRINT AND HEALTHCARE ACCESS AND QUALITY

The materiality of healthcare can be expressed by its total energy footprint, in joules. Resources need energy to be produced. For example, metals require energy to extract and crush the rocks, then to separate the ore from the rock, and separate the metal from the ore (Vidal et al., 2022). Resources can also be energy sources themselves, such as fossil fuels, but energy is also required to extract them (Delannoy et al., 2021). A total energy footprint across all the value chain includes all of the energy needed to produce the resources, but also the energy to transform these resources into machines or infrastructures and then to make these machines work. For example, energy is required to extract iron ore (the resource), to transform this iron into steel, to transform the steel into a medical equipment and to power the medical equipment. All of these steps are accounted for in the total energy footprint. Energy footprints in EXIOBASE3 cover the 1995-2015 period and are expressed in joules of final energy (Stadler, Wood, Bulavskaya, C.-J. Södersten, Simas, S. Schmidt, Usubiaga, Acosta-Fernández, Kuenen, Bruckner, Giljum, Lutter, Merciai, Jannick H. Schmidt, et al., 2018).

Energy is not used for its own sake but to provide energy services (Fell, 2017). In the present study, the energy service is to provide access to quality healthcare. The Healthcare Access and Quality (HAQ) index has been developed to measure this access to quality healthcare (Barber et al., 2017). The HAQ index is built for 195 countries for six reference years between 1990 and 2015 (Barber et al., 2017). This index takes into account 32 factors that may cause death but would not do so if people had access to a quality health system. Each year, every country is assigned a score per factor on a scale of 0 (1% worst performing countries) to 100 (1% best performing) over the 1990-2015 period. The final index is a score from 0 to 100 per country per year, constructed from the 32 causes studied (Barber et al., 2017). For the four rest of the world EXIOBASE3 regions, we have aggregated this index using population-weighted means.

We performed a panel data analysis to understand the relationship between HAQ and energy footprint per capita of healthcare systems. Panel data analysis allows to study data that is measured for the same objects (here regions) at different points in time. We chose the natural logarithm of the energy footprint per capita as the dependent variable and the HAQ index as the independent variable. We carried out a preliminary Hausmann test to choose the regression model. The result, giving a p-value of 0.0004 proved that the individual characteristics were correlated with the regressor and that the fixed-effect model was more appropriate than the random-effect. It makes sense as there are reasons to think that cultural or political characteristics of the various regions affect the HAQ index. We used the python statsmodel module to carry out the analysis.

As we found significant differences in energy footprints for countries with a similar HAQ index, we disaggregated the energy footprint of the ten countries with the highest HAQ index. We compared the energy used directly by healthcare sectors with that used for chemicals

production, other raw materials production, transport, equipment, construction, food, energy production and “other” for all other EXIOBASE sectors.

#### 5.1.2.4. HEALTHCARE SYSTEMS EFFICIENCY

Energy efficiency is defined as the inverse of energy intensity (energy use per unit of expenditure). To compare intensities between regions and across time, expenditures must be corrected to account for purchasing power parity (PPP) and inflation. One US\$PPP buys the same basket of goods in any region, whereas one US\$ buys goods according to market exchange rates. However, \$PPP data do not account for inflation. Consumer Price Indexes (CPI) account for inflation across time in a given country. We used expenditure data in \$PPP from the GHE database and corrected them using United-States healthcare CPI for the years 2002-2015, previous years not being available (*Eurostat - Data Explorer 2022*).

Changes in the obtained energy intensity can be explained by actual efficiency gains (using less energy to perform the same task) but also by changes in the input structure of the sector, for example of the cost of employment, which corresponds to zero energy input. To analyse this, we calculated the share of the cost of employment in the total inputs of the sector (the sum of intermediate consumption and value added).

#### 5.1.2.5. ROLE OF THE FUNDING SOURCE

The funder of this study had no role in study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the paper for publication. All authors had full access to all the data in the study and had the final responsibility for the decision to submit for publication.

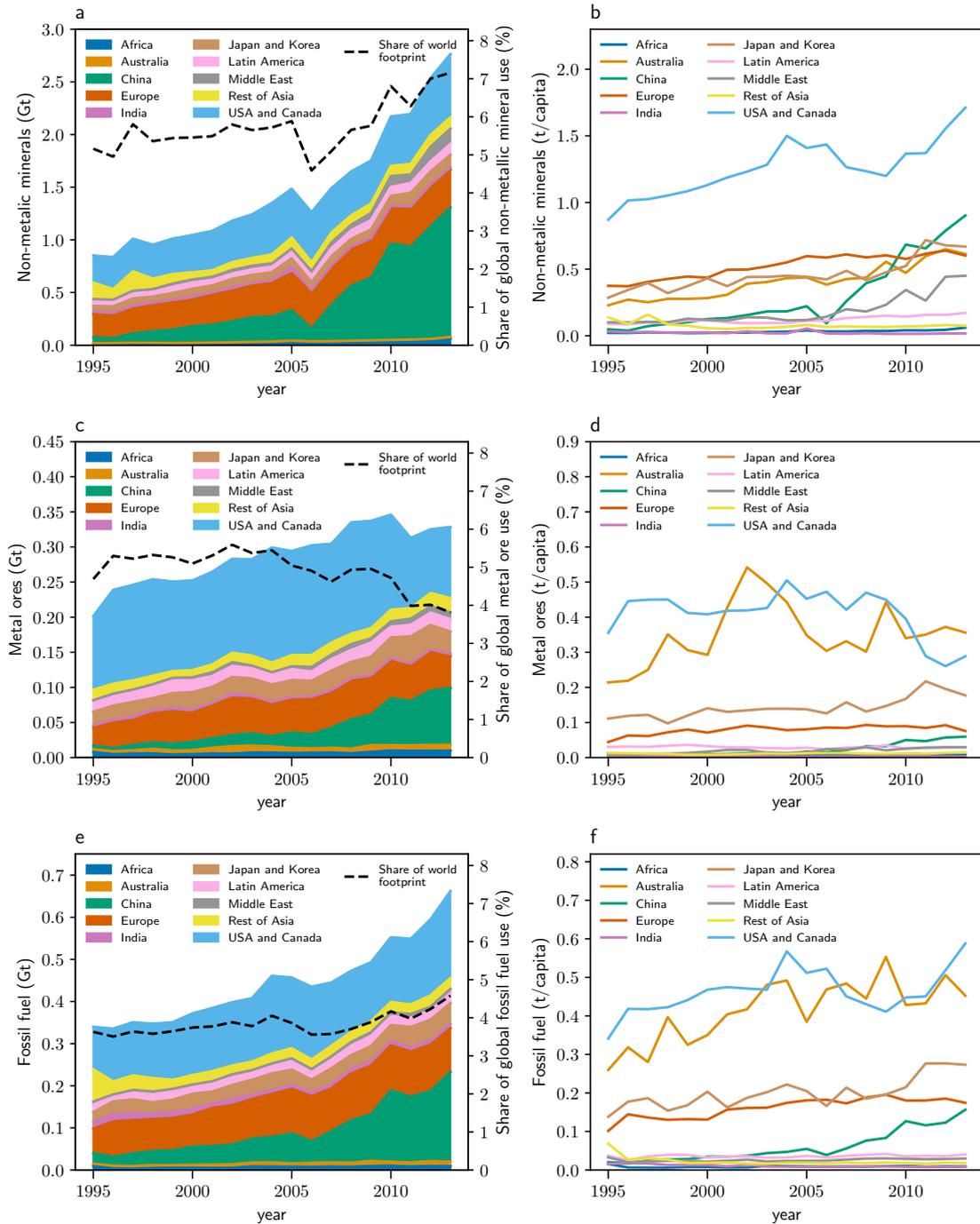
### 5.1.3. RESULTS

#### 5.1.3.1. EVOLUTION OF HEALTHCARE SYSTEMS' RESOURCES FOOTPRINTS BETWEEN 1995 AND 2013

The non-metallic minerals footprint of the world healthcare system has been multiplied by 3 over the 1995-2013 period to reach 2.8 Gt for 2013. This increase was mostly due to China, which represents 7% of the footprint in 1995 but 45% in 2013. An increase of healthcare systems' share in the world non-metallic minerals footprint is observed over the period, rising from 5% in 1995 to 7% in 2013 (figure 5.1a). In 2013, a North American individual had a non-metallic minerals footprint 96 times higher than an Indian one (1.7 t/capita vs. 0.018 t/capita).

The metal ores footprint (figure 5.1c) increased from 198 Mt in 1995 to 328 Mt in 2013. However, healthcare systems' share in the global footprint decreased from 5 to 4% over the period. In 2013, an Australian individual had a metal ores footprint 131 times higher than an Indian one (0.35 t/capita vs. 0.0027 t/capita).

Fossil fuels footprint (figure 5.1e) reached 662 Mt in 2013. Healthcare represents 4% of global fossil fuel use in 1995 but 5% in 2013. In 2013, a North American individual had a fossil fuels footprint 72 times higher than an Indian one (0.59 t/capita vs. 0.0081 t/capita).



**FIGURE 5.1:** Evolution of resource footprints of healthcare systems between 1995 and 2013. (a) Non-metallic minerals footprint. (b) Non-metallic minerals footprint per capita. (c) Metal ores footprint. (d) Metal ores footprint per capita. (e) Fossil fuels footprint. (f) Fossil fuels footprint per capita. Data for "USA and Canada" have been smoothed over 3 years to avoid sawtooths. See Supplementary Table 5.3 for the per capita data used in figures b-d-f.

In 2013, the footprint associated with capital goods and services (obtained via capital endogenization) represented respectively 35, 44 and 21% of the global footprint of non-metallic minerals, metal ores and final energy. Important variations exist in between countries on the share of the footprint due to capital expenditures. These differences could partly explain the differences in country rankings in Fig 5.1-b-d-f (supplementary table 5.3).

### 5.1.3.2. HEALTHCARE SYSTEMS' DEPENDENCY TO RESOURCES IN 2013

In 2013, 26 (53%) healthcare systems depended at more than 50% on imports of non-metallic minerals and 6 (12%) at more than 80% (figure 5.2a). This dependence was greater for metal ores, for which 43 (88%) systems relied at more than 50% on imports and 35 (71%) at more than 80% on imports (figure 5.2b). Finally, 39 (80%) relied at more than 50% on fossil fuels imports and 28 (57%) at more than 80% (figure 5.2c). This dependency takes into account exports re-imported. For example, the Middle East relies at 67% on fossil fuel imports (supplementary table 5.8) even though it produces an important share of the fossil fuel used by healthcare sectors globally (supplementary figure 5.12).

**TABLE 5.1:** Regression results between the HAQ index (independent variable) and the natural logarithm of the energy footprint (dependent variable) with region-fixed effects (FE). Data in parenthesis represent 95% CI.

|                       | R-squared (Between) | R-squared (Within) | R-squared (Overall) | Log-likelihood | P-value | slope                  | origin              |
|-----------------------|---------------------|--------------------|---------------------|----------------|---------|------------------------|---------------------|
| FE regression results | 0.726               | 0.360              | 0.692               | -36.8          | 0.0000  | 0.0513 (0.0416 0.0610) | -2.73 (-4.45 -2.02) |

### 5.1.3.3. RELATIONSHIP BETWEEN THE ENERGY FOOTPRINT AND ACCESS AND QUALITY (HAQ INDEX)

Healthcare systems' energy footprint per capita follows a power law of healthcare access and quality between regions (but not within regions) (Figure 5.3). Though the power law is visually clear for the cross-sectional data, the time-series data of some countries do not follow a power law. This is confirmed by the panel data analysis, for which the R<sup>2</sup>-between regions (0.73) is twice higher than the R<sup>2</sup>-within regions (0.36) (Table 5.1). Some countries, such as the United-States or Switzerland, under-performed while others, such as Spain or Croatia, over-performed (see the estimated regional fixed effects in Supplementary Table 5.10). During the 1995-2015 period, the HAQ indexes increased in all 49 EXIOBASE3 regions. However, five regions—India, “Rest of the world Africa”, Indonesia, South Africa and “Rest of the world Asia and Pacific”—, representing half of world population, still had HAQ indexes below 55 in 2015.

Countries of the Global South not only have lower HAQ indexes than countries of the Global North but also suffer from some of the impacts associated with the high HAQ indexes of rich countries. For example, 64% of the impacts associated with healthcare-related non-ferrous metal ores extraction take place in Global South without China, though this region's consumption is responsible for only 19% of the impacts (Appendix Table 5.6).

In 2015, ten countries had an HAQ index between 88.7 and 91.8, but the per capita energy footprint of their health sector varied by more than four times, from 3.5 GJ per capita in Spain to 15.3 GJ per capita in Switzerland (Figure 5.4a). These differences are partly explained by the amount of per capita spending on health care, which is twice higher in Switzerland than in Spain

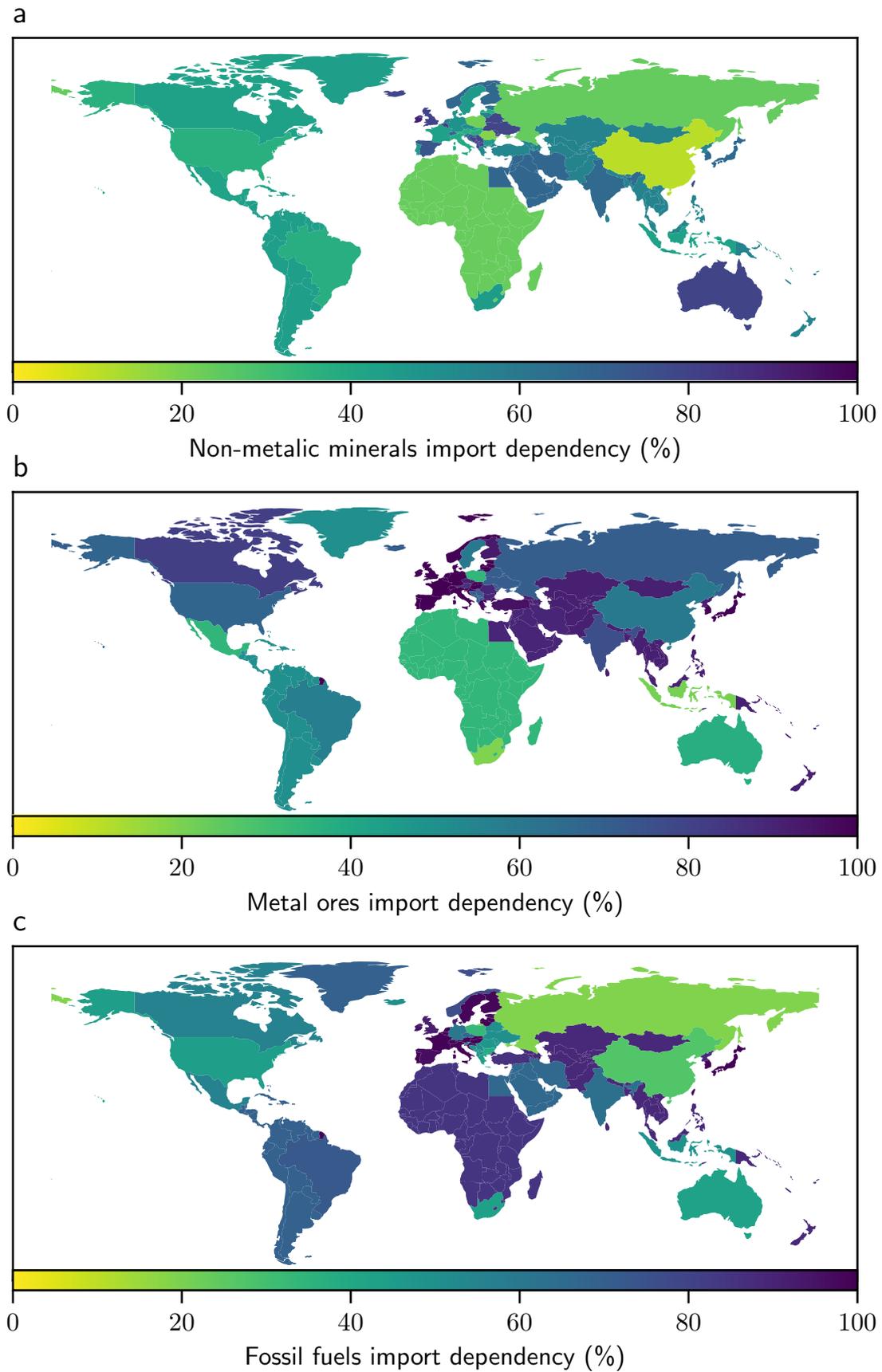
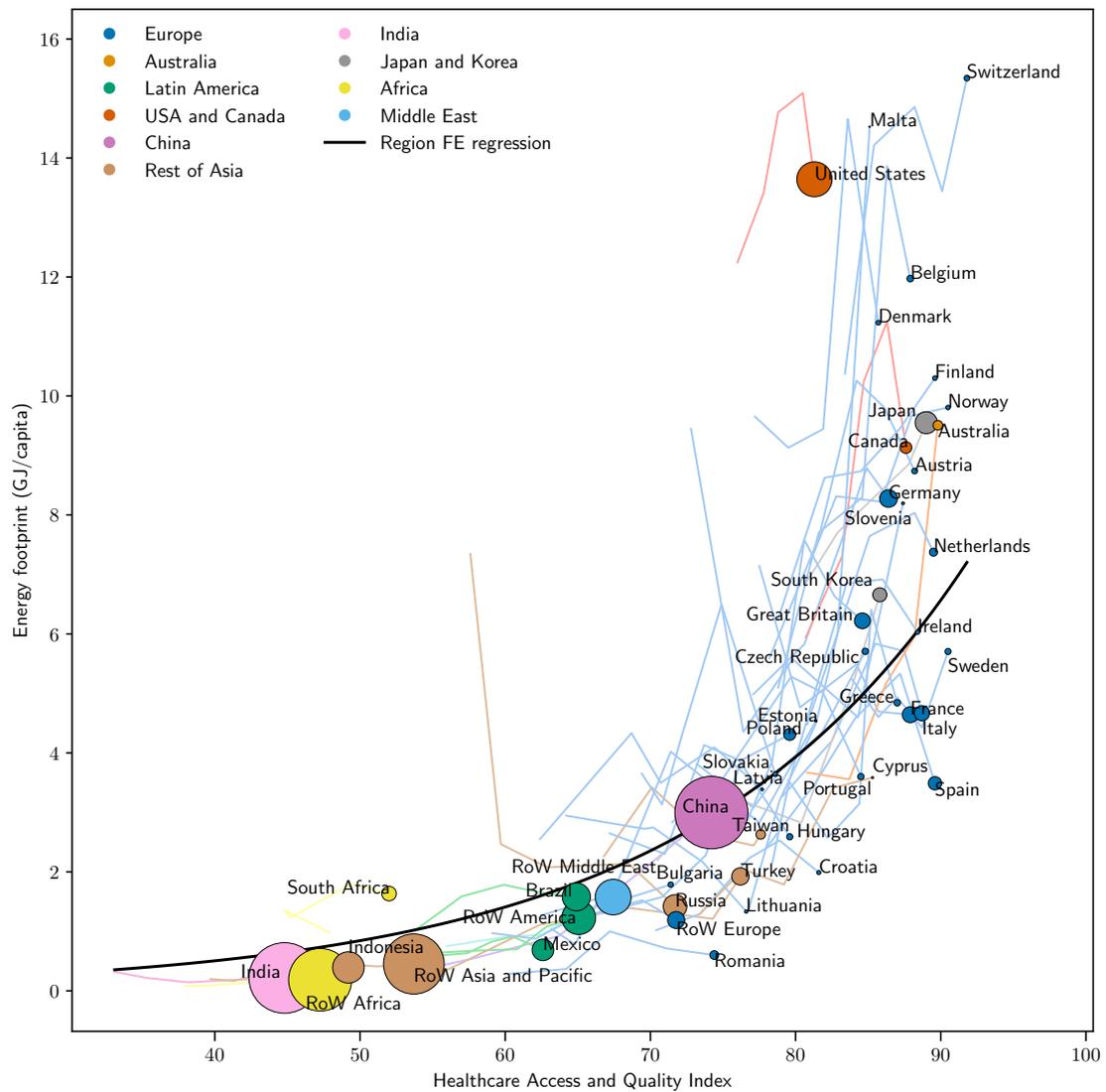


FIGURE 5.2: Healthcare systems' resource dependency in 2013 (a) Non-metallic minerals import dependency. (b) Metal ores import dependency. (c) Fossil fuels import dependency. See Appendix Figures 5.6-5.14 and Tables 5.5-5.9 for details.



**FIGURE 5.3:** Energy footprint of healthcare systems scales exponentially with HAQ index. Lines represent the evolution for years 1995, 2000, 2005, 2010 and 2015. Dots are proportional to population in 2015. The black line represents the regression with country fixed effects (see table 5.1 for coefficients). Luxembourg is an outlier and has therefore not been shown (see Appendix Figure 5.15 for Luxembourg). For ten countries, data has been smoothed over three years to avoid sawtooths that did not reflect real dynamics.

(black crosses of Figure 5.4a). Important differences remain: for example, Sweden's footprint is 55% lower than Finland's, while its per capita health expenditure is 29% higher. Disaggregating the footprint by sector also reveals differences. Direct energy use (blue bars in Figure 5.4a) is almost always the largest energy use sector, ranging from 13.2% of energy use in Switzerland to 47.5% in Japan (Figure 5.4b). The next largest energy use sectors are chemicals, other raw materials and transport which, together with direct energy use, account for 80% of the total footprint. The remaining 20% includes equipment, construction, food, energy production and "other". The low share of the energy production sector is due to the fact that final energy and not primary energy is studied here.

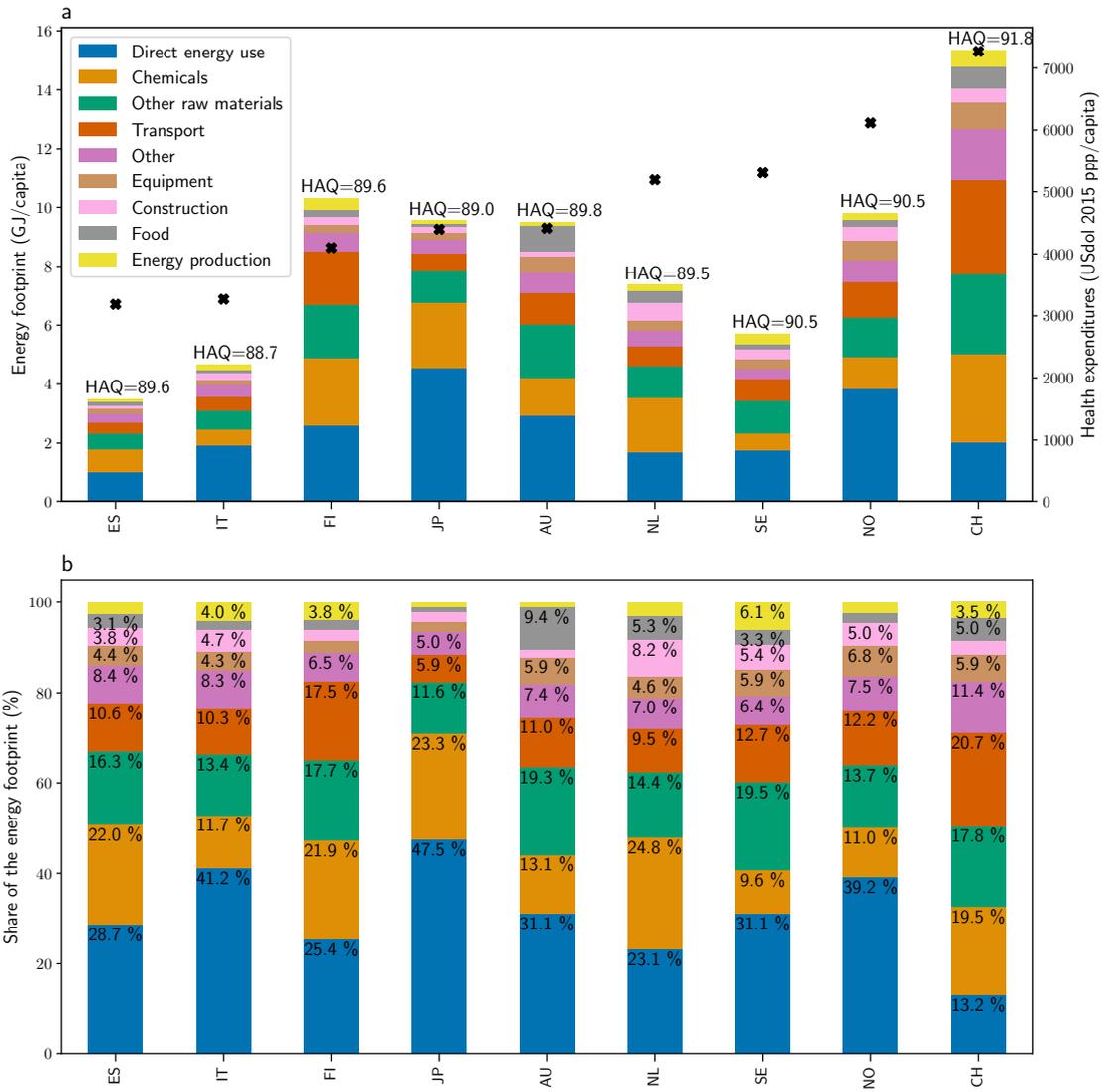
#### 5.1.3.4. ENERGY EFFICIENCY

Future variations in energy efficiency could also modify energy demand. When calculated in current US\$, energy intensities (the inverse of efficiency) decreased as a function of expenditures (figure 5.5a) and time (figure 5.5b). When calculated in constant 2015US\$ppp, no global trend was seen as a function of expenditures (figure 5.5c) or time (figure 5.5d). China was the only country whose energy intensity in constant 2015US\$ppp clearly increased, both as a function of time and expenditures (figure 5.5 c-d). This could be partly explained by the changes in the input structure of the sector. Over the 2002-2015 period, an increase in the cost of employment in the total inputs of the sector was correlated to a decrease of energy intensity (Supplementary Figure 5.16). For China, the cost of employment in total inputs dropped by 25% (Supplementary Table 5.13) while the energy intensity in constant 2015US\$ppp increased by 49% (Supplementary Table 5.14). However, as the cost of employment is linked to inflation, and that we corrected expenditure data for inflation, the exact role of the cost of employment in the energy intensity remains unclear.

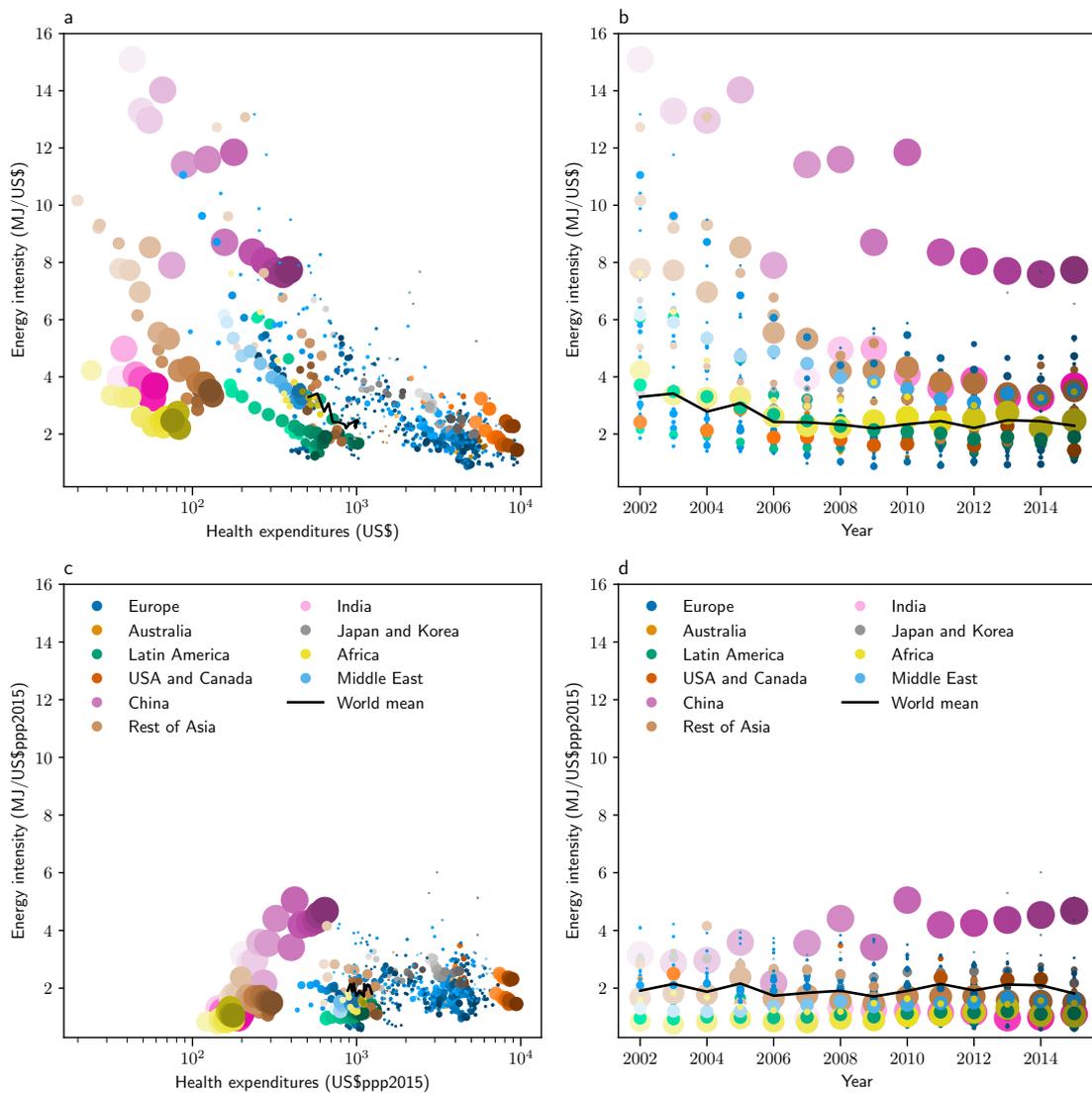
#### 5.1.4. DISCUSSION

Healthcare's resource footprints increased over the last two decades, reaching 7% of global non-metallic minerals, 4% of global metal ores and 5% of global fossil fuels use. In 2013, 80% of the healthcare systems relied at more than 50% on fossil fuels imports and 88% at more than 50% on metal ores imports. We found that the per capita energy footprint of healthcare scales exponentially with the HAQ index between regions (but not within regions). Moreover, the reference of the HAQ index being relative to the best reference region, the energy footprint for a given index could grow even more if healthcare systems keep shifting towards energy-intensive treatments. Energy footprint should therefore be taken into account in any new treatment or innovation in healthcare systems. Important differences exist between countries with a comparable HAQ index, showing that the exponential relationship could be changed. Direct energy use together with chemicals production represent around 50% of all the energy footprint. Finally, energy efficiency has not improved significantly between 2002 and 2015.

As no other study has assessed the global energy footprint of healthcare systems, we compare our greenhouse gas emissions results with previous studies. Our results for CO<sub>2</sub> emissions in



**FIGURE 5.4:** Energy footprint disaggregation for regions with HAQ indexes ranging from 88.7 to 91.8. (a) The stacked bars represent the energy footprint per capita of healthcare sectors, units are on the left-y-axis and colours correspond to sectors. The black crosses represent the health expenditures per capita; units are read on the right-y-axis. (b) Percentage disaggregation over the value chain of healthcare’s energy footprint. (a and b) ES: Spain, IT: Italy, FI: Finland, JP: Japan, AU: Australia, NL: Netherlands, SE: Sweden, NO: Norway, CH: Switzerland. Results for all countries are available in supplementary Tables 5.11 and 5.12.



**FIGURE 5.5:** Evolution of healthcare systems' energy intensities (inverse of efficiency) between 2002 and 2015. (a) Energy intensity in current dollars as a function of health expenditures. (b) Energy intensity in current dollars as a function of time. (c) Energy intensity in constant dollars as a function of health expenditures. (d) Energy intensity in constant dollars as a function of time. (a-d) Dots are proportional to population size. The darker the dots, the more recent the years.

2014 were similar to the previous multi-regional estimates using the Eora EE-MRIO database (Pichler et al., 2019) (Appendix Figure 5.17). Our results were also close to the values reported for 2015 in the Health Care Without Harm (Harm, 2019), which used the GTAP database to assess healthcare systems' climate footprint in 43 countries (Appendix Figure 5.18). In contrast, our results for greenhouse gases in 2015 differed significantly from those of Lenzen and colleagues (Lenzen, Malik, et al., 2020) (Appendix Figure 5.19). Unlike the other two multi-regional studies, they used the healthcare-related sectors directly from Eora, without harmonising the expenses with WHO's NHA database. This has the advantage of providing the best possible disaggregation of regional footprints but limits international comparisons due to different healthcare definitions. Furthermore, we account for the consumption of capital, which is not the case for Lenzen and colleagues.

Only top-down data were available for the present study, contrary to national studies that may have included bottom-up or hybrid approaches. The footprints of Austria (Weisz et al., 2020), Netherlands (Steenmeijer et al., 2022), Canada (Eckelman, J. D. Sherman, et al., 2018), and Australia (Malik et al., 2018) may have therefore been underestimated respectively by 27, 25, 12, and 11% while those of Japan (Nansai et al., 2020), China (X. Wu et al., 2021), England (Tennison et al., 2021), and the United-States (Eckelman and J. Sherman, 2016), and may have been overestimated respectively by 41, 36, 13 and 6%. Discrepancies can be explained by various definitions of healthcare systems along with more precise data available for single-country analysis due to the bottom-up or hybrid approaches used. For example, the top-down approach used in the present study does not include emissions by personal vehicles of patients, staff and visitors.

The exponential relationship between energy footprint and healthcare access and quality (Figure 5.4) can be explained by the fact that the disease burden—measured as disability-adjusted life years (DALYs) per 100,000 individuals—does not decrease linearly with health expenditures per capita. (Sterck et al., 2018) At low levels of expenditures, DALYs per 100,000 decrease exponentially but this steep decrease stops at around 500US\$ health expenditures per capita. (Roser et al., 2021) DALYs decrease slightly or not at all between 500US\$ and 9,500US\$. The steep decline corresponds to the drastic decrease of communicable diseases. (Roser et al., 2021) However, once DALYs due to communicable diseases are low, avoiding DALYs due to non-communicable diseases is much harder.

We found that energy efficiencies of healthcare systems have not changed significantly between 2002 and 2015. A previous study (Lenzen, Malik, et al., 2020) had shown that environmental intensities (impact per unit of expenditures) of a number of environmental indicators were steeply decreasing. However, these intensities were calculated using expenditures in current US\$ and not in constant US\$ppp, which accounts both for inflation and for differences in purchasing power. Energy transition scenarios rely heavily on energy intensity reduction to reach climate targets. An inter-comparison of three models has shown that a reduction of energy intensity from 2.4 to 6.8% per year for the next decade is necessary to reach the 2°C goal. (Gambhir et al., 2017) Our results show that the healthcare sector is not on such trend.

Our analysis shows that the environmental impacts of healthcare are not limited to green-

house gas emissions but rely on important resources use. The extraction and processing of these resources in turn impact human health and the environment.(Farjana et al., 2019) The IPBES states that “mining has had significant negative impacts on biodiversity, emissions of highly toxic pollutants, water quality and water distribution, and human health”.(Watson et al., n.d.) Most of the resources used by healthcare sectors in the Global North comes from the Global South, which has a lower HAQ index. Focusing on the decarbonization of energy systems will therefore not be enough for a transition towards just and sustainable healthcare and to navigate back into planetary boundaries.(Steffen et al., 2015)

Reducing healthcare systems' resource footprints is an imperative, especially in the Global North. In an analysis of Germany's healthcare sector's raw materials footprint combining quantitative data with desk research, interviews and a written survey, four priority areas were identified for resource efficiency: pharmaceuticals, medical devices, construction and supply of food and beverages.(Ostertag et al., 2021) Detailed strategies were elaborated for each of these areas and will be of great help for any health organization wishing to reduce its footprint.(Ostertag et al., 2021)

There are ethical reasons to argue that the reduction of healthcare's environmental footprint should not be patient-facing.(Katz, 2022) Here, we develop two parallel strategies that could be followed to reduce healthcare systems' footprint with neutral or positive impacts on health. The first strategy consists in engineering and sociotechnical interventions. These interventions could reduce by up to 40% the energy use of the England's National Health System (Tennison et al., 2021). All healthcare stakeholders should carry out material flow analysis on top of carbon footprints assessments. For example, surgical interventions are material intensive and unsustainable (Thiel, Schehlein, et al., 2017) but assessments that include resource and energy footprints for surgery are scarce (Drew et al., 2021). The use of appropriate auditing tools would help identify opportunities to reduce the footprint of surgical interventions (Thiel, Cassels-Brown, et al., 2020). Resource footprints would also be reduced by better designs of medical products and increased recycling.(Kane et al., 2018) Healthcare is also vulnerable to oil supply crises (Hess et al., 2011). For example, changes in energy prices affect ambulance systems' performance and safety characteristics.(Brown et al., 2013) To protect public health from future crises, energy scarcity must be anticipated and prepared, by reducing the demand and adapting systems (Frumkin et al., 2007). Some petroleum use consist in wasteful practices and can be simply reduced, such as using less single use plastics. Others are lifesaving, such as ambulances. Thermic ambulances could be replaced by electric ones as the electric mix shifts towards renewables. Though they would still rely on important resource consumptions, electric ambulances would be more resilient to oil crises and have a smaller climate impact. Other options to limit energy and resource consumption include developing telemedicine, limiting distances travelled for training and conferences, reducing food waste and systematically offering vegetarian meals sourced locally and in season.

The second strategy is based on the prevention of lifestyle-related non-communicable diseases. These diseases are currently responsible for the increased demand of healthcare systems. Reducing their prevalence would therefore reduce energy demand. For example, cardiovascu-

lar diseases, cancer and depressive disorders are three major causes of quality adjusted life years loss in Western countries.(Vos et al., 2020) The increasing prevalence of depressive disorders (Torre et al., 2021) has been associated with multiple environmental factors associated with the Western lifestyle relying on environmental degradation (e.g. impaired food quality (Marx et al., 2021), air pollution (Borroni et al., 2022), tobacco smoking (Wootton et al., 2020), a productivity-based society inducing burnout and professional bullying at the workplace (Allison et al., 2017)). Addressing these risk factors would help improve both the risk of depressive and cardiovascular disorders and reduce their associated costs, reducing demand for healthcare systems. Diet is a good example: Western diet includes high proportions of red meat and ultra-processed food that have high energy costs for their production. Red meat consumption has been associated with increased risk of colon cancer and the consumption of ultra-processed food with increased risk of obesity. Promoting the Mediterranean diet (including reduced meat and fish consumption and increased organic legumes, fruits and vegetables) has a low environmental impact and is effective in the prevention of noncommunicable diseases (Lassale et al., 2019). Similarly, cycling and walking may help reduce transport energy cost and at the same time prevent non-communicable diseases induced by sedentary lifestyle (Woodcock et al., 2009). Pricing that favours prevention and health promotion, not just fee-for-service could encourage professionals to change their model more quickly.

This should take place in the broader planetary health care framework whose principles are (1) to reduce demand for health services, (2) to ensure appropriate care and avoid unnecessary investigations and treatments, and (3) to reduce impacts from the supply of health services (MacNeill et al., 2021). If these strategies combined are not enough to reduce healthcare's footprint to a sustainable level, an option would be to shift the remaining burden from healthcare to other sectors. However, that would require planning and explicit prioritisation of healthcare over other economic sectors.

Health care systems have a duty to set an example and act as ambassadors. Healthcare professionals would therefore have to be trained to respond to these issues properly. According to a recent study carried out in France among 3384 health students, only 60 (31%) of their 193 institutions integrated training over environmental issues.(Sarfati et al., 2022) When provided, these programs represent in average only 0.4% of the total training duration and a systematic approach and general strategy are often missing.(Orhan et al., 2021)) Moreover, courses on the environment are often optional, with no direct link to the management of institutions, financial profitability or resilience in the event of crises.

#### 5.1.4.1. LIMITS

The main limits are those inherent to input-output modelling, in particular to the raw data used to build environmental extensions. EXIOBASE3 does not provide measurement errors so it was not possible to propagate the uncertainties as can be done with other input-output databases. However, a previous study on the environmental footprints of healthcare systems (Lenzen, Malik, et al., 2020) used Monte-Carlo techniques to assess the uncertainty of their results from the standard deviations provided by the Eora database. They found final standard

deviations of less than 5%.(Lenzen, Malik, et al., 2020)

#### **5.1.5. CONCLUSION**

When comparing regions, we found that exponential amounts of resources were required to support the development of health access and quality systems. As the environmental impacts associated with these resources are responsible for an increase in some non-communicable diseases, health systems find themselves in the midst of a vicious cycle. To navigate back inside planetary boundaries, healthcare environmental strategies must be broader than greenhouse gases and include objectives in terms of resources use. As the exponential relationship exists between regions but not within regions, it seems possible to break the trend. We therefore call for the creation of a Healthcare Access, Quality and Efficiency (HAQE) index that would include both access/quality and resource/energy footprints in its calculation. This would encourage policy makers to act promptly to limit the environmental damage caused by health care systems.

#### **CONTRIBUTORS**

BA was responsible for conceptualisation. All authors contributed to literature search. BA and OV were responsible for data curation. All authors contributed to data analysis and interpretation of results. BA, GF and LM wrote the original draft. All authors were responsible for writing – review & editing. All authors had access to all data in the study and the corresponding author had final responsibility for the decision to submit for publication.

#### **DECLARATION OF INTERESTS**

ME is a consultant to P4H Network-WHO. All other authors declare no competing interests.

#### **DATA SHARING**

1239 socio-environmental impacts of 49 healthcare systems over the period 1995-2015 have been calculated. The dataset has been submitted along with the manuscript and will be made publicly available online upon publication. The code to reproduce the study is available at: <https://github.com/baptiste-an/Energy-and-HAQ>

#### **ACKNOWLEDGEMENTS**

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## 5.1.6. SUPPLEMENTARY INFORMATION

### 5.1.6.1. SUPPLEMENTARY METHODS

**Data collection** Footprint calculations over the whole period with available energy or resources data (1995-2015) are limited by data the World Health Organization’ Global Health Expenditures database (GHE), which starts in 2000.(World Health Organization, n.d.) We have completed GHE data using the OECD health expenditure database for years 1995-1999.(OECD, n.d.) For the regions missing from the OECD database, we have made the hypothesis that the global health expenditures were proportional to EXIOBASE3 expenditures in the sector “Health and social work services”, using the proportionality factor of year 2000. This resulted in aggregated health expenditures for all EXIOBASE regions between 1995 and 2015. These expenditures then had to be disaggregated into EXIOBASE sectors. We have used OECD health expenditure data to build a concordance matrix between aggregated health expenditures and EXIOBASE3 sectors (Table 5.2). OECD data is disaggregated into 9 provider categories and 23 sub-categories.(OECD, n.d.) Among these sub categories, seven correspond to sectors other than “Health and social work services”. The database provides 2621 out of 7203 possible data points (49 EXIOBASE regions, 21 years and seven sectors), all others are extrapolated or interpolated. If a region is not in the database at all, shares for these seven sub categories are considered equal to the weighted mean of all available data points.

TABLE 5.2: OECD-EXIOBASE3 concordance table

| OECD provider name   | Corresponding EXIOBASE3 sector                             |                                      |
|--|--|--------------------------------------|
| Hospitals<br><br><br><br><br><br>Residential long-term care facilities | General hospitals  | Health and social work services (85) |
|  | Mental health hospitals                                    | Health and social work services (85) |
|  | Specialised hospitals (other than mental health hospitals) | Health and social work services (85) |
|  | Long-term nursing care facilities                          | Health and social work services (85) |
|  | Mental health and substance abuse facilities               | Health and social work services (85) |
|  | Other residential long-term care facilities                | Health and social work services (85) |
|  |  |                                      |

Continued on next page

**Table 5.2 – continued from previous page**

| <b>OECD provider name</b>                                    | <b>Corresponding EXIOBASE3 sector</b>  |  |
|--|--|--|
| Providers of ambulatory health care                          | Medical practices<br>Dental practices<br>Other health care practitioners<br>Ambulatory health care centres<br>Providers of home health care services   | Health and social work services (85)<br>Health and social work services (85) |
| Providers of ancillary services                              | Providers of patient transportation and emergency rescue<br>Medical and diagnostic laboratories<br>Other providers of ancillary services   | Health and social work services (85)<br>Health and social work services (85)<br>Health and social work services (85)   |
| Retailers and other providers of medical goods               | Pharmacies<br>Retail sellers and other suppliers of durable medical goods and medical appliances<br>All other miscellaneous sellers and other suppliers of pharmaceuticals and medical goods | Chemicals nec<br>Retail trade services, except of motor vehicles and motorcycles; repair services of personal and household goods (52)<br>Health and social work services (85)                       |
| Providers of preventive care                                 | Health and social work services (85)   |  |
| Providers of health care system administration and financing | Government health administration agencies  | Public administration and defence services; compulsory social security services (75)   |
|  |  | Continued on next page   |

Table 5.2 – continued from previous page

| OECD provider name  | Corresponding EXIOBASE3 sector                             |   |
|---------------------|--|---|
| Rest of the economy | Social health insurance agencies                           | Insurance and pension funding services, except compulsory social security services (66) |
|                     | Private health insurance administration agencies           | Insurance and pension funding services, except compulsory social security services (66) |
|                     | Other administration agencies                              | Public administration and defence services; compulsory social security services (75)    |
|                     | Households as providers of home health care                | Private households with employed persons (95)   |
| Rest of the world   | All other industries as secondary providers of health care | Health and social work services (85)  |
| Providers unknown   | Health and social work services (85)                       |   |

**Data analysis** Calculations were made with the python module pymrio (Stadler, 2015). Matrix  $Z$  represents the inter-industries flows and  $Y$  the final consumption matrix. The total industrial output is given by

$$x = Z \cdot e + Y \cdot e \quad (5.1)$$

where  $e$  is a summation vector. Capital endogenization consists in adding to  $Z$  a matrix  $\bar{K}$  representing the inter-industries flows of capital (C.-J. H. Södersten et al., 2018b). We have chosen to endogenize the consumption of fixed capital as it measures only the decline in value of fixed assets due to the production process a given year and does not include further investments that will allow future production. Following input-output formalism, the direct requirement matrix  $A^K$  with capital endogenized is

$$A^K = (Z + \bar{K}) \cdot x^{-1} \quad (5.2)$$

And the Leontief inverse

$$L^K = (I - A^K)^{-1} \quad (5.3)$$

Energy and resources footprints are calculated using their associated environmental extensions  $f$ . The consumption-based account footprint  $D_{cba}$  of a vector of final consumption  $y$

writes:

$$D_{cba} = f \cdot L^K \cdot y \quad (5.4)$$

**Extensions** All the energy data in the paper refers to final energy. It was calculated by subtracting the EXIOBASE extension “Energy Carrier Net LOSS” to the EXIOBASE extension “Energy Carrier Net Total”, which refers to primary energy (Stadler, Wood, Bulavskaya, C.-J. Södersten, Simas, S. Schmidt, Usubiaga, Acosta-Fernández, Kuenen, Bruckner, Giljum, Lutter, Merciai, Jannick H. Schmidt, et al., 2018). The main data source for the construction of the energy extensions is the International Energy Agency’s (IEA) extended energy balances. The uncertainties associated with the extensions are those of the IEA data itself, combined with the uncertainty of conversion from the residence to the territory principle (Usubiaga et al., 2018). The EXIOBASE authors argue that these extensions are a good basis for calculating footprints at a macro-level, which is the case for the present study (we are not providing results with the value chain disaggregated at the meso level). For an extensive description and discussion on the energy extensions, see the following supplementary information from the EXIOBASE paper (Stadler, Wood, Bulavskaya, C.-J. Södersten, Simas, S. Schmidt, Usubiaga, Acosta-Fernández, Kuenen, Bruckner, Giljum, Lutter, Merciai, Jannick H. Schmidt, et al., 2018): EXIOBASE Supplementary Material 2 As for the minerals extensions, many data sources are used (BGS, WMD, USGS, and official statistics). The procedure to compile the extensions are detailed in a supplementary information but the uncertainties are not discussed in it (Giljum et al., 2018): EXIOBASE Supplementary Material 5

**Taiwan data** Taiwan was not in the Global Health Expenditure Database. (World Health Organization, n.d.) We calculated expenditures for Taiwan assuming that they were proportional to Chinese expenditures, using the ratio of proportionality for EXIOBASE’s sector “Health and social work services (85)”.

#### 5.1.6.2. SUPPLEMENTARY RESULTS

##### Evolution of resource footprints of healthcare systems between 1995 and 2013

|                       | region          | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|-----------------------|-----------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Fossil fuel           | Africa          | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
|                       | Australia       | 0.26 | 0.32 | 0.28 | 0.4  | 0.32 | 0.35 | 0.4  | 0.42 | 0.48 | 0.49 | 0.38 | 0.47 | 0.48 | 0.44 | 0.55 | 0.43 | 0.43 | 0.51 | 0.45 |
|                       | China           | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.04 | 0.05 | 0.05 | 0.04 | 0.06 | 0.08 | 0.08 | 0.13 | 0.12 | 0.12 | 0.16 |
|                       | Europe          | 0.1  | 0.14 | 0.14 | 0.13 | 0.13 | 0.13 | 0.16 | 0.16 | 0.16 | 0.17 | 0.18 | 0.18 | 0.17 | 0.19 | 0.2  | 0.18 | 0.18 | 0.19 | 0.17 |
|                       | India           | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
|                       | Japan and Korea | 0.14 | 0.18 | 0.19 | 0.15 | 0.17 | 0.2  | 0.16 | 0.19 | 0.2  | 0.22 | 0.21 | 0.17 | 0.21 | 0.19 | 0.2  | 0.21 | 0.28 | 0.28 | 0.27 |
|                       | Latin America   | 0.04 | 0.03 | 0.04 | 0.04 | 0.04 | 0.03 | 0.04 | 0.04 | 0.03 | 0.03 | 0.04 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
|                       | Middle East     | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
|                       | Rest of Asia    | 0.07 | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
|                       | USA and Canada  | 0.34 | 0.42 | 0.42 | 0.42 | 0.44 | 0.47 | 0.47 | 0.47 | 0.47 | 0.47 | 0.57 | 0.51 | 0.52 | 0.45 | 0.43 | 0.41 | 0.45 | 0.45 | 0.52 |
| Metal ores            | Africa          | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
|                       | Australia       | 0.21 | 0.22 | 0.25 | 0.35 | 0.31 | 0.29 | 0.43 | 0.54 | 0.5  | 0.44 | 0.35 | 0.3  | 0.33 | 0.3  | 0.44 | 0.34 | 0.35 | 0.37 | 0.36 |
|                       | China           | 0    | 0    | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.05 | 0.05 | 0.06 | 0.06 |
|                       | Europe          | 0.04 | 0.06 | 0.06 | 0.07 | 0.08 | 0.07 | 0.08 | 0.09 | 0.09 | 0.08 | 0.08 | 0.09 | 0.08 | 0.09 | 0.09 | 0.09 | 0.09 | 0.08 | 0.09 |
|                       | India           | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0.01 | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |
|                       | Japan and Korea | 0.11 | 0.12 | 0.12 | 0.1  | 0.12 | 0.14 | 0.13 | 0.13 | 0.14 | 0.14 | 0.14 | 0.13 | 0.16 | 0.13 | 0.15 | 0.17 | 0.22 | 0.2  | 0.18 |
|                       | Latin America   | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
|                       | Middle East     | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.03 | 0.03 |
|                       | Rest of Asia    | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
|                       | USA and Canada  | 0.36 | 0.45 | 0.45 | 0.45 | 0.41 | 0.41 | 0.42 | 0.42 | 0.43 | 0.5  | 0.45 | 0.47 | 0.42 | 0.47 | 0.45 | 0.4  | 0.29 | 0.26 | 0.29 |
| Non-metallic minerals | Africa          | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.03 | 0.03 | 0.04 | 0.03 | 0.03 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.06 |
|                       | Australia       | 0.23 | 0.27 | 0.25 | 0.28 | 0.28 | 0.28 | 0.31 | 0.39 | 0.4  | 0.43 | 0.44 | 0.38 | 0.43 | 0.44 | 0.56 | 0.47 | 0.6  | 0.65 | 0.61 |
|                       | China           | 0.05 | 0.04 | 0.07 | 0.09 | 0.1  | 0.13 | 0.13 | 0.16 | 0.18 | 0.18 | 0.22 | 0.09 | 0.26 | 0.39 | 0.45 | 0.68 | 0.66 | 0.79 | 0.9  |
|                       | Europe          | 0.37 | 0.37 | 0.4  | 0.43 | 0.44 | 0.44 | 0.5  | 0.5  | 0.52 | 0.55 | 0.6  | 0.59 | 0.61 | 0.59 | 0.6  | 0.58 | 0.62 | 0.64 | 0.6  |
|                       | India           | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 | 0.03 | 0.02 | 0.03 | 0.02 | 0.02 | 0.05 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 |
|                       | Japan and Korea | 0.29 | 0.34 | 0.4  | 0.32 | 0.37 | 0.43 | 0.37 | 0.44 | 0.44 | 0.45 | 0.44 | 0.42 | 0.49 | 0.42 | 0.48 | 0.52 | 0.72 | 0.68 | 0.67 |
|                       | Latin America   | 0.09 | 0.09 | 0.1  | 0.09 | 0.12 | 0.11 | 0.1  | 0.09 | 0.1  | 0.1  | 0.11 | 0.11 | 0.13 | 0.14 | 0.15 | 0.14 | 0.16 | 0.16 | 0.17 |
|                       | Middle East     | 0.1  | 0.1  | 0.1  | 0.1  | 0.13 | 0.12 | 0.11 | 0.14 | 0.14 | 0.12 | 0.12 | 0.14 | 0.2  | 0.18 | 0.23 | 0.34 | 0.26 | 0.44 | 0.45 |
|                       | Rest of Asia    | 0.14 | 0.09 | 0.16 | 0.09 | 0.08 | 0.06 | 0.05 | 0.06 | 0.06 | 0.07 | 0.08 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.08 | 0.07 |
|                       | USA and Canada  | 0.87 | 1.02 | 1.02 | 1.05 | 1.09 | 1.13 | 1.19 | 1.23 | 1.28 | 1.5  | 1.41 | 1.44 | 1.26 | 1.23 | 1.2  | 1.37 | 1.37 | 1.55 | 1.71 |

TABLE 5.3: Figure 5.1 b-d-f data, per capita footprints

|       | Non-metallic minerals | Metal ores | Fossil fuel | Final energy |
|-------|-----------------------|------------|-------------|--------------|
| World | 35.3                  | 44.0       | 21.0        | 18.5         |
| AT    | 62.0                  | 52.2       | 22.6        | 17.5         |
| AU    | 43.1                  | 35.7       | 27.0        | 15.9         |
| BE    | 39.9                  | 39.0       | 21.0        | 18.7         |
| BG    | 30.0                  | 36.5       | 11.8        | 16.4         |
| BR    | 42.4                  | 44.3       | 20.5        | 19.4         |
| CA    | 61.5                  | 19.3       | 26.3        | 16.7         |
| CH    | 59.2                  | 37.3       | 43.5        | 30.6         |
| CN    | 14.8                  | 40.8       | 16.2        | 14.2         |
| CY    | 33.7                  | 43.6       | 16.7        | 16.3         |
| CZ    | 49.2                  | 39.4       | 16.4        | 16.5         |
| DE    | 53.2                  | 50.8       | 33.7        | 20.2         |
| DK    | 63.6                  | 58.8       | 34.8        | 12.9         |
| EE    | 51.4                  | 35.6       | 25.6        | 15.3         |
| ES    | 41.3                  | 37.8       | 18.6        | 21.0         |
| FI    | 52.3                  | 40.6       | 23.1        | 12.9         |
| FR    | 71.0                  | 69.5       | 43.6        | 33.6         |
| GB    | 35.6                  | 35.8       | 15.7        | 13.6         |
| GR    | 75.6                  | 57.2       | 22.4        | 17.6         |
| HR    | 27.6                  | 38.0       | 21.0        | 15.7         |
| HU    | 25.6                  | 45.6       | 14.6        | 16.4         |
| "ID"  | 69.0                  | 77.1       | 25.6        | 18.5         |
| IE    | 58.9                  | 59.7       | 36.9        | 24.8         |
| IN    | 25.5                  | 40.6       | 26.9        | 17.5         |
| IT    | 65.8                  | 55.8       | 18.9        | 21.4         |
| JP    | 46.6                  | 50.9       | 23.1        | 16.9         |
| KR    | 53.3                  | 59.8       | 24.7        | 19.0         |
| LT    | 14.9                  | 31.9       | 6.9         | 13.3         |
| LU    | 23.4                  | 29.8       | 15.3        | 14.5         |
| LV    | 72.7                  | 48.9       | 30.9        | 22.5         |
| MT    | 11.6                  | 16.6       | 9.9         | 11.8         |
| MX    | 63.4                  | 34.8       | 12.6        | 19.7         |
| NL    | 66.1                  | 56.3       | 31.6        | 31.0         |
| NO    | 51.2                  | 43.1       | 30.6        | 22.0         |
| PL    | 62.6                  | 43.9       | 12.7        | 5.8          |
| PT    | 51.7                  | 41.3       | 21.6        | 15.1         |
| RO    | 66.0                  | 50.7       | 26.8        | 20.6         |
| RU    | 64.4                  | 38.9       | 17.3        | 15.5         |
| SE    | 66.6                  | 51.4       | 39.9        | 24.6         |
| SI    | 48.8                  | 43.2       | 15.5        | 16.9         |
| SK    | 52.5                  | 38.7       | 19.9        | 11.6         |
| TR    | 18.5                  | 35.5       | 14.4        | 5.7          |
| TW    | 56.0                  | 44.4       | 13.8        | 8.9          |
| US    | 61.8                  | 47.6       | 22.7        | 20.5         |
| WA    | 47.3                  | 55.4       | 26.4        | 22.4         |
| WE    | 37.6                  | 29.5       | 10.6        | 9.6          |
| WF    | 40.2                  | 22.3       | 23.4        | 26.1         |
| WL    | 42.4                  | 29.5       | 17.1        | 16.6         |
| WM    | 27.6                  | 40.2       | 31.5        | 25.0         |
| ZA    | 53.3                  | 30.2       | 20.4        | 24.9         |

TABLE 5.4: Share of the total footprint due to the endogenization of capital, in %. See Table 5.15 for region names abbreviations.

**Healthcare systems' dependency to resources in 2013** We assessed the flows of resources in between regions to find out if some regions produced more resources than what they used, taking into account only the resources used by healthcare systems.

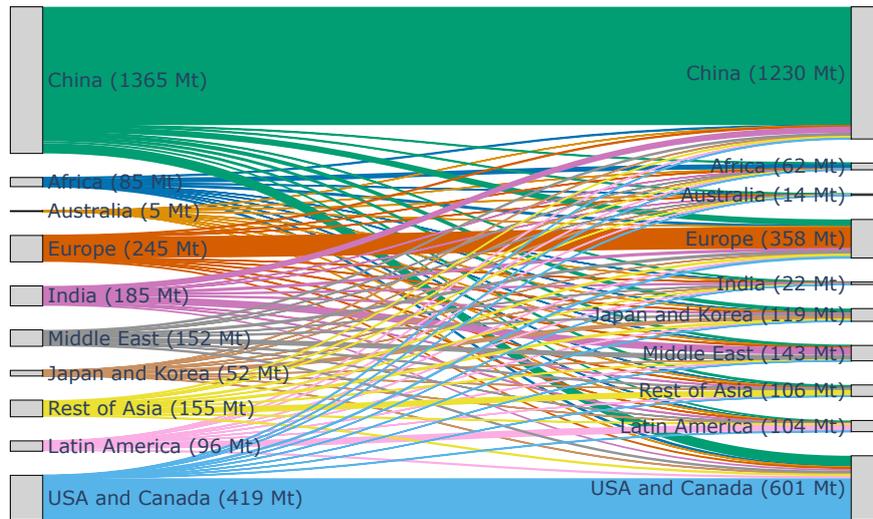


FIGURE 5.6: Healthcare non-metallic minerals sankey diagram for 2013

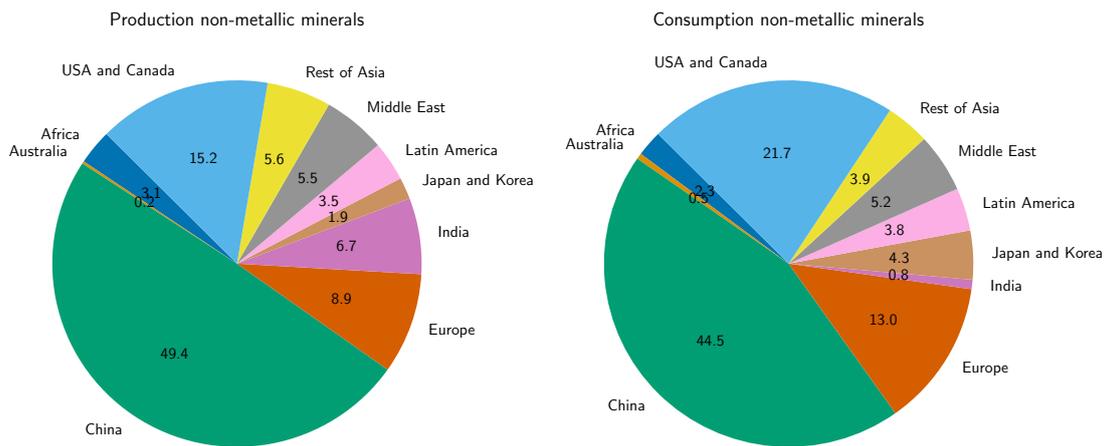


FIGURE 5.7: Healthcare non-metallic minerals production and consumption in 2013

| Non-metallic minerals | Production (%) | Consumption (%) | Population (%) |
|-----------------------|----------------|-----------------|----------------|
| Global North          | 27             | 40              | 18             |
| China                 | 49             | 44              | 19             |
| Rest of Global South  | 24             | 16              | 63             |

TABLE 5.5: Non-metallic minerals shares

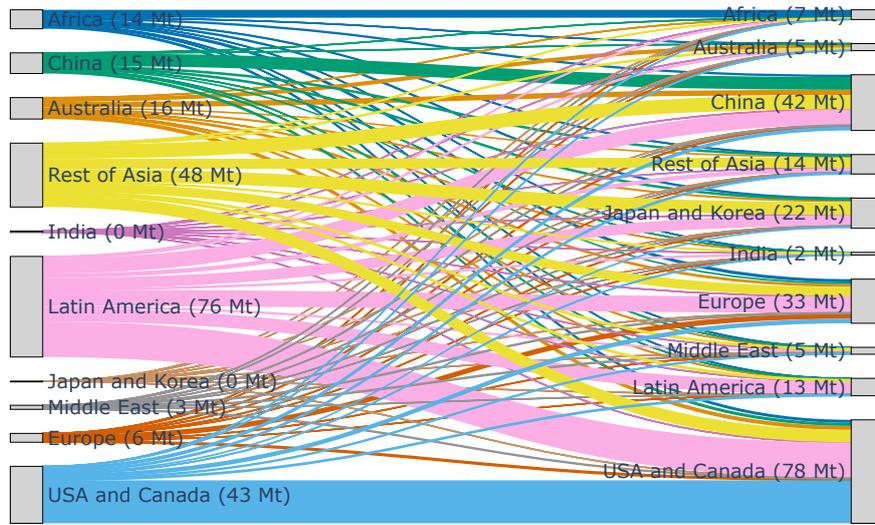


FIGURE 5.8: Healthcare non-ferrous metal ores sankey diagram for 2013

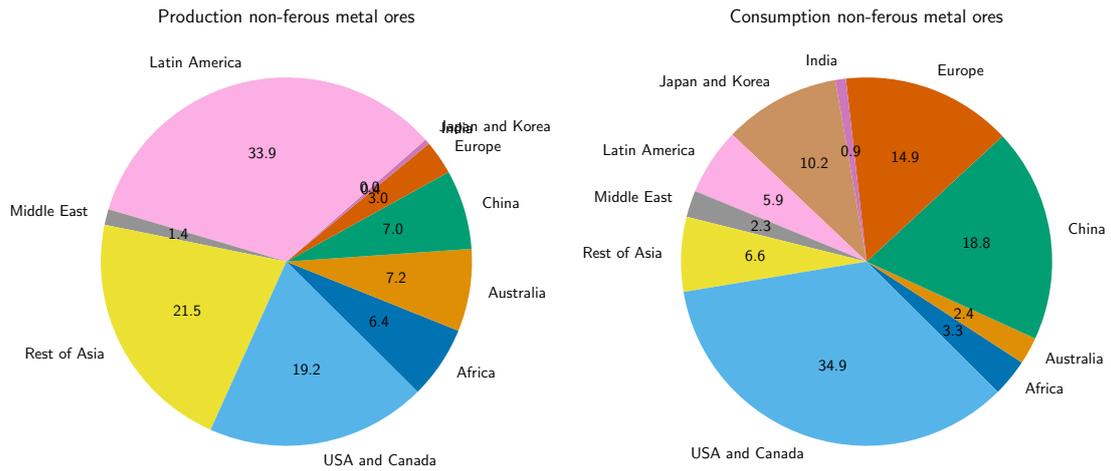


FIGURE 5.9: Healthcare non-ferrous metal ores production and consumption in 2013

| Non-ferrous metal ores | Production (%) | Consumption (%) | Population (%) |
|------------------------|----------------|-----------------|----------------|
| Global North           | 29             | 62              | 18             |
| China                  | 7              | 19              | 19             |
| Rest of Global South   | 64             | 19              | 63             |

TABLE 5.6: Non-ferrous metal ores shares

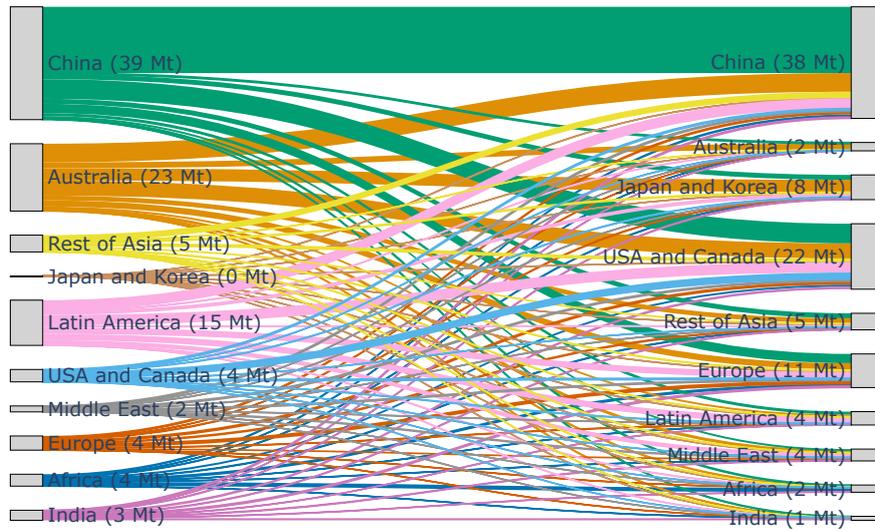


FIGURE 5.10: Healthcare iron ore sankey diagram for 2013

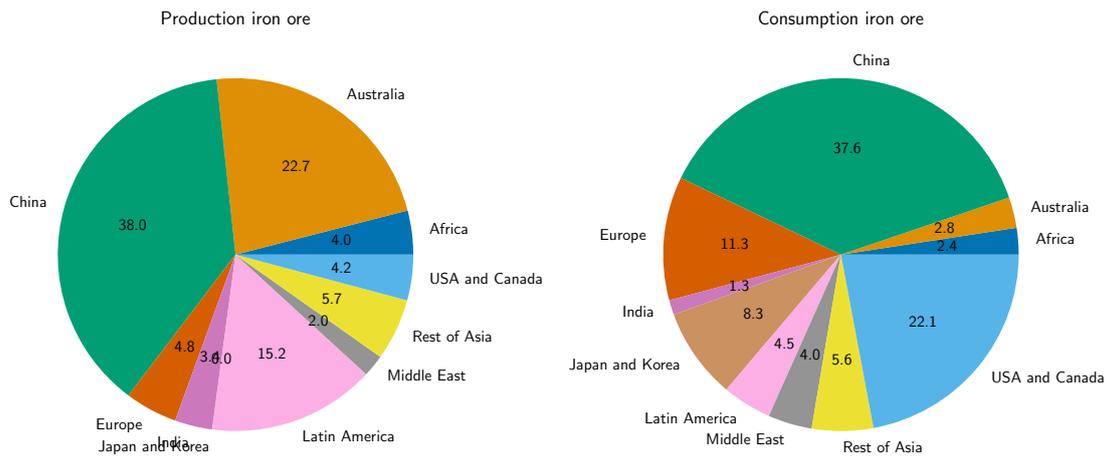


FIGURE 5.11: Healthcare iron ore production and consumption in 2013

| Iron ore             | Production (%) | Consumption (%) | Population (%) |
|----------------------|----------------|-----------------|----------------|
| Global North         | 32             | 44              | 18             |
| China                | 38             | 38              | 19             |
| Rest of Global South | 30             | 18              | 63             |

TABLE 5.7: Iron ore shares

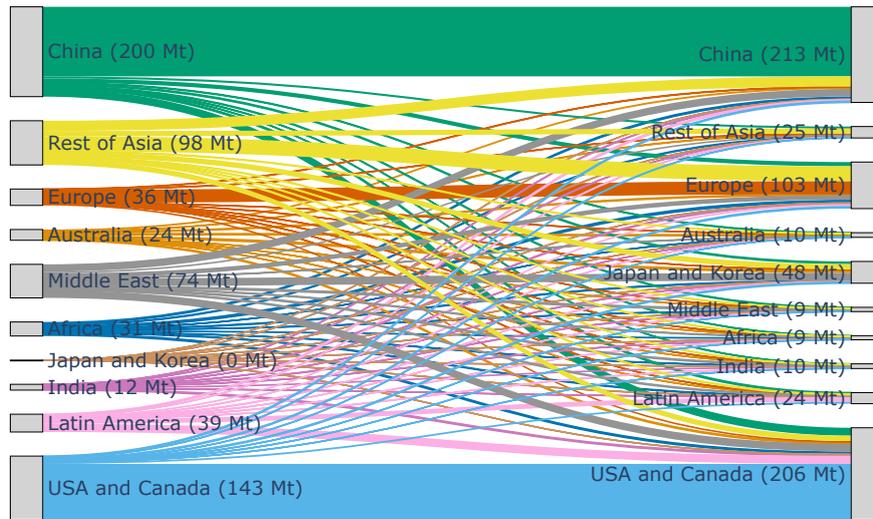


FIGURE 5.12: Healthcare fossil fuels sankey diagram in 2013

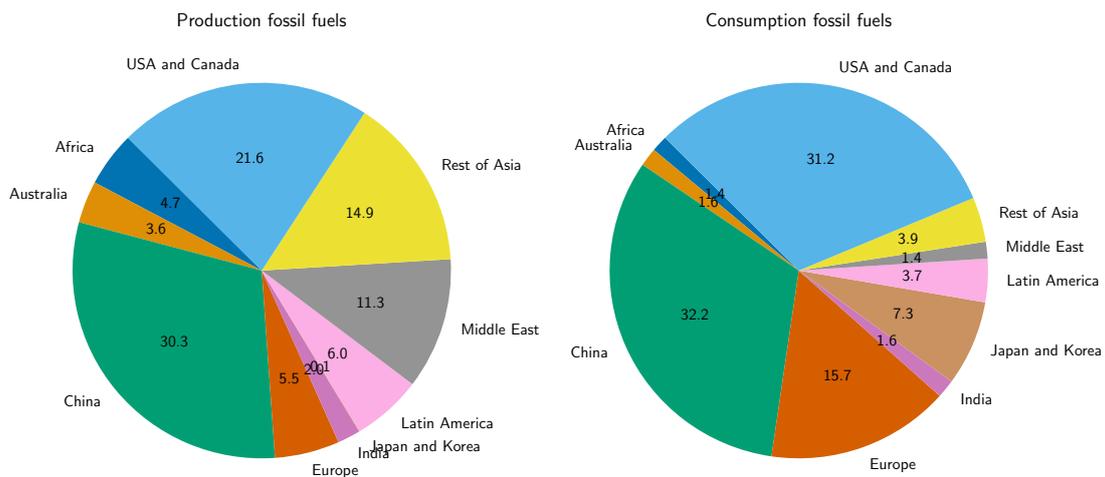


FIGURE 5.13: Healthcare fossil fuels production and consumption diagram for 2013

| Fossil fuels         | Production (%) | Consumption (%) | Population (%) |
|----------------------|----------------|-----------------|----------------|
| Global North         | 31             | 56              | 18             |
| China                | 30             | 32              | 19             |
| Rest of Global South | 39             | 12              | 63             |

TABLE 5.8: Fossil fuel shares

These flows allowed to produce the maps of figure 5.2 in the paper. The detailed percentages of imports are given in figure 5.14 and table 5.9.

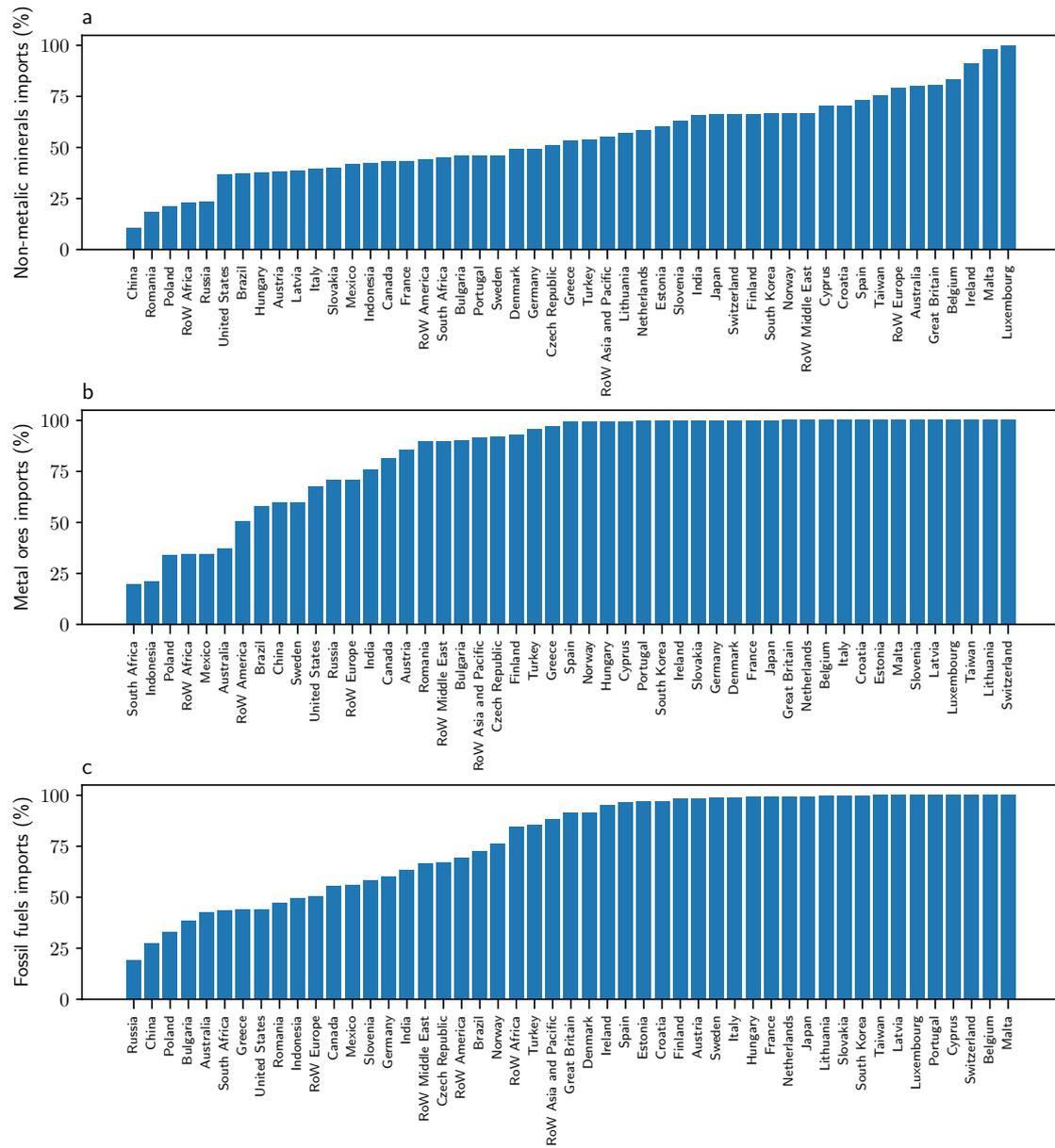


FIGURE 5.14: Regional import dependencies

|                      | Non-metallic minerals | Metal ores | Fossil fuels |
|----------------------|-----------------------|------------|--------------|
| Austria              | 38%                   | 86%        | 99%          |
| Australia            | 80%                   | 37%        | 43%          |
| Belgium              | 83%                   | 100%       | 100%         |
| Bulgaria             | 46%                   | 90%        | 39%          |
| Brazil               | 37%                   | 58%        | 73%          |
| Canada               | 43%                   | 81%        | 56%          |
| Switzerland          | 66%                   | 100%       | 100%         |
| China                | 10%                   | 60%        | 27%          |
| Cyprus               | 70%                   | 100%       | 100%         |
| Czech Republic       | 51%                   | 92%        | 67%          |
| Germany              | 49%                   | 100%       | 60%          |
| Denmark              | 49%                   | 100%       | 92%          |
| Estonia              | 60%                   | 100%       | 97%          |
| Spain                | 73%                   | 99%        | 97%          |
| Finland              | 66%                   | 93%        | 98%          |
| France               | 43%                   | 100%       | 99%          |
| Great Britain        | 80%                   | 100%       | 92%          |
| Greece               | 53%                   | 97%        | 44%          |
| Croatia              | 70%                   | 100%       | 97%          |
| Hungary              | 38%                   | 99%        | 99%          |
| Indonesia            | 42%                   | 21%        | 50%          |
| Ireland              | 91%                   | 100%       | 95%          |
| India                | 66%                   | 76%        | 63%          |
| Italy                | 39%                   | 100%       | 99%          |
| Japan                | 66%                   | 100%       | 99%          |
| South Korea          | 67%                   | 100%       | 100%         |
| Lithuania            | 57%                   | 100%       | 100%         |
| Luxembourg           | 100%                  | 100%       | 100%         |
| Latvia               | 38%                   | 100%       | 100%         |
| Malta                | 98%                   | 100%       | 100%         |
| Mexico               | 42%                   | 35%        | 56%          |
| Netherlands          | 58%                   | 100%       | 99%          |
| Norway               | 67%                   | 99%        | 76%          |
| Poland               | 21%                   | 34%        | 33%          |
| Portugal             | 46%                   | 100%       | 100%         |
| Romania              | 19%                   | 89%        | 47%          |
| Russia               | 24%                   | 71%        | 19%          |
| Sweden               | 46%                   | 60%        | 99%          |
| Slovenia             | 63%                   | 100%       | 58%          |
| Slovakia             | 40%                   | 100%       | 100%         |
| Turkey               | 54%                   | 96%        | 86%          |
| Taiwan               | 75%                   | 100%       | 100%         |
| United States        | 37%                   | 68%        | 44%          |
| RoW Asia and Pacific | 55%                   | 91%        | 88%          |
| RoW Europe           | 79%                   | 71%        | 50%          |
| RoW Africa           | 23%                   | 34%        | 85%          |
| RoW America          | 44%                   | 50%        | 69%          |
| RoW Middle East      | 67%                   | 89%        | 67%          |
| South Africa         | 45%                   | 19%        | 43%          |

TABLE 5.9: Regional import dependencies

Some regions show surprisingly high levels of import dependency. Though the Middle East produces 74 Mt of fossil fuels for healthcare systems and consumes only 9 Mt, it is dependent

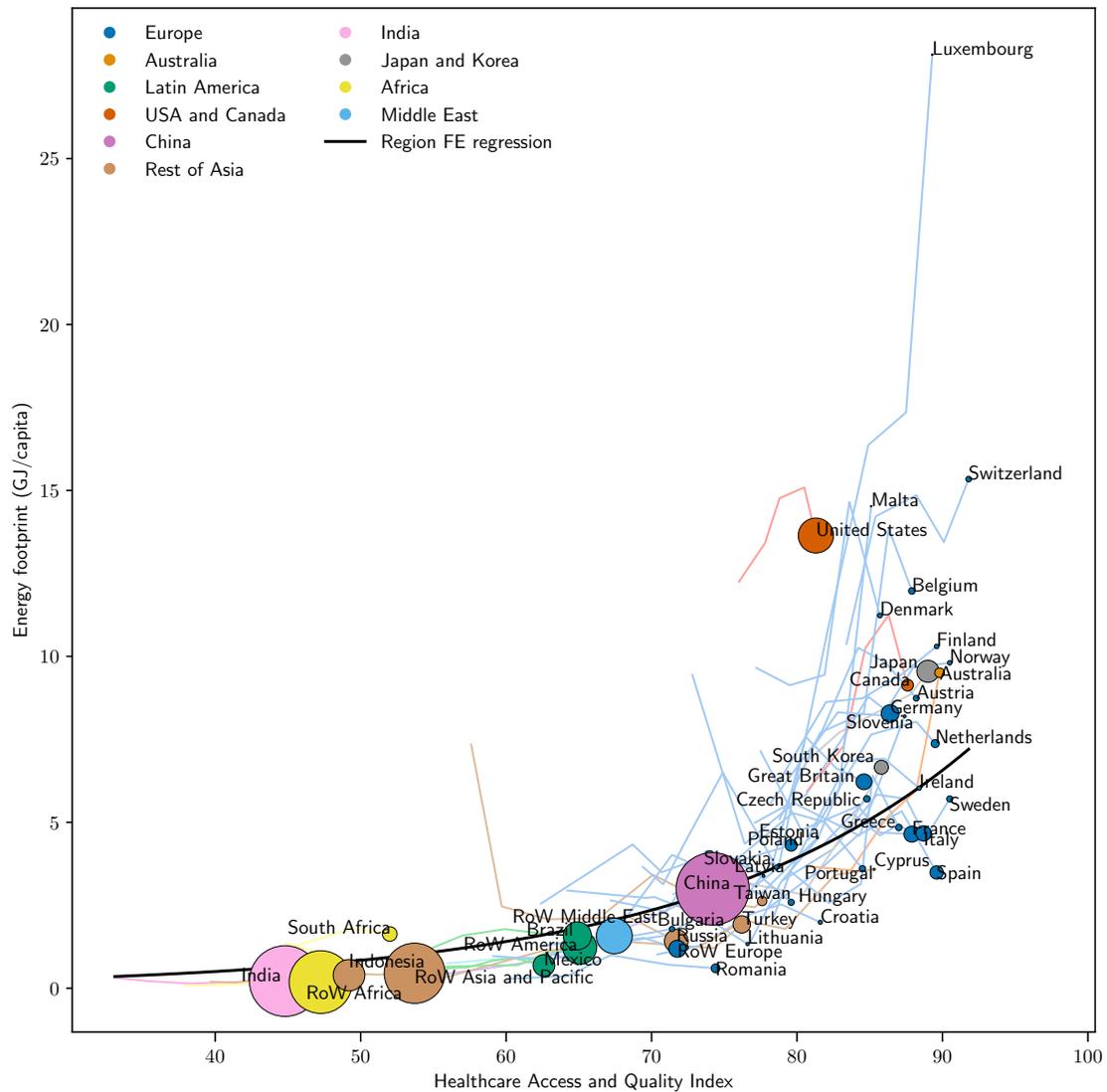


FIGURE 5.15: Energy footprint of healthcare systems including Luxembourg Identical to Figure 5.3 in the paper but including Luxembourg

at 67% on fossil fuel imports. This comes from the fossil fuels embodied in the goods imported in the Middle East. For example, if the Middle East imports drugs from the United States and that these drugs were produced using fossil fuels that did not come from the Middle East.

**Relationship between the energy footprint and access and quality (HAQ index)** As Luxembourg is an outlier, it was cut out of Figure 5.3 in the paper to increase its readability. Figure 5.15 corresponds to Figure 5.3 in the paper, including Luxembourg.

| region | Estimated effect |
|--------|------------------|
| WF     | -1.5             |
| RO     | -1.34            |
| ID     | -0.87            |
| IN     | -0.81            |
| WA     | -0.72            |
| TR     | -0.72            |
| HR     | -0.64            |
| MX     | -0.61            |
| WL     | -0.54            |
| CN     | -0.53            |
| CY     | -0.53            |
| WE     | -0.5             |
| BG     | -0.43            |
| WM     | -0.4             |
| ES     | -0.26            |
| GR     | -0.2             |
| PL     | -0.16            |
| SE     | -0.13            |
| LT     | -0.07            |
| IT     | -0.07            |
| EE     | -0.03            |
| AU     | -0.01            |
| KR     | -0.01            |
| TW     | 0.01             |
| IE     | 0.01             |
| HU     | 0.07             |
| CZ     | 0.07             |
| PT     | 0.08             |
| BR     | 0.08             |
| FR     | 0.13             |
| MT     | 0.15             |
| GB     | 0.23             |
| NL     | 0.28             |
| LV     | 0.36             |
| RU     | 0.4              |
| SK     | 0.42             |
| SI     | 0.42             |
| DE     | 0.44             |
| NO     | 0.46             |
| JP     | 0.47             |
| CA     | 0.54             |
| AT     | 0.55             |
| ZA     | 0.59             |
| FI     | 0.61             |
| BE     | 0.61             |
| CH     | 0.85             |
| DK     | 0.92             |
| LU     | 0.94             |
| US     | 1.39             |

TABLE 5.10: Regional fixed effects results. See Table 5.15 for region names abbreviations.

|      | Chemicals | Construction | Direct energy use | Energy production | Equipment | Food | Other | Other raw materials | Transport |
|------|-----------|--------------|-------------------|-------------------|-----------|------|-------|---------------------|-----------|
| AT   | 0.59      | 0.35         | 4.70              | 0.11              | 0.30      | 0.24 | 0.55  | 1.06                | 0.85      |
| AU   | 1.24      | 0.16         | 2.95              | 0.10              | 0.57      | 0.90 | 0.70  | 1.83                | 1.05      |
| BE   | 3.78      | 0.29         | 2.46              | 0.31              | 0.54      | 0.74 | 0.81  | 1.83                | 1.20      |
| BG   | 0.27      | 0.05         | 0.49              | 0.05              | 0.09      | 0.06 | 0.32  | 0.30                | 0.15      |
| BR   | 0.36      | 0.02         | 0.35              | 0.05              | 0.04      | 0.04 | 0.17  | 0.43                | 0.11      |
| CA   | 1.54      | 0.34         | 3.38              | 0.44              | 0.29      | 0.11 | 0.54  | 1.18                | 1.32      |
| CH   | 2.99      | 0.45         | 2.02              | 0.54              | 0.91      | 0.77 | 1.75  | 2.73                | 3.18      |
| CN   | 1.51      | 0.02         | 0.49              | 0.06              | 0.10      | 0.08 | 0.09  | 0.48                | 0.16      |
| CY   | 1.37      | 0.05         | 0.91              | 0.08              | 0.06      | 0.23 | 0.15  | 0.37                | 0.36      |
| CZ   | 1.46      | 0.34         | 1.93              | 0.23              | 0.14      | 0.13 | 0.29  | 0.62                | 0.55      |
| DE   | 0.61      | 0.31         | 4.05              | 0.35              | 0.33      | 0.37 | 0.63  | 0.93                | 0.70      |
| DK   | 0.56      | 0.16         | 3.05              | 0.24              | 0.25      | 0.30 | 0.41  | 0.86                | 5.42      |
| EE   | 1.84      | 0.13         | 1.09              | 0.13              | 0.14      | 0.19 | 0.15  | 0.58                | 0.29      |
| ES   | 0.77      | 0.13         | 1.00              | 0.09              | 0.15      | 0.11 | 0.29  | 0.57                | 0.37      |
| FI   | 2.25      | 0.25         | 2.62              | 0.39              | 0.28      | 0.23 | 0.67  | 1.82                | 1.80      |
| FR   | 0.67      | 0.21         | 1.16              | 0.09              | 0.27      | 0.21 | 0.48  | 0.85                | 0.70      |
| GB   | 1.63      | 0.14         | 1.92              | 0.11              | 0.29      | 0.22 | 0.40  | 0.79                | 0.71      |
| GR   | 0.23      | 0.19         | 1.26              | 0.03              | 0.17      | 0.06 | 0.36  | 0.50                | 2.03      |
| HR   | 0.17      | 0.06         | 0.74              | 0.09              | 0.24      | 0.03 | 0.15  | 0.32                | 0.19      |
| HU   | 0.39      | 0.11         | 1.01              | 0.12              | 0.13      | 0.12 | 0.18  | 0.34                | 0.19      |
| "ID" | 0.05      | 0.01         | 0.17              | 0.01              | 0.01      | 0.03 | 0.03  | 0.03                | 0.05      |
| IE   | 0.72      | 0.27         | 2.14              | 0.16              | 0.51      | 0.14 | 0.57  | 0.90                | 0.63      |
| IN   | 0.05      | 0.01         | 0.03              | 0.00              | 0.01      | 0.05 | 0.01  | 0.04                | 0.02      |
| IT   | 0.54      | 0.22         | 1.92              | 0.19              | 0.20      | 0.10 | 0.39  | 0.63                | 0.48      |
| JP   | 2.23      | 0.20         | 4.54              | 0.10              | 0.23      | 0.11 | 0.47  | 1.11                | 0.57      |
| KR   | 1.78      | 0.17         | 1.57              | 0.36              | 0.22      | 0.41 | 0.40  | 0.92                | 0.83      |
| LT   | 0.17      | 0.08         | 0.40              | 0.16              | 0.09      | 0.05 | 0.11  | 0.17                | 0.11      |
| LU   | 14.35     | 0.67         | 1.42              | 0.50              | 0.89      | 1.96 | 1.24  | 4.59                | 2.51      |
| LV   | 1.03      | 0.17         | 1.04              | 0.11              | 0.08      | 0.08 | 0.15  | 0.41                | 0.31      |
| MT   | 7.70      | 0.28         | 1.61              | 0.44              | 0.26      | 0.70 | 0.48  | 1.57                | 1.48      |
| MX   | 0.15      | 0.03         | 0.11              | 0.02              | 0.03      | 0.02 | 0.08  | 0.18                | 0.07      |
| NL   | 1.83      | 0.60         | 1.71              | 0.22              | 0.34      | 0.39 | 0.52  | 1.06                | 0.70      |
| NO   | 1.08      | 0.49         | 3.84              | 0.22              | 0.66      | 0.23 | 0.74  | 1.34                | 1.19      |
| PL   | 0.40      | 0.10         | 3.09              | 0.09              | 0.08      | 0.04 | 0.11  | 0.28                | 0.12      |
| PT   | 0.21      | 0.12         | 2.09              | 0.09              | 0.08      | 0.15 | 0.17  | 0.50                | 0.20      |
| RO   | 0.07      | 0.03         | 0.15              | 0.02              | 0.02      | 0.04 | 0.05  | 0.12                | 0.09      |
| RU   | 0.08      | 0.05         | 0.59              | 0.04              | 0.03      | 0.06 | 0.23  | 0.20                | 0.14      |
| SE   | 0.55      | 0.31         | 1.77              | 0.35              | 0.34      | 0.19 | 0.36  | 1.11                | 0.72      |
| SI   | 2.72      | 0.26         | 2.39              | 0.20              | 0.28      | 0.24 | 0.48  | 1.10                | 0.51      |
| SK   | 0.34      | 0.15         | 1.97              | 0.10              | 0.13      | 0.06 | 0.18  | 0.45                | 0.26      |
| TR   | 0.24      | 0.03         | 0.80              | 0.06              | 0.02      | 0.08 | 0.11  | 0.28                | 0.29      |
| TW   | 1.09      | 0.03         | 0.95              | 0.03              | 0.06      | 0.03 | 0.07  | 0.25                | 0.13      |
| US   | 1.98      | 0.73         | 4.17              | 0.14              | 0.61      | 0.81 | 1.35  | 1.92                | 1.94      |
| WA   | 0.10      | 0.05         | 0.15              | 0.00              | 0.01      | 0.01 | 0.02  | 0.06                | 0.04      |
| WE   | 0.18      | 0.05         | 0.52              | 0.03              | 0.03      | 0.05 | 0.07  | 0.17                | 0.09      |
| WF   | 0.02      | 0.02         | 0.05              | 0.01              | 0.01      | 0.01 | 0.01  | 0.04                | 0.01      |
| WL   | 0.33      | 0.04         | 0.23              | 0.03              | 0.06      | 0.07 | 0.09  | 0.27                | 0.12      |
| WM   | 0.24      | 0.12         | 0.37              | 0.03              | 0.05      | 0.05 | 0.17  | 0.29                | 0.25      |
| ZA   | 0.29      | 0.07         | 0.11              | 0.07              | 0.05      | 0.05 | 0.20  | 0.63                | 0.16      |

TABLE 5.11: Footprint by scope (in GJ per capita). See Table 5.15 for region names abbreviations.

|      | Chemicals | Construction | Direct energy use | Energy production | Equipment | Food | Other | Other raw materials | Transport |
|------|-----------|--------------|-------------------|-------------------|-----------|------|-------|---------------------|-----------|
| AT   | 6.7       | 4            | 53.7              | 1.3               | 3.5       | 2.7  | 6.2   | 12.1                | 9.7       |
| AU   | 13.1      | 1.7          | 31.1              | 1.1               | 5.9       | 9.4  | 7.4   | 19.3                | 11        |
| BE   | 31.6      | 2.4          | 20.5              | 2.6               | 4.5       | 6.2  | 6.8   | 15.3                | 10        |
| BG   | 15.1      | 2.7          | 27.2              | 2.8               | 5.3       | 3.5  | 18.1  | 16.8                | 8.5       |
| BR   | 22.8      | 1.4          | 22.4              | 3.2               | 2.5       | 2.4  | 10.7  | 27.4                | 7.3       |
| CA   | 16.8      | 3.7          | 37                | 4.8               | 3.2       | 1.2  | 5.9   | 12.9                | 14.5      |
| CH   | 19.5      | 3            | 13.2              | 3.5               | 5.9       | 5    | 11.4  | 17.8                | 20.7      |
| CN   | 50.3      | 0.8          | 16.3              | 2                 | 3.3       | 2.8  | 2.9   | 16.1                | 5.5       |
| CY   | 38.1      | 1.3          | 25.5              | 2.4               | 1.8       | 6.3  | 4.2   | 10.5                | 10        |
| CZ   | 25.6      | 6            | 33.8              | 4.1               | 2.5       | 2.3  | 5.1   | 10.9                | 9.7       |
| DE   | 7.3       | 3.7          | 49                | 4.2               | 4         | 4.5  | 7.6   | 11.2                | 8.5       |
| DK   | 5         | 1.5          | 27.1              | 2.2               | 2.2       | 2.6  | 3.6   | 7.6                 | 48.2      |
| EE   | 40.7      | 2.9          | 23.9              | 2.8               | 3         | 4.2  | 3.2   | 12.8                | 6.4       |
| ES   | 22        | 3.8          | 28.7              | 2.6               | 4.4       | 3.1  | 8.4   | 16.3                | 10.6      |
| FI   | 21.9      | 2.4          | 25.4              | 3.8               | 2.7       | 2.2  | 6.5   | 17.7                | 17.5      |
| FR   | 14.4      | 4.4          | 25                | 1.9               | 5.9       | 4.5  | 10.3  | 18.4                | 15.1      |
| GB   | 26.2      | 2.3          | 30.9              | 1.8               | 4.7       | 3.5  | 6.5   | 12.8                | 11.4      |
| GR   | 4.9       | 3.8          | 26.1              | 0.6               | 3.6       | 1.3  | 7.4   | 10.4                | 42        |
| HR   | 8.7       | 3            | 37.1              | 4.5               | 12        | 1.5  | 7.8   | 15.9                | 9.5       |
| HU   | 15.1      | 4.2          | 38.9              | 4.6               | 5         | 4.5  | 7     | 13.2                | 7.5       |
| "ID" | 12.5      | 1.3          | 43.9              | 1.9               | 3.1       | 8.2  | 8.6   | 8.5                 | 11.8      |
| IE   | 11.9      | 4.5          | 35.5              | 2.6               | 8.4       | 2.3  | 9.5   | 14.8                | 10.4      |
| IN   | 21.8      | 4.3          | 16                | 2                 | 3.5       | 21.7 | 5.4   | 17                  | 8.4       |
| IT   | 11.7      | 4.7          | 41.2              | 4                 | 4.3       | 2.2  | 8.3   | 13.4                | 10.3      |
| JP   | 23.3      | 2.1          | 47.5              | 1.1               | 2.4       | 1.1  | 5     | 11.6                | 5.9       |
| KR   | 26.7      | 2.6          | 23.6              | 5.4               | 3.3       | 6.1  | 5.9   | 13.9                | 12.4      |
| LT   | 12.9      | 5.8          | 29.9              | 11.7              | 6.6       | 3.7  | 8.5   | 12.7                | 8.2       |
| LU   | 51        | 2.4          | 5                 | 1.8               | 3.2       | 7    | 4.4   | 16.3                | 8.9       |
| LV   | 30.5      | 5.1          | 30.8              | 3.3               | 2.3       | 2.5  | 4.5   | 12.1                | 9.1       |
| MT   | 53        | 1.9          | 11.1              | 3                 | 1.8       | 4.8  | 3.3   | 10.8                | 10.2      |
| MX   | 22.4      | 4.2          | 16.5              | 2.2               | 4.7       | 3    | 11    | 25.8                | 10.2      |
| NL   | 24.8      | 8.2          | 23.1              | 3                 | 4.6       | 5.3  | 7     | 14.4                | 9.5       |
| NO   | 11        | 5            | 39.2              | 2.3               | 6.8       | 2.4  | 7.5   | 13.7                | 12.2      |
| PL   | 9.3       | 2.4          | 71.6              | 2                 | 1.9       | 1    | 2.6   | 6.5                 | 2.8       |
| PT   | 5.8       | 3.3          | 58.1              | 2.6               | 2.3       | 4.1  | 4.7   | 13.8                | 5.4       |
| RO   | 11.5      | 4.6          | 25                | 3.8               | 4         | 6.9  | 8.9   | 20.6                | 14.7      |
| RU   | 5.8       | 3.2          | 41.3              | 3                 | 2.3       | 4.5  | 16    | 14.1                | 9.7       |
| SE   | 9.6       | 5.4          | 31.1              | 6.1               | 5.9       | 3.3  | 6.4   | 19.5                | 12.7      |
| SI   | 33.2      | 3.2          | 29.2              | 2.4               | 3.4       | 3    | 5.9   | 13.5                | 6.2       |
| SK   | 9.3       | 4.2          | 54                | 2.7               | 3.4       | 1.7  | 4.9   | 12.4                | 7.2       |
| TR   | 12.5      | 1.5          | 41.7              | 3.3               | 1.1       | 4.1  | 5.8   | 14.8                | 15.2      |
| TW   | 41.4      | 1            | 36.2              | 1.1               | 2.1       | 1.3  | 2.5   | 9.6                 | 4.8       |
| US   | 14.5      | 5.3          | 30.5              | 1                 | 4.4       | 5.9  | 9.9   | 14.1                | 14.2      |
| WA   | 22.2      | 12           | 32.3              | 1                 | 2.6       | 2.7  | 4.7   | 14                  | 8.4       |
| WE   | 14.8      | 4.2          | 43.4              | 2.5               | 2.5       | 4.3  | 6.3   | 14.4                | 7.6       |
| WF   | 11.4      | 10.1         | 28.9              | 5.3               | 4.5       | 5.7  | 6.9   | 20.3                | 6.9       |
| WL   | 26.8      | 3.5          | 18.8              | 2.1               | 4.5       | 5.4  | 7.2   | 21.6                | 10.1      |
| WM   | 15        | 7.5          | 23.5              | 2                 | 3.5       | 3.4  | 10.9  | 18.1                | 16.1      |
| ZA   | 18        | 4.5          | 6.5               | 4.2               | 3.1       | 3    | 12.1  | 38.6                | 10.1      |

TABLE 5.12: Footprint by scope (in %). See Table 5.15 for region names abbreviations.

### Energy footprint disaggregation

| region | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|--------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| AT     | 57%  | 59%  | 58%  | 59%  | 59%  | 60%  | 56%  | 57%  | 58%  | 58%  | 56%  | 57%  | 56%  | 56%  |
| AU     | 64%  | 63%  | 65%  | 63%  | 65%  | 65%  | 66%  | 57%  | 59%  | 58%  | 57%  | 56%  | 56%  | 54%  |
| BE     | 48%  | 48%  | 45%  | 51%  | 49%  | 48%  | 46%  | 48%  | 45%  | 45%  | 44%  | 44%  | 45%  | 45%  |
| BG     | 32%  | 47%  | 49%  | 54%  | 51%  | 51%  | 46%  | 37%  | 41%  | 47%  | 43%  | 44%  | 40%  | 39%  |
| BR     | 38%  | 37%  | 35%  | 35%  | 38%  | 38%  | 42%  | 41%  | 46%  | 46%  | 46%  | 47%  | 48%  | 49%  |
| CA     | 57%  | 55%  | 53%  | 2%   | 2%   | 54%  | 2%   | 53%  | 50%  | 53%  | 50%  | 54%  | 50%  | 54%  |
| CH     | 5%   | 50%  | 5%   | 4%   | 5%   | 52%  | 5%   | 53%  | 5%   | 5%   | 53%  | 6%   | 53%  | 5%   |
| CN     | 33%  | 30%  | 30%  | 26%  | 36%  | 23%  | 0%   | 36%  | 0%   | 29%  | 31%  | 28%  | 28%  | 25%  |
| CY     | 41%  | 44%  | 40%  | 45%  | 44%  | 43%  | 41%  | 44%  | 47%  | 48%  | 47%  | 45%  | 43%  | 40%  |
| CZ     | 46%  | 48%  | 44%  | 48%  | 46%  | 44%  | 48%  | 46%  | 49%  | 48%  | 48%  | 48%  | 47%  | 46%  |
| DE     | 48%  | 49%  | 48%  | 44%  | 44%  | 43%  | 44%  | 45%  | 46%  | 45%  | 44%  | 45%  | 46%  | 46%  |
| DK     | 63%  | 64%  | 64%  | 64%  | 63%  | 61%  | 60%  | 62%  | 61%  | 61%  | 63%  | 62%  | 59%  | 62%  |
| EE     | 65%  | 56%  | 65%  | 60%  | 59%  | 70%  | 72%  | 73%  | 71%  | 73%  | 65%  | 65%  | 64%  | 61%  |
| ES     | 53%  | 54%  | 53%  | 53%  | 56%  | 55%  | 54%  | 57%  | 57%  | 55%  | 55%  | 59%  | 57%  | 60%  |
| FI     | 62%  | 62%  | 64%  | 63%  | 61%  | 62%  | 67%  | 60%  | 56%  | 59%  | 55%  | 55%  | 57%  | 54%  |
| FR     | 51%  | 52%  | 52%  | 52%  | 56%  | 53%  | 53%  | 54%  | 53%  | 54%  | 53%  | 53%  | 53%  | 54%  |
| GB     | 49%  | 48%  | 49%  | 48%  | 46%  | 44%  | 44%  | 45%  | 48%  | 46%  | 43%  | 43%  | 43%  | 45%  |
| GR     | 40%  | 38%  | 47%  | 49%  | 45%  | 40%  | 41%  | 43%  | 36%  | 37%  | 36%  | 39%  | 37%  | 36%  |
| HR     | 67%  | 67%  | 68%  | 65%  | 67%  | 72%  | 68%  | 75%  | 73%  | 64%  | 65%  | 69%  | 73%  | 69%  |
| HU     | 54%  | 53%  | 56%  | 56%  | 55%  | 56%  | 59%  | 52%  | 46%  | 45%  | 49%  | 54%  | 52%  | 51%  |
| "ID"   | 20%  | 15%  | 16%  | 13%  | 11%  | 15%  | 13%  | 4%   | 4%   | 4%   | 3%   | 5%   | 3%   | 7%   |
| IE     | 49%  | 57%  | 54%  | 56%  | 59%  | 67%  | 65%  | 70%  | 61%  | 69%  | 67%  | 67%  | 68%  | 67%  |
| IN     | 0%   | 41%  | 46%  | 46%  | 47%  | 48%  | 43%  | 45%  | 47%  | 47%  | 45%  | 50%  | 50%  | 52%  |
| IT     | 54%  | 54%  | 53%  | 53%  | 53%  | 53%  | 53%  | 51%  | 51%  | 52%  | 51%  | 51%  | 53%  | 52%  |
| JP     | 45%  | 45%  | 44%  | 46%  | 49%  | 41%  | 49%  | 41%  | 41%  | 39%  | 39%  | 35%  | 39%  | 40%  |
| KR     | 41%  | 41%  | 41%  | 51%  | 44%  | 42%  | 44%  | 43%  | 41%  | 42%  | 42%  | 42%  | 0%   | 35%  |
| LT     | 68%  | 63%  | 63%  | 62%  | 64%  | 68%  | 67%  | 70%  | 68%  | 69%  | 70%  | 71%  | 68%  | 69%  |
| LU     | 58%  | 66%  | 59%  | 57%  | 54%  | 55%  | 55%  | 53%  | 54%  | 49%  | 47%  | 46%  | 38%  | 28%  |
| LV     | 65%  | 62%  | 56%  | 61%  | 59%  | 65%  | 58%  | 55%  | 52%  | 60%  | 64%  | 65%  | 64%  | 64%  |
| MT     | 59%  | 60%  | 67%  | 57%  | 55%  | 38%  | 57%  | 46%  | 45%  | 59%  | 58%  | 0%   | 0%   | 0%   |
| MX     | 38%  | 38%  | 40%  | 42%  | 45%  | 43%  | 43%  | 43%  | 42%  | 42%  | 47%  | 42%  | 40%  | 46%  |
| NL     | 53%  | 55%  | 55%  | 55%  | 56%  | 55%  | 56%  | 57%  | 54%  | 54%  | 53%  | 56%  | 55%  | 54%  |
| NO     | 68%  | 69%  | 69%  | 70%  | 69%  | 71%  | 70%  | 70%  | 72%  | 70%  | 70%  | 73%  | 76%  | 72%  |
| PL     | 51%  | 47%  | 43%  | 42%  | 44%  | 44%  | 48%  | 42%  | 43%  | 44%  | 41%  | 43%  | 41%  | 42%  |
| PT     | 48%  | 47%  | 46%  | 48%  | 44%  | 50%  | 52%  | 53%  | 51%  | 53%  | 51%  | 52%  | 55%  | 55%  |
| RO     | 43%  | 39%  | 43%  | 44%  | 47%  | 54%  | 53%  | 61%  | 51%  | 59%  | 54%  | 54%  | 53%  | 56%  |
| RU     | 51%  | 55%  | 5%   | 55%  | 55%  | 54%  | 70%  | 71%  | 60%  | 78%  | 69%  | 74%  | 72%  | 73%  |
| SE     | 72%  | 70%  | 69%  | 68%  | 68%  | 69%  | 65%  | 64%  | 66%  | 65%  | 64%  | 65%  | 65%  | 65%  |
| SI     | 61%  | 57%  | 56%  | 53%  | 52%  | 58%  | 60%  | 59%  | 63%  | 61%  | 59%  | 60%  | 57%  | 3%   |
| SK     | 59%  | 55%  | 44%  | 44%  | 55%  | 49%  | 54%  | 46%  | 47%  | 48%  | 49%  | 44%  | 45%  | 45%  |
| TR     | 28%  | 30%  | 30%  | 33%  | 33%  | 33%  | 34%  | 28%  | 48%  | 23%  | 33%  | 27%  | 23%  | 25%  |
| TW     | 0%   | 53%  | 52%  | 0%   | 0%   | 44%  | 0%   | 42%  | 0%   | 63%  | 55%  | 51%  | 55%  | 49%  |
| US     | 48%  | 4%   | 48%  | 4%   | 48%  | 48%  | 48%  | 50%  | 48%  | 4%   | 48%  | 4%   | 4%   | 47%  |
| WA     | 41%  | 43%  | 42%  | 2%   | 40%  | 39%  | 40%  | 41%  | 40%  | 40%  | 40%  | 42%  | 43%  | 47%  |
| WE     | 50%  | 50%  | 46%  | 46%  | 49%  | 45%  | 43%  | 47%  | 46%  | 45%  | 46%  | 48%  | 48%  | 48%  |
| WF     | 36%  | 38%  | 37%  | 37%  | 37%  | 37%  | 37%  | 37%  | 36%  | 36%  | 36%  | 35%  | 36%  | 37%  |
| WL     | 49%  | 51%  | 51%  | 51%  | 50%  | 49%  | 49%  | 50%  | 50%  | 50%  | 50%  | 50%  | 50%  | 50%  |
| WM     | 39%  | 39%  | 40%  | 40%  | 38%  | 38%  | 38%  | 39%  | 39%  | 38%  | 39%  | 38%  | 40%  | 39%  |
| ZA     | 26%  | 21%  | 19%  | 19%  | 18%  | 19%  | 19%  | 18%  | 15%  | 15%  | 13%  | 14%  | 11%  | 13%  |

TABLE 5.13: Cost of employment (in % of total inputs). See Table 5.15 for region names abbreviations.

| region | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|--------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| AT     | 2.2  | 2.2  | 2.2  | 2.5  | 2.3  | 2.1  | 2.3  | 2.1  | 2.1  | 2.0  | 2.0  | 1.9  | 1.8  | 1.7  |
| AU     | 1.4  | 1.5  | 1.5  | 1.5  | 1.4  | 1.4  | 1.5  | 1.8  | 1.5  | 2.3  | 2.5  | 2.1  | 2.3  | 2.2  |
| BE     | 2.4  | 2.6  | 3.0  | 2.2  | 2.4  | 2.4  | 3.0  | 2.8  | 3.1  | 2.7  | 2.8  | 2.6  | 2.6  | 2.5  |
| BG     | 2.1  | 1.9  | 1.8  | 1.9  | 1.8  | 1.7  | 1.5  | 1.7  | 1.3  | 1.4  | 1.4  | 1.3  | 1.3  | 1.3  |
| BR     | 1.4  | 1.5  | 1.6  | 1.7  | 1.4  | 1.6  | 1.5  | 1.5  | 1.3  | 1.4  | 1.3  | 1.3  | 1.3  | 1.2  |
| CA     | 2.3  | 2.1  | 2.2  | 2.8  | 2.7  | 2.7  | 3.5  | 2.2  | 2.2  | 3.0  | 2.3  | 2.2  | 2.1  | 1.9  |
| CH     | 2.8  | 2.0  | 2.9  | 3.0  | 2.8  | 1.6  | 2.4  | 1.6  | 2.4  | 2.7  | 1.6  | 1.9  | 1.4  | 2.1  |
| CN     | 3.2  | 2.9  | 3.0  | 3.6  | 2.2  | 3.6  | 4.4  | 3.4  | 5.1  | 4.2  | 4.3  | 4.4  | 4.5  | 4.7  |
| CY     | 1.7  | 1.7  | 1.9  | 1.4  | 1.5  | 1.6  | 3.2  | 1.5  | 1.9  | 1.8  | 1.9  | 1.6  | 1.9  | 2.3  |
| CZ     | 2.1  | 2.1  | 2.3  | 2.2  | 2.3  | 2.3  | 2.1  | 2.1  | 2.1  | 2.2  | 2.5  | 2.4  | 2.4  | 2.3  |
| DE     | 1.5  | 2.1  | 1.6  | 1.9  | 1.7  | 1.9  | 1.9  | 1.9  | 1.9  | 1.8  | 1.9  | 1.6  | 1.5  | 1.6  |
| DK     | 2.7  | 2.8  | 3.0  | 2.5  | 3.2  | 3.0  | 3.6  | 2.9  | 3.1  | 3.1  | 2.8  | 2.8  | 2.5  | 2.2  |
| EE     | 2.5  | 2.5  | 2.7  | 3.9  | 3.7  | 1.9  | 1.9  | 1.6  | 1.9  | 1.8  | 2.0  | 2.1  | 3.1  | 2.4  |
| ES     | 1.6  | 1.8  | 1.9  | 1.8  | 1.3  | 1.8  | 1.8  | 1.6  | 1.7  | 1.7  | 1.8  | 1.5  | 1.5  | 1.1  |
| FI     | 4.1  | 3.8  | 2.3  | 2.4  | 3.3  | 2.3  | 1.9  | 2.0  | 3.0  | 2.3  | 2.9  | 2.9  | 2.3  | 2.5  |
| FR     | 1.5  | 1.6  | 1.5  | 1.4  | 1.4  | 1.3  | 1.2  | 0.9  | 1.1  | 1.0  | 1.1  | 1.0  | 1.0  | 1.0  |
| GB     | 2.0  | 1.7  | 2.1  | 2.3  | 2.3  | 2.4  | 2.1  | 1.9  | 1.7  | 1.7  | 2.1  | 2.0  | 1.8  | 1.5  |
| GR     | 2.2  | 1.7  | 1.5  | 1.2  | 1.3  | 1.4  | 1.3  | 1.3  | 2.2  | 2.4  | 2.2  | 1.9  | 2.3  | 2.2  |
| HR     | 1.4  | 1.6  | 1.2  | 1.7  | 1.6  | 1.5  | 1.5  | 1.2  | 1.5  | 1.9  | 1.9  | 1.5  | 1.1  | 1.3  |
| HU     | 2.2  | 2.5  | 2.5  | 2.5  | 2.3  | 2.0  | 1.6  | 1.8  | 2.2  | 2.1  | 1.8  | 1.3  | 1.4  | 1.4  |
| "ID"   | 1.4  | 1.4  | 1.5  | 1.5  | 1.3  | 1.3  | 1.3  | 1.2  | 1.2  | 1.1  | 1.1  | 1.2  | 1.3  | 1.3  |
| IE     | 2.0  | 1.8  | 1.9  | 1.8  | 1.9  | 1.1  | 1.2  | 1.1  | 1.4  | 1.1  | 1.4  | 1.4  | 1.5  | 1.2  |
| IN     | 1.8  | 1.1  | 1.0  | 1.0  | 1.0  | 1.0  | 1.3  | 1.2  | 1.2  | 1.2  | 1.2  | 1.0  | 1.0  | 1.1  |
| IT     | 1.8  | 1.6  | 1.9  | 1.9  | 1.9  | 1.6  | 1.7  | 1.9  | 1.7  | 1.7  | 1.6  | 1.6  | 1.4  | 1.4  |
| JP     | 3.0  | 3.1  | 3.0  | 2.8  | 2.6  | 2.7  | 2.4  | 2.4  | 2.6  | 2.6  | 2.6  | 2.6  | 2.1  | 2.2  |
| KR     | 3.1  | 3.3  | 3.0  | 2.0  | 2.4  | 2.6  | 2.3  | 2.3  | 2.5  | 2.6  | 2.5  | 2.4  | 2.8  | 2.6  |
| LT     | 2.7  | 2.8  | 2.4  | 2.8  | 2.5  | 2.2  | 1.7  | 0.9  | 1.5  | 0.8  | 0.9  | 0.7  | 0.7  | 0.7  |
| LU     | 2.1  | 2.0  | 2.5  | 2.7  | 3.0  | 2.0  | 2.5  | 2.5  | 2.7  | 2.8  | 3.2  | 3.2  | 3.8  | 5.1  |
| LV     | 4.1  | 4.2  | 3.9  | 3.5  | 3.6  | 2.4  | 3.8  | 3.6  | 3.5  | 2.8  | 2.3  | 2.7  | 2.7  | 2.4  |
| MT     | 2.1  | 1.9  | 1.9  | 2.3  | 1.6  | 3.2  | 1.7  | 2.2  | 3.2  | 1.9  | 1.9  | 5.3  | 6.0  | 4.4  |
| MX     | 1.1  | 0.9  | 1.0  | 0.9  | 0.8  | 0.9  | 0.9  | 0.8  | 1.0  | 1.0  | 0.8  | 1.0  | 1.0  | 0.7  |
| NL     | 1.9  | 2.0  | 1.8  | 1.9  | 1.7  | 1.7  | 1.7  | 1.2  | 1.9  | 1.8  | 1.8  | 1.3  | 1.7  | 1.4  |
| NO     | 2.3  | 1.9  | 1.8  | 1.7  | 1.6  | 1.7  | 1.6  | 1.6  | 1.6  | 1.9  | 1.8  | 1.7  | 1.4  | 1.6  |
| PL     | 1.9  | 2.1  | 2.1  | 2.3  | 2.4  | 2.3  | 2.2  | 2.3  | 2.7  | 2.5  | 2.8  | 2.6  | 2.6  | 2.5  |
| PT     | 2.0  | 1.9  | 1.9  | 2.0  | 1.8  | 1.8  | 1.6  | 1.5  | 1.7  | 1.5  | 1.6  | 1.5  | 1.3  | 1.3  |
| RO     | 1.2  | 1.4  | 1.3  | 1.5  | 2.1  | 1.4  | 1.1  | 0.7  | 0.7  | 0.7  | 0.6  | 0.7  | 0.6  | 0.6  |
| RU     | 2.8  | 2.4  | 4.2  | 2.8  | 2.7  | 2.6  | 2.5  | 2.1  | 1.8  | 1.1  | 1.3  | 1.1  | 1.1  | 1.1  |
| SE     | 1.4  | 1.4  | 1.4  | 1.5  | 1.4  | 1.3  | 1.3  | 1.2  | 1.2  | 1.2  | 1.2  | 1.2  | 1.2  | 1.1  |
| SI     | 2.2  | 2.8  | 2.4  | 2.5  | 2.3  | 1.6  | 1.9  | 1.7  | 1.6  | 2.0  | 1.8  | 1.8  | 1.8  | 3.0  |
| SK     | 2.6  | 2.4  | 3.3  | 3.7  | 2.6  | 1.9  | 2.2  | 3.7  | 2.7  | 3.1  | 2.2  | 2.2  | 1.8  | 1.8  |
| TR     | 1.5  | 1.9  | 1.9  | 1.9  | 1.9  | 1.8  | 2.0  | 1.6  | 1.3  | 2.0  | 2.3  | 2.2  | 2.2  | 1.8  |
| US     | 1.8  | 2.5  | 1.7  | 2.4  | 1.6  | 1.6  | 1.7  | 1.5  | 1.5  | 2.4  | 1.6  | 2.3  | 2.3  | 1.5  |
| WA     | 1.7  | 1.8  | 1.8  | 2.4  | 1.6  | 1.8  | 1.6  | 1.5  | 1.7  | 1.7  | 1.7  | 1.6  | 1.5  | 1.5  |
| WE     | 2.1  | 2.1  | 2.2  | 2.0  | 1.9  | 2.0  | 2.0  | 1.6  | 2.1  | 2.0  | 1.8  | 1.7  | 1.5  | 1.4  |
| WF     | 0.8  | 0.7  | 0.8  | 0.9  | 0.8  | 0.8  | 0.9  | 0.9  | 1.0  | 1.1  | 1.2  | 1.3  | 1.1  | 1.1  |
| WL     | 1.0  | 0.9  | 1.0  | 1.0  | 1.0  | 1.0  | 1.1  | 1.0  | 1.1  | 1.2  | 1.2  | 1.2  | 1.1  | 1.1  |
| WM     | 1.3  | 1.2  | 1.2  | 1.2  | 1.4  | 1.4  | 1.5  | 1.4  | 1.4  | 1.5  | 1.5  | 1.7  | 1.6  | 1.6  |
| ZA     | 1.6  | 1.8  | 1.7  | 1.3  | 1.2  | 1.2  | 1.2  | 1.5  | 1.6  | 1.5  | 1.6  | 1.4  | 1.6  | 1.5  |

TABLE 5.14: Energy intensity (in MJ/US\$2015ppp). See Table 5.15 for region names abbreviations.

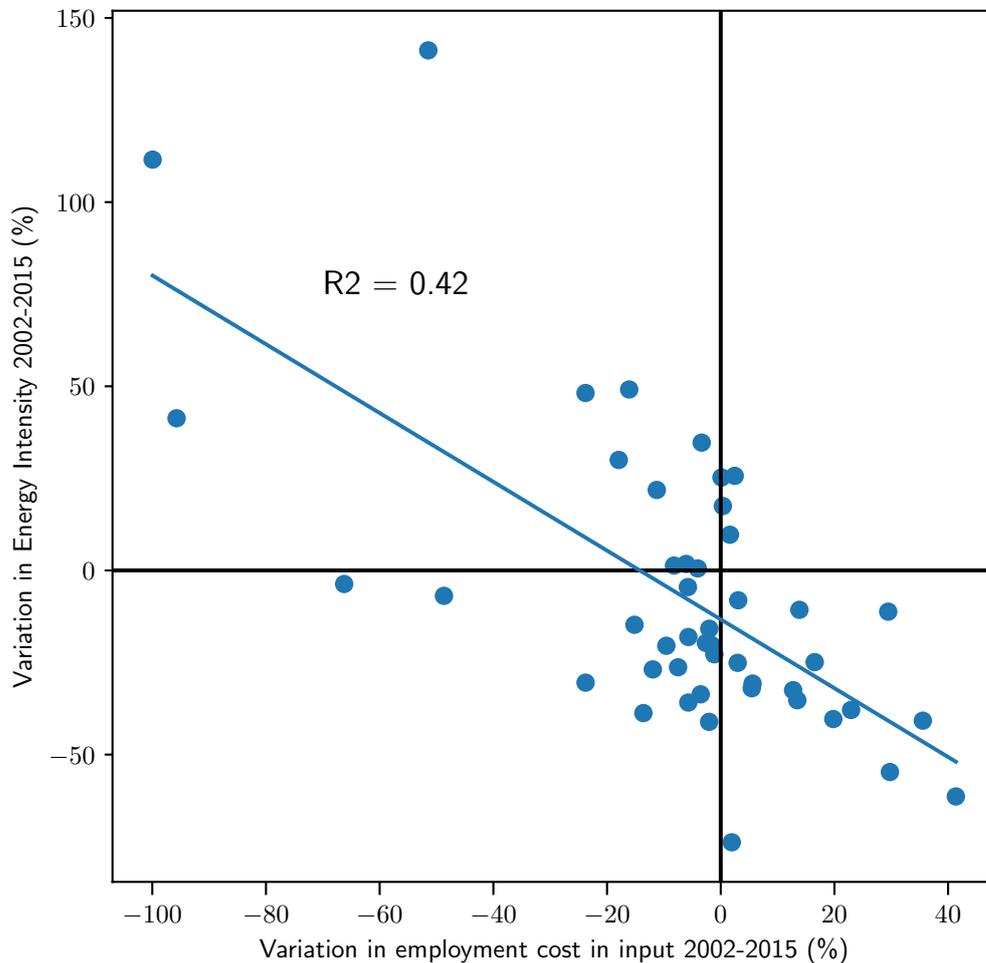


FIGURE 5.16: Variation in energy intensity as a function of variation in employment cost over period 2002-2015. Based on Supplementary Tables 5.12 and 5.13.

### Energy efficiency

#### 5.1.6.3. SUPPLEMENTARY DISCUSSION

Our results for CO<sub>2</sub> emissions in 2014 were similar to the previous multi-regional estimates using the Eora EE-MRIO database (Pichler et al., 2019) (Figure 5.17). Apart from Luxembourg and Malta, our results were also close to the values reported for 2015 in the Health Care Without Harm, which used the GTAP database to assess healthcare systems' climate footprint in 43 countries (Harm, 2019) (Figure 5.18). Both studies used expenditure data from World Health Organization's National Health Expenditures database and included capital (investments) goods and infrastructures. The fact that using EXIOBASE3 yields similar results than Eora and GTAP confirms the similarity of input-output databases.

However, our results differ from those of Lenzen and colleagues (Lenzen, Malik, et al., 2020)

(Figure 5.19) who used the healthcare-related sectors directly from Eora, without harmonising the expenses with WHO’s NHA database and accounting for capital expenditures. This highlights the importance of expenditure data when calculating footprints. For footprints to be compared in between regions, expenditure data must come from a common source and have the same scope. Using Eora’s sectors has the advantage of providing the best possible disaggregation of regional footprints but limits international comparisons due to different healthcare definitions.

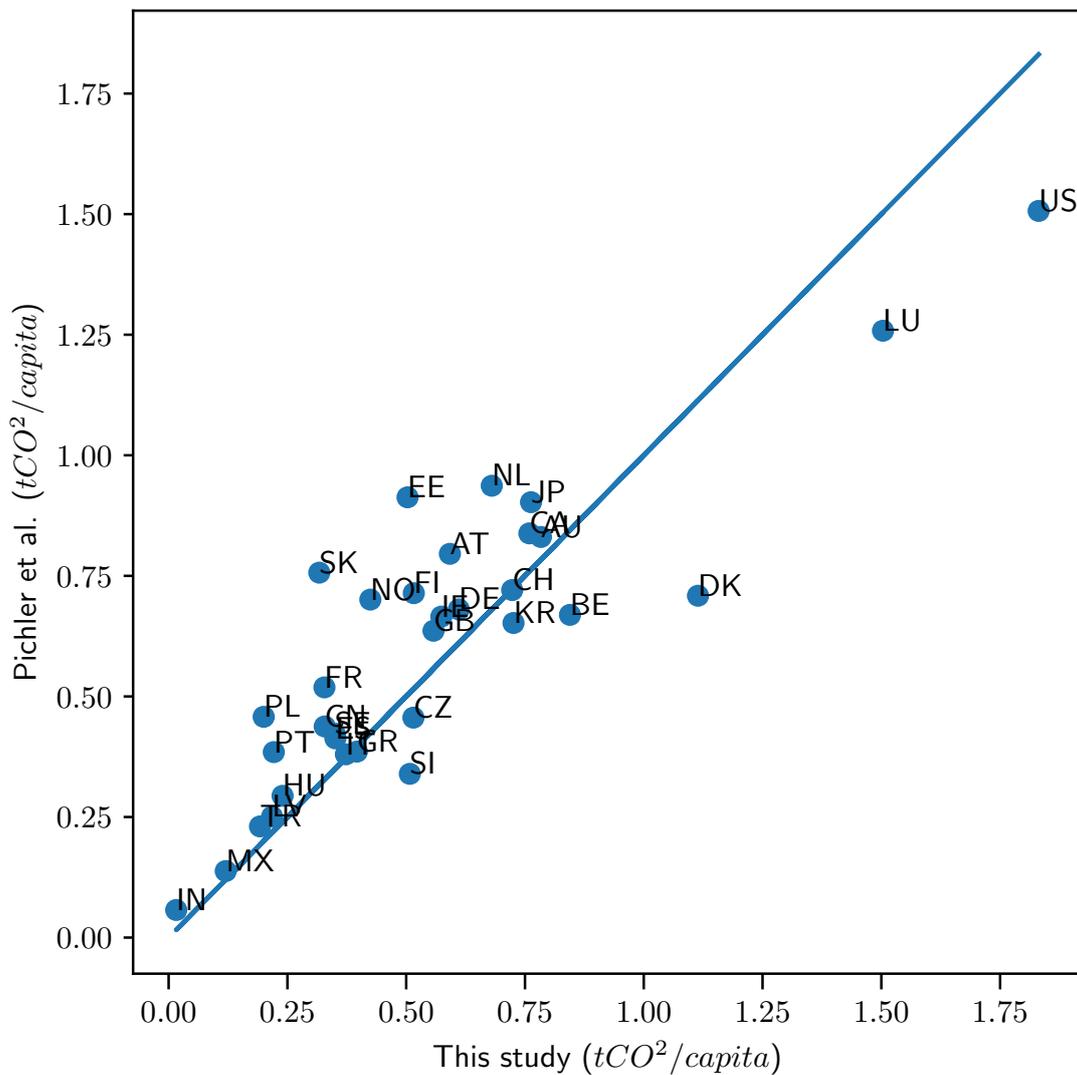


FIGURE 5.17: Healthcare carbon footprint in 2014, comparison with Pichler et al. See Table 5.15 for region names abbreviations.

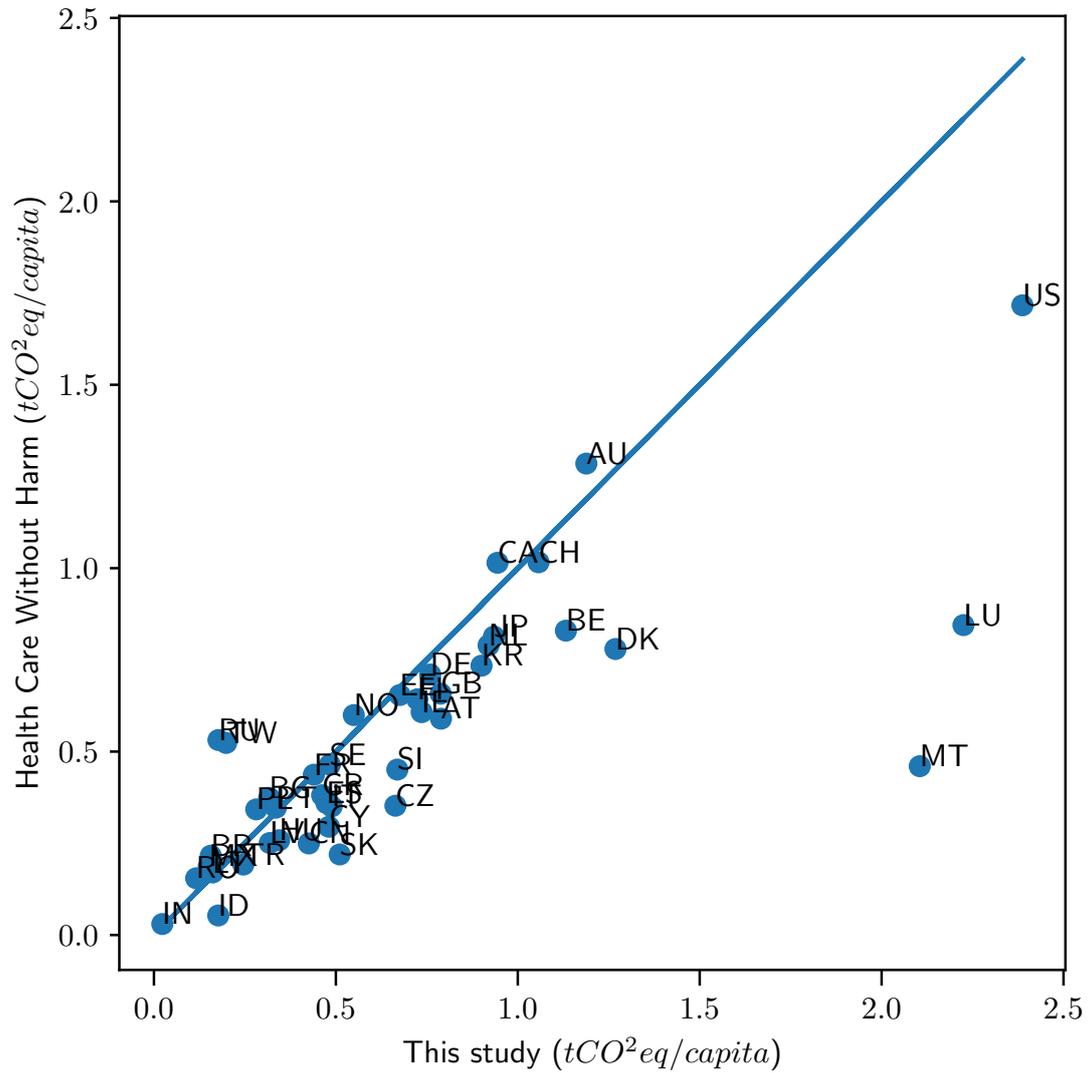


FIGURE 5.18: Healthcare carbon footprint in 2014, comparison with Health Care Without Harm. See Table 5.15 for region names abbreviations.

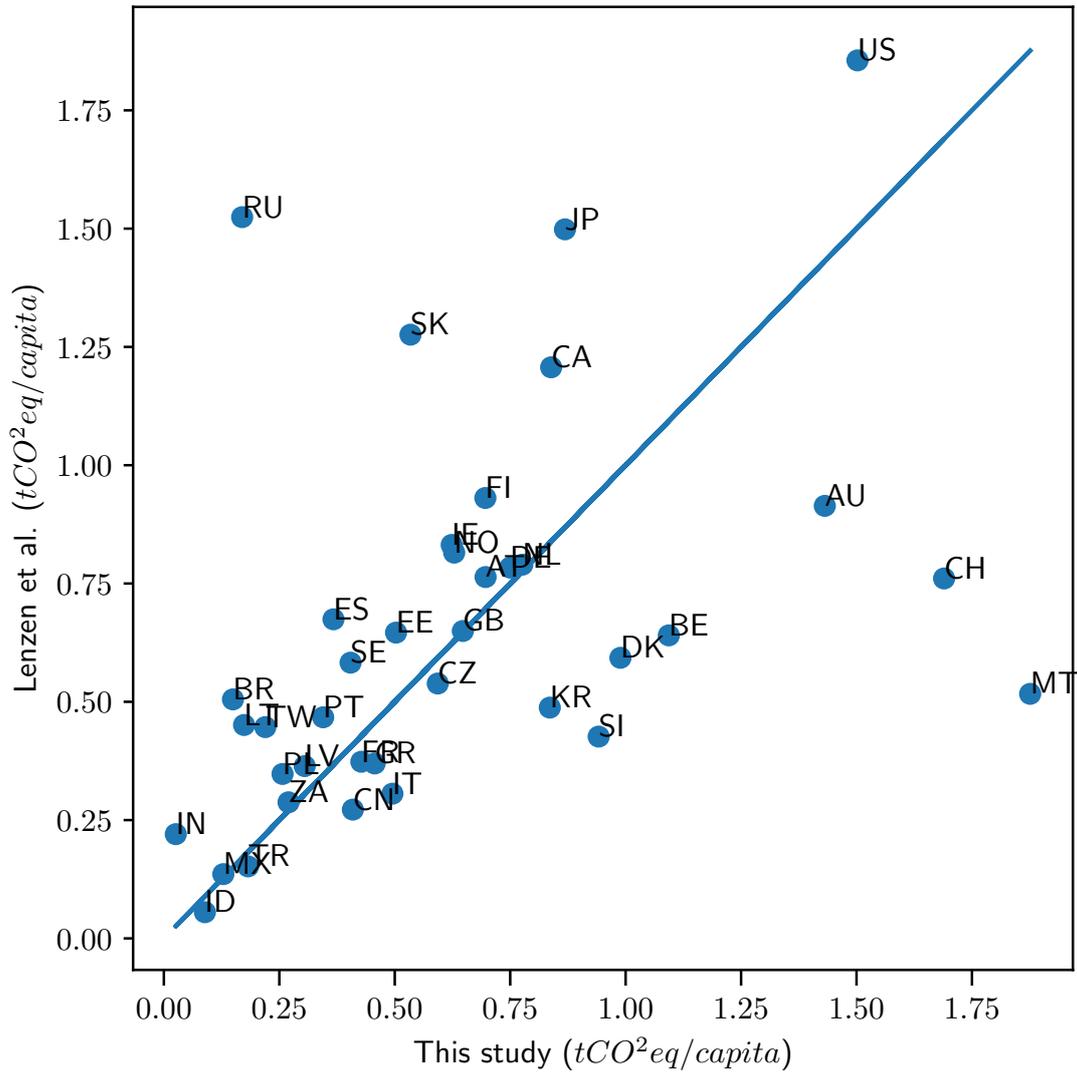


FIGURE 5.19: Healthcare carbon footprint in 2015, comparison with Lenzen et al. See Table 5.15 for region names abbreviations.

| EXIOBASE region | full name            |
|-----------------|----------------------|
| AT              | Austria              |
| BE              | Belgium              |
| BG              | Bulgaria             |
| CY              | Cyprus               |
| CZ              | Czech Republic       |
| DE              | Germany              |
| DK              | Denmark              |
| EE              | Estonia              |
| ES              | Spain                |
| FI              | Finland              |
| FR              | France               |
| GR              | Greece               |
| HR              | Croatia              |
| HU              | Hungary              |
| IE              | Ireland              |
| IT              | Italy                |
| LT              | Lithuania            |
| LU              | Luxembourg           |
| LV              | Latvia               |
| MT              | Malta                |
| NL              | Netherlands          |
| PL              | Poland               |
| PT              | Portugal             |
| RO              | Romania              |
| SE              | Sweden               |
| SI              | Slovenia             |
| SK              | Slovakia             |
| GB              | Great Britain        |
| US              | United States        |
| JP              | Japan                |
| CN              | China                |
| CA              | Canada               |
| KR              | South Korea          |
| BR              | Brazil               |
| IN              | India                |
| MX              | Mexico               |
| RU              | Russia               |
| AU              | Australia            |
| CH              | Switzerland          |
| TR              | Turkey               |
| TW              | Taiwan               |
| NO              | Norway               |
| ID              | Indonesia            |
| ZA              | South Africa         |
| WA              | RoW Asia and Pacific |
| WL              | RoW America          |
| WE              | RoW Europe           |
| WF              | RoW Africa           |
| WM              | RoW Middle East      |

TABLE 5.15: Region names

## 5.2. ASSOCIATIONS BETWEEN REGIONAL ENERGY FOOTPRINT AND THE OCCURRENCE OF DISEASES

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### ABSTRACT

The Energy Footprint per Capita (EFC) measures the amount of energy required to sustain an individual's lifestyle. Previous research has shown that the human development index is positively correlated to EFC. However, the relationship between EFC and diseases remains unknown. To address this gap, we compared regional EFC data with the incidence, Years Lived with Disability (YLDs) and Years of Life Lost (YLLs) of 293 diseases in 176 countries over the period 1990-2019. High EFC is correlated to low rates of enteric infections, maternal and neonatal disorders, nutritional deficiencies and sexually transmissible infections. However, high EFC is also correlated to high rates of substance use disorders, neoplasms, neurological, mental and musculoskeletal disorders, and diabetes and kidney diseases. These results could be explained by both positive outcomes (access to vaccination, hygiene, education and prevention) and negative outcomes (specific immune dysfunctions induced by an energy-intensive lifestyle) of energy use.

### 5.2.1. INTRODUCTION

The availability and increasing extraction of fossil energy since the industrial revolution has shaped every aspects of our modern societies (Smil, n.d.). Whenever an action takes place, energy is involved: to move from one place to another, to change the temperature or lighting of a place, to transform raw materials into everyday objects, to perform a chemical reaction for the synthesis of drugs or fertilizers etc. If the action is performed directly by the human body, for example by riding a bike, the energy comes from the food we eat. If the action is performed by machines, the energy can come from fossil, nuclear or renewable sources, but is still mainly based on fossil fuels (Smil, n.d.; "Statistical Review of World Energy 2022" 2022). This poses two problems: climate change on the one hand, and the risks of supply shortages on the other (Delannoy et al., 2021). These risks may be geopolitical (e.g., Nord Stream ("Borders and pipelines" 2022)) or physical, if production can no longer meet demand (e.g., peak oil (Delannoy et al., 2021)). In theory, a transition to renewable energy sources can avoid these two risks. However, there are practical limits to the speed of deployment of renewable energy and it is essential to activate energy sufficiency levers in parallel. This raises the question of the potential impacts on health of reducing energy consumption.

Energy has the potential to improve health (Rahman et al., 2021), through the construction of clean water systems (reducing fecal peril) (Shobande, 2020), the production of refrig-

erators (reducing the risk of infection and stomach cancers related to the salting of meat (Yan et al., 2018)), the reduction of malnutrition, the production of vaccines to prevent infectious diseases, the provision of means to prevent communicable diseases, the increase of the general standard of living of the population who thus gain access to more education on hygiene and health promoting behaviors, as well as access to expensive medical care, drugs, or interventions (Youssef et al., 2016). Overall, the human development index, which accounts for health and socio-economic indicators, is positively correlated to the energy footprint per capita (Arto et al., 2016). It could be argued that the above improvements are related to gross domestic product and not energy. As both metrics quantify the same transformations (energy allows products to be transformed, thereby increasing their value added), they are positively correlated (Stern, 2019) and could thus be interchangeable. We choose to study energy and not gross domestic product because there are physical risks associated with energy consumption (climate change and supply shortages). Focusing on energy sheds light on the trade-offs by distinguishing between energy uses that have positive health effects from those that have negative effects.

Using a lot of energy is an ambivalent action. The Human Development Index growth saturates when the energy footprint is high and could even reach a turning point where energy consumption ends up having a negative effect on well-being (Akizu-Gardoki et al., 2020). The energy footprint per capita (EFC) expresses the total energy consumption attributed to an individual. It includes energy consumed directly (e.g., to heat a house), as well as indirectly through the energy required to produce the goods and services ultimately consumed (e.g., the energy consumed by a factory to produce a car) (Andrieu, Vidal, et al., 2022). EFC is directly correlated to lifestyles: the more we travel from place to place, the bigger our homes, the more we eat processed foods and buy goods, the more energy we use. Although the health systems of energy-intensive countries show positive outcomes, the lifestyles of people living in these countries have evolved towards reduced occupational physical activities and active transportation, as well as diets rich in processed food, added sugars and saturated fats, above the recommendations in terms of animal-based products, leading to an epidemic of obesity and food addictions (Figueiredo et al., 2022), gut dysbiosis (Battson et al., 2018) and metaflammation (metabolic disorders associated with immuno-inflammatory dysfunction) (Christ et al., 2019). Insufficient physical activity combined with unhealthy diet are well-known risk factors for multiple chronic diseases. These diseases may increase the number of years of life with disability (YLDs) and Years of Life Lost (YLLs). The aim of the healthcare systems is to reduce YLDs and YLLs, and healthcare systems of countries with higher EFC are supposed to be more efficient in this purpose compared to those with low EFC.

However, the correlation between EFC and the incidence, YLDs and YLLs of diseases has never been studied thus far. We hypothesize that high EFC is correlated to low incidence, YLDs and YLLs of communicable diseases, but also to high incidence of non-communicable diseases, with various correlation to YLDs and YLLs according to the disease lethality and the healthcare systems' efficiency. We also hypothesize that these correlations are stable over time. Our primary objective is to determine whether the incidence, YLDs and/or YLLs of the 21 disease categories of the Global Burden of Disease (GBD) (Vos et al., 2020) were correlated to EFC in

176 countries over the period 1990-2019 via a pooled-meta analysis. Secondary objectives are to better understand differences between diseases and to determine whether these correlations are stable over time. For this purpose, we calculate correlation coefficients between EFC and 293 GBD diseases. To assess stability over time, we replicate the pooled-meta-analysis for each year between 1990 and 2019.

## 5.2.2. METHODS

### 5.2.2.1. ENERGY FOOTPRINT

Energy can be used by households directly (in their home for example) or indirectly, through the goods and services they purchase (Andrieu, Vidal, et al., 2022). If this final consumption is produced abroad, part of the energy use is delocalized. Input-output databases are tables that trace economic flows between regions. They allow to allocate intermediate production (e.g., steel) around the world to the final demand of a given region (cars bought by households in France, for example) (Ronald E. Miller et al., 2009b). Using matrices of energy consumption per dollar of intermediate production, it is possible to calculate the energy footprint of a region's final demand. For example, the energy used in a Chinese factory to produce goods purchased in the United-States will be counted for in the United-States' footprint. In input-output formalism, the footprint is given by:

$$E = F\hat{x}^{-1}(I - Z\hat{x}^{-1})^{-1}y + E_{hh}$$

With  $F$  the energy factor of production matrix,  $\hat{x}$  the diagonalized total industry output,  $I$  the identity matrix,  $Z$  the transaction matrix representing global inter-industries economic flows,  $y$  the final demand vector and  $E_{hh}$  the direct energy consumption by households.

We use the EORA database for EFC as it provides the best regional and temporal disaggregation: 190 countries over the 1990-2019 period (Lenzen, Kanemoto, et al., 2012; Lenzen, Moran, et al., 2013). Population data comes from the WorldBank (*Population, total* | *Data* 2022).

### 5.2.2.2. GLOBAL BURDEN OF DISEASES

The Global Burden of Diseases, Injuries, and Risk Factors Study (Vos et al., 2020) database is available in the Global Health Data Exchange catalog (*VizHub - GBD Results* 2023). It was created as a dedicated place for anyone interested in global health and demography to quickly find and share information about data along with actual datasets. For the purpose of this study, we used the Cause of death or injury dataset of 176 countries also present in the EORA database (including origin death or disability including injury, disease and condition). We used three measures: incidence, YLDs and YLLs. The years 1990-2019 were included, with annual results for all measures. All data were age-standardized and both sexes were included.

### 5.2.2.3. STATISTICAL ANALYSES

A first screening of the incidence, YLDs and YLLs plots as a function of EFC showed that when a tendency could be found, it seemed to follow a power law, except for outliers at very low energy footprint levels where there was a plateau. We therefore excluded the lowest 5% of energy footprints. For 293 GBD diseases, we calculated the least squared linear regression between the natural logarithm of EFC and the natural logarithm of the rates of incidence, YLDs and YLLs. The slopes of the linear log-log regressions can be interpreted as elasticities, that is the percentage change of disease incidence per percentage change of EFC. A slope of 0.5 is interpreted as a 0.5% increase of incidence for every 1% increase of EFC.

For each of the 21 GBD diseases categories (Codes of Diseases A.1 HIV-AIDS and sexually transmitted infections, A.2 Respiratory infections and tuberculosis, A.3 Enteric infections, A.4 Neglected tropical diseases and malaria, A.5 Other infectious diseases, A.6 Maternal and neonatal disorders, A.7 Nutritional deficiencies, B.1 Neoplasms, B.2 Cardiovascular diseases, B.3 Chronic respiratory diseases, B.4 Digestive diseases, B.5 Neurological disorders, B.6 Mental disorders, B.7 Substance use disorders, B.8 Diabetes and kidney diseases, B.9 Skin and subcutaneous diseases, B.10 Sense organ diseases, B.11 Musculoskeletal disorders, B.12 Other non-communicable diseases, C.1 Transport injuries, C.2 Unintentional injuries, C.3 Self-harm and interpersonal violence), we carry out a pooled meta-analysis of the correlation coefficients computed at the diseases' level to address our main objective (i.e., to determine whether the incidence, YLDs and/or YLLs of the 21 disease categories of the GBD were correlated to EFC in 176 countries over the period 1990-2019).

To address our secondary objective (to gain insights at the disease-level and not just at the category-level), we then focus on the regression results at the most detailed disease level for incidence.

To address our last objective (time stability), we also perform pooled meta-analyses for each year between 1990 and 2019.

#### DATA AVAILABILITY

EORA provides free licenses to academic users. IHME makes data freely available so that policymakers have the evidence they need to make informed decisions about how to allocate resources to best improve population health.

#### CODE AVAILABILITY

The code is available online: [baptiste-an/Energy-footprint-and-Global-Burden-of-Diseases](https://github.com/baptiste-an/Energy-footprint-and-Global-Burden-of-Diseases) (github.com)

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### 5.2.3. RESULTS

#### 5.2.3.1. ENERGY AND COMMUNICABLE, NON-COMMUNICABLE AND INJURIES DISEASES CATEGORIES

In the main category “A. Communicable, maternal, neonatal, and nutritional diseases”, all incidence, YLDs and YLLs rates were negatively correlated to EFC, except the incidence rate of “A.2 – respiratory infections and tuberculosis”, which was not statistically significant (Figure 5.20). The biggest effect size was for the incidence rate of the category “A.3 – Enteric infections” ( $r = -0.57$ ), followed by “A.6 – Maternal and neonatal disorders” ( $r = -0.53$ ), “A.5 – Other infectious diseases” ( $r = -0.49$ ), “A.7 – Nutritional deficiencies” ( $r = -0.49$ ), “A.1 – HIV/AIDS and sexually transmissible infections” ( $r = -0.44$ ) and “A.4 – Neglected tropical diseases and malaria” ( $r = -0.32$ ). The size effect of YLLs was systematically higher than that of incidence, while that of YLDs was closer to that of incidence.

In the main category “B. Non-Communicable diseases”, the incidence, YLDs and YLLs rates of “B.1 – Neoplasms” and “B.7 – Substance use disorders” were positively correlated to EFC (Figure 5.20). For categories “B.5 – Neurological disorders”, “B.6 – Mental disorders” and “B.11 – Musculoskeletal disorders”, the incidence and YLDs rates were positively correlated to energy footprint while the YLLs were non-significant. In category “B.8 – Diabetes and kidney diseases”, the incidence rate was positively correlated to the energy footprint while the YLDs rate was not statistically significant and the YLLs was negatively correlated to EFC. The YLLs rates of categories “B.4 – Digestive diseases”, “B.10 – Sense organ diseases” and “B.12 – Other non-communicable diseases” were negatively correlated to EFC. All other results in category B were not statistically significant.

In the main category “C. Injuries”, all YLLs rates were negatively correlated to EFC. The YLDs rate of “C.1 – Transport injuries” was negatively correlated to EFC while that of “C.2 – Unintentional injuries” and “C.3 – Self-harm and interpersonal violence” were not statistically significant (Figure 5.20). The incidence rates correlations were not statistically significant.

All results were stable over time, except for category “C.1 – Transport injuries”, whose effect size got bigger with time.

#### 5.2.3.2. ENERGY AND THE 293 DISEASES

At the disease level, out of the 293 diseases available in the GBD, 243 had incidence rates. Among these 243 incidence rates, 238 (98%) were significantly correlated to EFC ( $p\text{-value} < 0.05$ , Supplementary Table 5.16). Of these, 106 (44%) had a negative slope (lower incidence at high EFC) and 132 (56%) had a positive slope (higher incidence at high EFC) (Supplementary Table 1). Beyond  $p$ -value, the trends begin to be visually clear when  $R^2$  values reach 0.1 and are very clear for  $R^2$  values above 0.2. Of the 101 correlations with a  $R^2 > 0.2$ , 47 had a negative slope (diseases presented in Figure 5.21) and 44 had a positive slope (diseases presented in Figure 5.22).

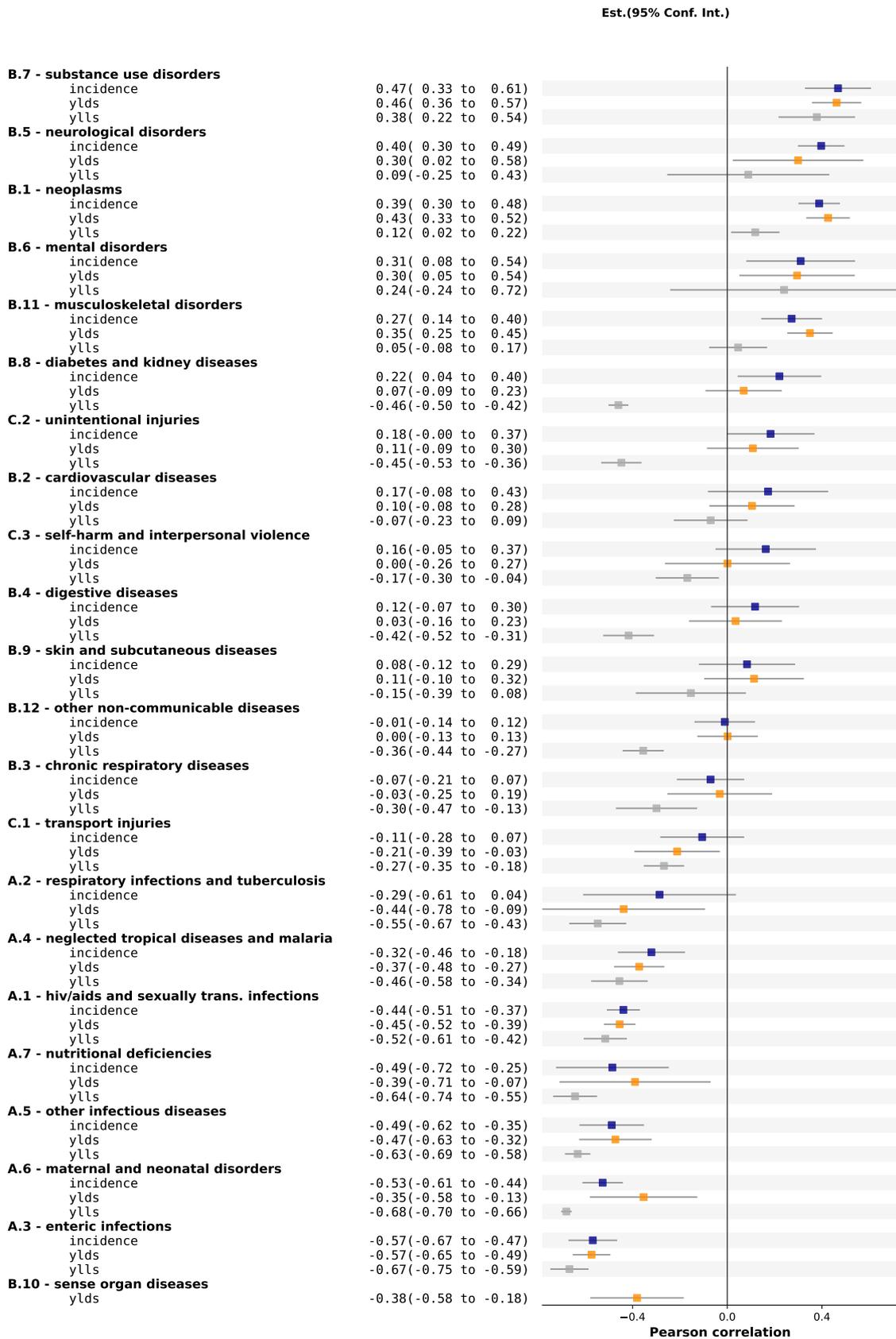
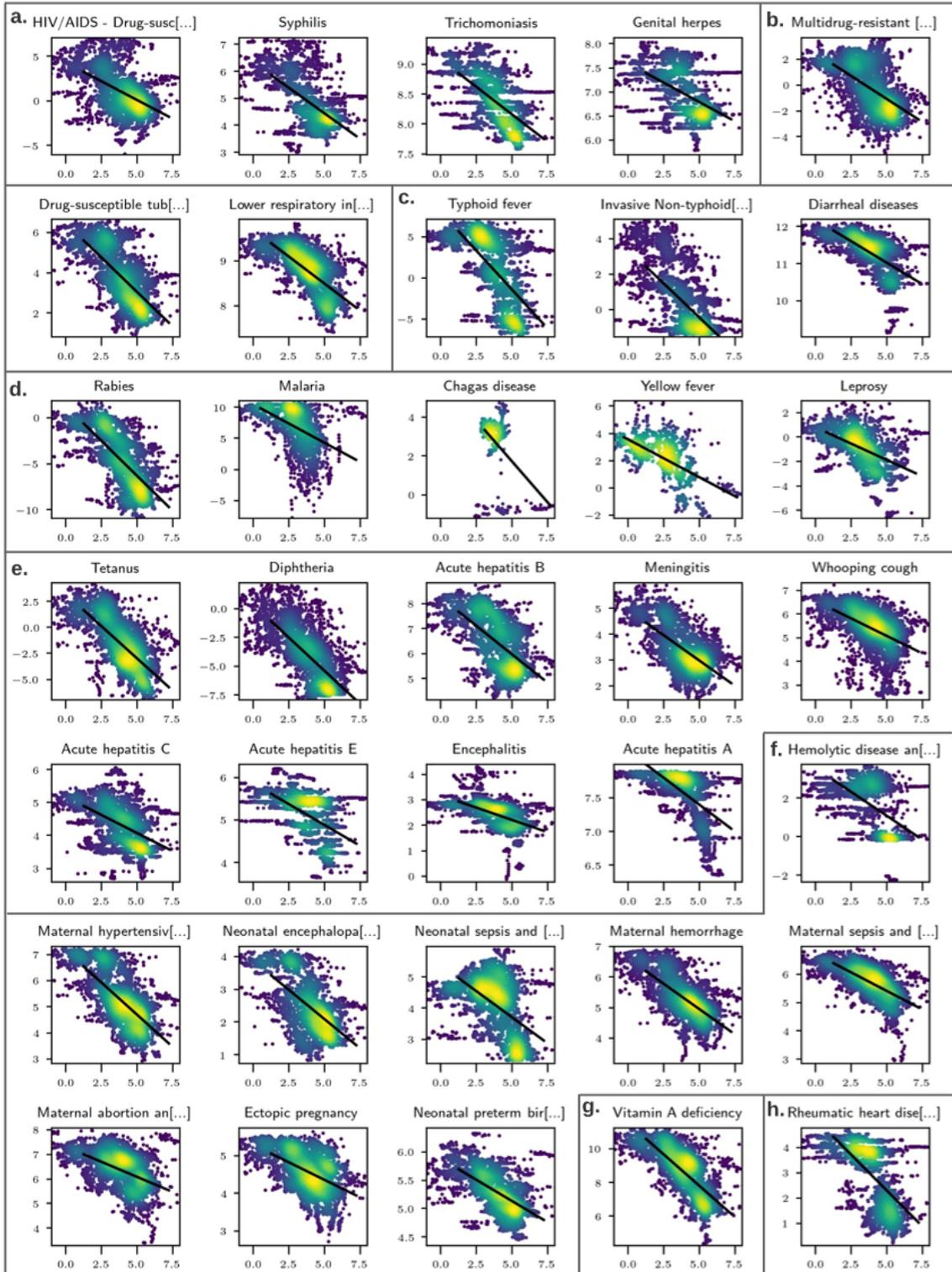
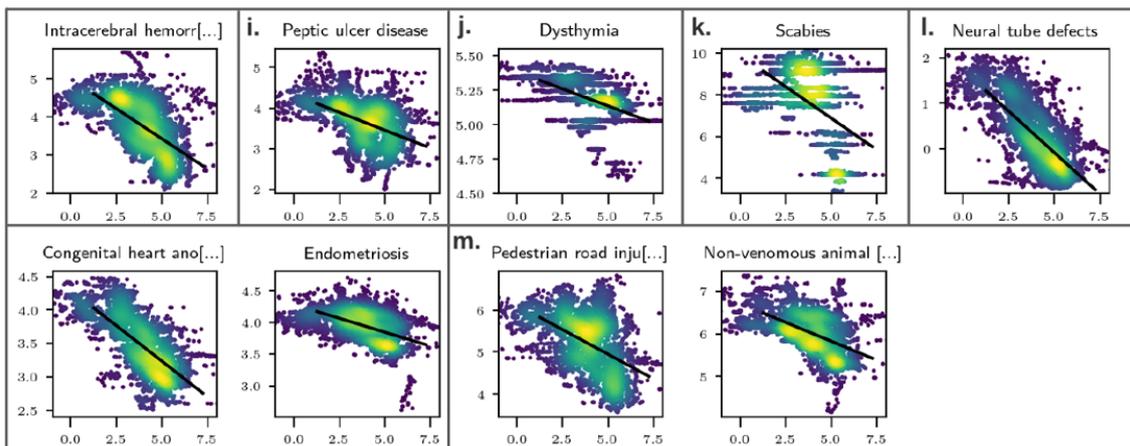


FIGURE 5.20: Pooled meta-analysis of the Pearson correlation coefficients between energy footprint per capita (EFC) and respectively incidence, Years of Life with Disability (YLDs) and Years of Life Lost (YLLs) rates of the 21 Global Burden of Diseases (GBD) categories. For category B.10, only data for YLDs were available.



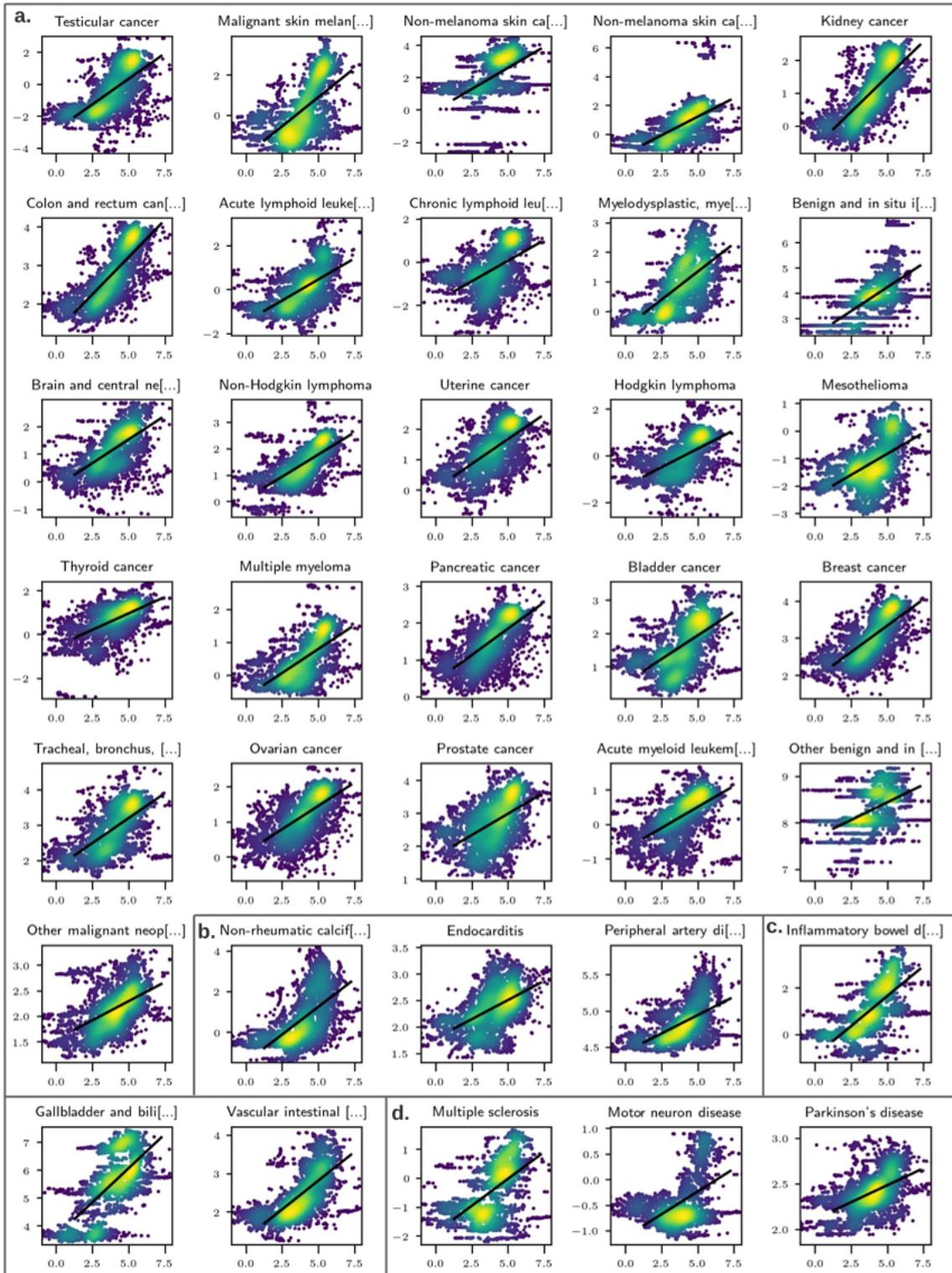


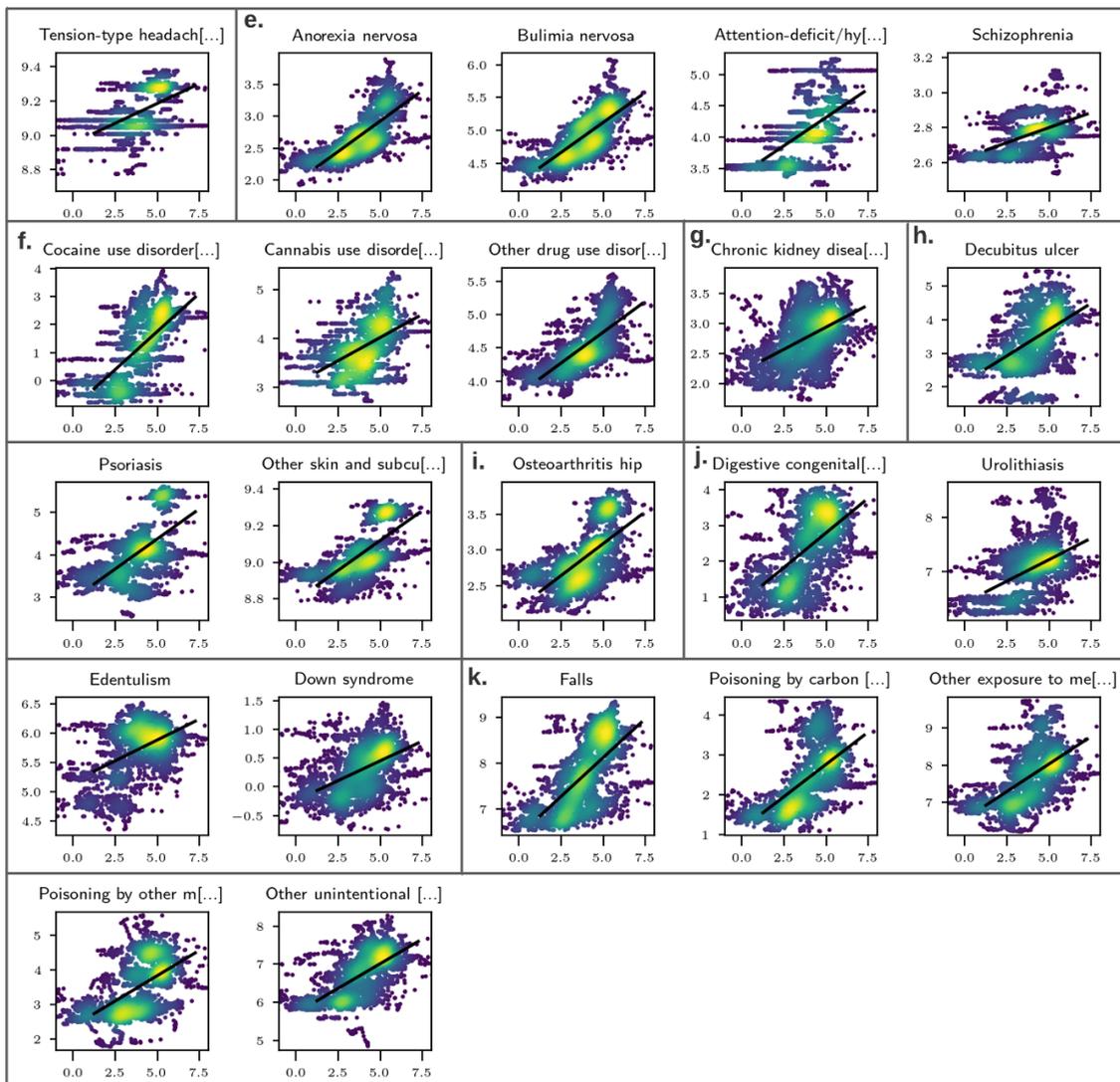
**FIGURE 5.21:** Diseases with lower incidence levels at high levels of energy. Y-axis is the natural logarithm of incidence per 100 000 persons. X-axis is the natural logarithm of the energy footprint per capita in giga joules. The black line corresponds to the regression. Full disease names can be found in Supplementary Table 1. **a.** HIV-AIDS and sexually transmitted infections, **b.** Respiratory infections and tuberculosis, **c.** Enteric infections, **d.** Neglected tropical diseases and malaria, **e.** Other infectious diseases, **f.** Maternal and neonatal disorders, **g.** Nutritional deficiencies, **h.** Cardiovascular diseases, **i.** Digestive diseases, **j.** Mental disorders, **k.** Skin and subcutaneous diseases, **l.** Other non-communicable diseases, **m.** Transport injuries.

#### 5.2.4. DISCUSSION

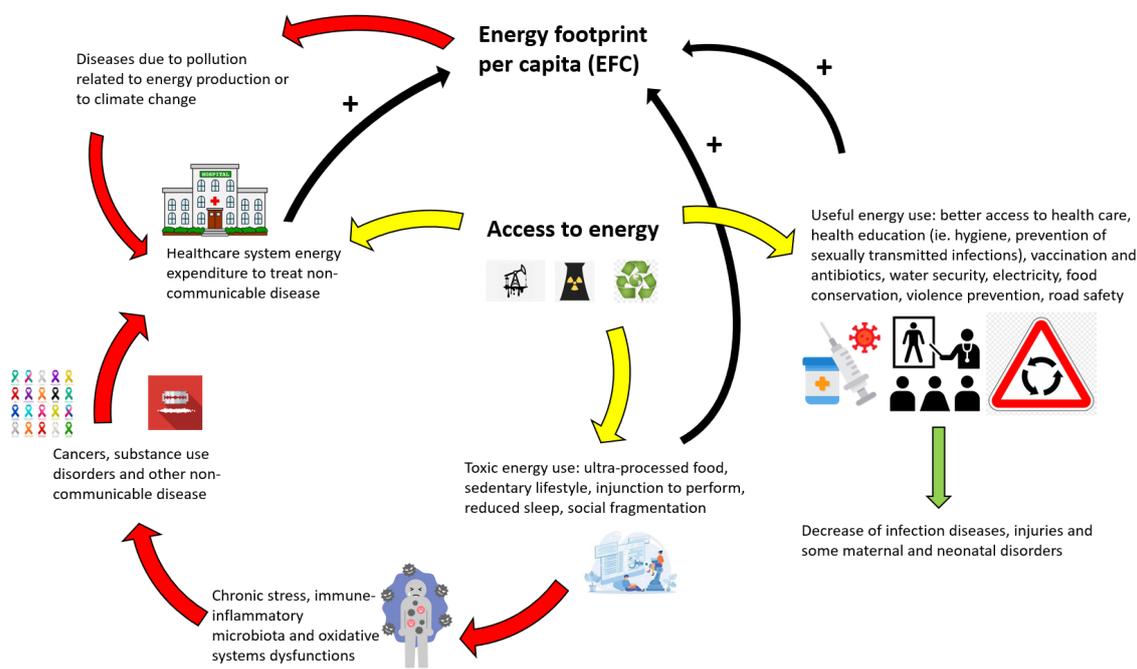
Over the period 1990-2019 and in order of decreasing Pearson correlation coefficient, high EFC is correlated to low rates of incidence, YLDs and YLLs of enteric infections, maternal and neonatal disorders, HIV/AIDS and other sexually transmitted diseases, and infectious diseases (on top of the list are typhoid fever, rabies, malaria, tetanus and diphtheria). At the disease level, the incidence rates of 44 diseases were negatively correlated to EFC (mostly communicable diseases and some post-infection cardiovascular diseases, some maternal and neonatal complications and vitamin A deficiency). High EFC was also negatively correlated to YLDs and YLLs for respiratory infections and tuberculosis and to transport injuries, and to lower YLLs due to chronic respiratory diseases, digestive disease, self-harm and interpersonal violence, unintentional injuries and diabetes and kidney diseases. As mentioned in the rationale, one hypothesis to explain the discrepancies between incidence, YLDs and YLLs is that most disease do not reduce life expectancy, and for those with potential sequelae and/or lethality, that the healthcare systems of countries with high EFC are successful in limiting the impact of these diseases or injuries on life expectancy but not in preventing them or in limiting their impact on YLDs. In other words, the healthcare systems of wealthy countries are more efficient for curing and preventing acute than chronic disease (Yach et al., 2004).

High EFC is also correlated to high incidence rates of substance use disorders (mostly cocaine and cannabis use), and to 26 different forms of neoplasms (with testicular, skin, kidney, colon and rectum and hematopoietic neoplasms on top of the list). These correlations are confirmed for YLDs and YLLs rates. This suggests that energy-intensive lifestyles are correlated to the increase of the incidence of some chronic diseases, and that the healthcare systems of countries with high EFC are not totally successful in preventing and treating these diseases. For





**FIGURE 5.22:** Diseases with higher incidence levels at high levels of energy. Y-axis is the natural logarithm of incidence per 100 000 persons. X-axis is the natural logarithm of the energy footprint per capita in giga joules. The black line corresponds to the regression. Full disease names can be found in Supplementary Table 1. **a.** Neoplasms, **b.** Cardiovascular diseases, **c.** Digestive diseases, **d.** Neurological disorders, **e.** Mental disorders, **f.** Substance use disorders, **g.** Diabetes and kidney diseases, **h.** Skin and subcutaneous diseases, **i.** Musculoskeletal disorders, **j.** Other non-communicable diseases, **k.** Unintentional injuries.



**FIGURE 5.23:** Explanatory model of the relationship between energy access, energy footprint and positive and negative health outcomes. The sum of the three black arrows is equal to the energy footprint per capita. Yellow arrows represent energy use. Green arrows represent positive health outcomes (due to healthcare, education, etc.). Red arrows represent negative health outcomes (e.g., due to sedentary lifestyle, etc.).

neurological disorders (multiple sclerosis, motor neuron disease and tension-type headache), mental disorders (mostly eating disorders) and musculoskeletal disorders, we have found a positive correlation between EFC and incidence and YLDs but not for YLLs. This is probably explained by the fact that most of these diseases do not reduce or slightly reduce life expectancy.

At the disease level and all diseases combined, we have found the strongest positive correlations (slope > 0.5, corresponding to a 0.5% increase of incidence for every 1% increase of energy footprint) for testicular cancer, skin cancers, non-rheumatic calcific aortic valve disease, inflammatory bowel disease and cocaine use disorders.

The results are stable over time and an overall picture emerges (illustrated in Figure 5.23).

On the one hand, a high EFC correlates to low rates of incidence, YLDs and YLLs of most communicable diseases and injuries. A plausible explanation is better access to health care, health education (including hygiene and prevention of sexually transmitted infections), vaccination and antibiotics, access to safe water, electricity, food preservation, road safety etc. Results for malaria and tropical diseases should be tempered, as almost all countries with low EFC are located in the tropics.

On the other hand, high EFC correlates with high rates of incidence, YLDs and YLLs of neoplasms, substance use disorders, and many other non-communicable diseases. Population aging cannot explain the results because (i) we used age-standardized data and (ii) many of the diseases positively correlated to a high EFC in our results are not age-related, such as testicular neoplasm, some hematopoietic neoplasms, inflammatory bowel disease, eating disorders, multiple sclerosis, motor neuron disease, tension-type headache occurring in young people. It also

seems unlikely that better screening could explain our results. Mental and substance use disorders, motor neuron disease, tension-type headache are clinical diagnoses that do not require extensive investigation. Breast cancer, for which routine screening is developed in high-income countries, is not at the top of the list of neoplasms whose incidence is correlated to EFC. Screening programs are also not always effective in the general population of high-income countries due to inequalities in access to care (Bygrave et al., 2020). Most hematopoietic neoplasms are detected with a simple blood draw. If increased detection fully explained our results, other diseases such as major depression and type 2 diabetes should be positively correlated to EFC, whereas we found no significant correlation for these diseases. The only potential confounding factor could be the proportion of white-skin phototypes for skin cancers, as many countries with high EFC (but not all) have a higher proportion of white ethnicity. The incidence of multiple sclerosis has also been described to vary with latitude (Sabel et al., 2021). Altogether, our results cannot be fully explained by age, screening, access to care, proportion of white ethnicity or latitude. Furthermore, no common risk factors were identified for the 26 forms of neoplasms whose incidence is positively correlated to EFC.

Specific immune dysfunctions in countries with high EFC are a likely explanatory factor. As mentioned in the rationale, this weakness could be induced by inflammatory/ultra-processed food (Mathieu et al., 2017), increased sedentary lifestyle, reduced and disturbed sleep (Shiri et al., 2017), chronic stress due to the work environment (Xu et al., 2019) and social isolation. The injunction to perform and non-compliance with circadian rhythms also probably explain the strong correlations between EFC and cocaine (to excite and cope with chronic sleep deprivation) (Ashok et al., 2017) and cannabis use disorders (to relax and induce sleep).

In 2019, 64% of all YLLs were due to non-communicable diseases, including 10% due to neoplasms only (Vos et al., 2020), which are positively correlated to EFC. Energy is not always used well, otherwise EFC would not be positively correlated to the YLLs of any disease. Reducing toxic or unnecessary energy use would benefit both global health and the energy transition. Examples of EFC reduction levers with a positive impact on health include: producing low-resource food (by decreasing red meat and ultra-processed food for example), insulating buildings (less energy consumption and reduction of fuel poverty), non-essential transport reduction (working locally and at home), promoting low-energy transport (especially active transport such as walking and cycling) and health prevention at work. This will create a virtuous cycle by decreasing healthcare expenditures, an energy-intensive sector itself (Andrieu, Marraud, et al., 2022). The Lancet Countdown identifies these examples as climate and health co-benefits (Romanello et al., 2022). Indirect benefits would also include the improvement of other environmental parameters such as air and water pollution, thereby reducing the incidence of other diseases not listed in our results (Grubler et al., 2018).

In 2019, communicable diseases were still responsible for 26% of all YLLs, mostly in the Global South (Vos et al., 2020). To reduce global energy consumption while allowing to reduce the YLLs due to communicable diseases, it is necessary that the Global South has access to enough energy. Huge inequalities currently exist between regional EFC (illustrated by the need to use a logarithmic scale in figures 5.21 and 5.22). These inequalities are perpetuated

in energy transition scenarios, in which Global North's EFC is maintained at a level 2.3 times higher than in the Global South (Hickel and Slamersak, 2022). The energy demand of some regions of the South is even projected to fall below levels deemed critical for decent living standards (Semieniuk et al., 2021). A global convergence in EFC, i.e. a similar EFC for every world region (Hickel and Slamersak, 2022; Hickel, Brockway, et al., 2021), would help reduce the incidence of communicable diseases (e.g. malaria and HIV/AIDS in Africa) (Grubler et al., 2018) in the Global South and encourage a healthier lifestyle in the Global North.

Overall, our results could be explained by both positive outcomes (better access to vaccination, hygiene, education and prevention in countries) and negative outcomes (specific immune dysfunctions induced by the energy-intensive lifestyle) in countries with high EFC. In light of the need to consume less energy to achieve a successful energy transition and become more resilient to the risks of energy supply contraction, it is critical to make better use of energy, allocating it to what improves health and not to what may increase chronic disease risk. For example, large-scale prevention, promotion of active transportation and a healthier diet would both reduce energy use and several non-communicable diseases. On the other hand, universal access to energy in the Global South would contribute to the eradication of many communicable diseases.

**Limits** We have addressed two potential limitations, the effect of age (by using age-standardized data) and the effect of screening (by providing counter examples). Our results could not capture indirect factors such as air pollution, which is responsible for noncommunicable diseases, including cardiovascular diseases, stroke, chronic obstructive pulmonary disease and lung cancer (Organisation, 2022). The main sources of air pollution are the combustion of fossil resources (thermal transport, fossil power plants, industrial uses), household waste and industrial activities (Organisation, 2022) but also dust storms in regions close to deserts, which adds noise to the correlations. Moreover, air pollution may have consequences far away from its emission sources. Our results may therefore underestimate the strength of the correlations between EFC and environmental degradation-induced diseases (Wang et al., 2020; Hanif, 2018).

### 5.2.5. APPENDIX

TABLE 5.16: Results for incidence, YLDs and YLLs for all GBD diseases.

| Code    | Disease   | incidence |        |       | YLDs |        |       | YLLs |        |       |
|---------|---|-----------|--------|-------|------|--------|-------|------|--------|-------|
|         |   | R2        | pvalue | slope | R2   | pvalue | slope | R2   | pvalue | slope |
| A.1.1.1 | HIV/AIDS - Drug-susceptible Tuberculosis                                      | 0,22      | 0      | -0,84 | 0,25 | 0      | -0,9  | 0,22 | 0      | -0,95 |
| A.1.1.2 | HIV/AIDS - Multidrug-resistant Tuberculosis without extensive drug resistance | 0,19      | 0      | -0,87 | 0,22 | 0      | -0,94 | 0,2  | 0      | -0,98 |
| A.1.1.3 | HIV/AIDS - Extensively drug-resistant Tuberculosis                            | 0,06      | 0      | -0,42 | 0,08 | 0      | -0,5  | 0,08 | 0      | -0,54 |
| A.1.1.4 | HIV/AIDS resulting in other diseases  | 0,13      | 0      | -0,59 | 0,09 | 0      | -0,52 | 0,16 | 0      | -0,71 |
| A.1.2.1 | Syphilis  | 0,33      | 0      | -0,38 | 0,11 | 0      | -0,22 | 0,46 | 0      | -1,46 |
| A.1.2.2 | Chlamydial infection  | 0,14      | 0      | -0,24 | 0,28 | 0      | -0,26 | 0,35 | 0      | -0,54 |
| A.1.2.3 | Gonococcal infection  | 0,19      | 0      | -0,3  | 0,27 | 0      | -0,31 | 0,34 | 0      | -0,53 |
| A.1.2.4 | Trichomoniasis  | 0,35      | 0      | -0,18 | 0,33 | 0      | -0,32 |      |        |       |
| A.1.2.5 | Genital herpes  | 0,21      | 0      | -0,16 | 0,2  | 0      | -0,17 |      |        |       |
| A.2.1.2 | Drug-susceptible tuberculosis   | 0,44      | 0      | -0,68 | 0,49 | 0      | -0,77 | 0,48 | 0      | -1,09 |
| A.2.1.3 | Multidrug-resistant tuberculosis without extensive drug resistance            | 0,27      | 0      | -0,71 | 0,33 | 0      | -0,8  | 0,4  | 0      | -1,12 |
| A.2.1.4 | Extensively drug-resistant tuberculosis                                       | 0,03      | 0      | -0,26 | 0,06 | 0      | -0,36 | 0,19 | 0      | -0,66 |
| A.2.2   | Lower respiratory infections  | 0,44      | 0      | -0,24 | 0,44 | 0      | -0,24 | 0,48 | 0      | -0,6  |
| A.2.3   | Upper respiratory infections  | 0,12      | 0      | 0,05  | 0,13 | 0      | 0,05  | 0,24 | 0      | -0,64 |
| A.2.4   | Otitis media  | 0         | 0,04   | 0     | 0,62 | 0      | -0,17 | 0,11 | 0      | -0,57 |
| A.3.1   | Diarrheal diseases  | 0,4       | 0      | -0,23 | 0,4  | 0      | -0,24 | 0,53 | 0      | -1,27 |
| A.3.2.1 | Typhoid fever   | 0,39      | 0      | -1,89 | 0,39 | 0      | -1,89 | 0,41 | 0      | -2,03 |
| A.3.2.2 | Paratyphoid fever   | 0,17      | 0      | -0,84 | 0,17 | 0      | -0,84 | 0,27 | 0      | -1,13 |
| A.3.3   | Invasive Non-typhoidal Salmonella (iNTS)                                      | 0,37      | 0      | -0,77 | 0,37 | 0      | -0,77 | 0,46 | 0      | -1,42 |
| A.4.1   | Malaria   | 0,23      | 0      | -1,23 | 0,28 | 0      | -0,97 | 0,28 | 0      | -1,45 |
| A.4.11  | Dengue  | 0,02      | 0      | 0,06  | 0,02 | 0      | 0,06  | 0    | 0,06   | 0,08  |
| A.4.12  | Yellow fever  | 0,36      | 0      | -0,56 | 0,36 | 0      | -0,56 | 0,37 | 0      | -0,63 |

|         |   |      |      |       |      |      |       |      |     |       |
|---------|---|------|------|-------|------|------|-------|------|-----|-------|
| A.4.13  | Rabies  | 0,46 | 0    | -1,52 | 0,46 | 0    | -1,52 | 0,47 | 0   | -1,61 |
| A.4.16  | Leprosy                                       | 0,22 | 0    | -0,53 | 0,33 | 0    | -0,67 |      |     |       |
| A.4.17  | Ebola   | 0,1  | 0,11 | -0,68 | 0,09 | 0,07 | -0,72 | 0,02 | 0,5 | -0,3  |
| A.4.18  | Zika virus                                    | 0,09 | 0    | -1,11 | 0,02 | 0,07 | -0,44 | 0,01 | 0,4 | 0,17  |
| A.4.19  | Guinea worm disease                           | 0,02 | 0,01 | -0,49 | 0,02 | 0,01 | -0,49 |      |     |       |
| A.4.2   | Chagas disease                                | 0,24 | 0    | -0,84 | 0,4  | 0    | -2,16 | 0,18 | 0   | -0,86 |
| A.4.3.1 | Visceral leishmaniasis                        | 0,03 | 0    | -0,26 | 0,03 | 0    | -0,26 | 0,08 | 0   | -0,47 |
| A.4.3.2 | Cutaneous and mucocutaneous leishmaniasis     | 0,04 | 0    | -0,52 | 0,2  | 0    | -1,27 |      |     |       |
| A.4.4   | African trypanosomiasis                       | 0,07 | 0    | -0,51 | 0,05 | 0    | -0,58 | 0,1  | 0   | -0,54 |
| A.4.7   | Cystic echinococcosis                         | 0,02 | 0    | -0,24 | 0,01 | 0    | -0,23 | 0,33 | 0   | -0,77 |
| A.5.1   | Meningitis                                    | 0,38 | 0    | -0,39 | 0,45 | 0    | -0,44 | 0,51 | 0   | -0,79 |
| A.5.2   | Encephalitis                                  | 0,26 | 0    | -0,19 | 0,44 | 0    | -0,32 | 0,18 | 0   | -0,3  |
| A.5.3   | Diphtheria                                    | 0,44 | 0    | -1,15 | 0,44 | 0    | -1,15 | 0,48 | 0   | -1,37 |
| A.5.4   | Whooping cough                                | 0,22 | 0    | -0,3  | 0,22 | 0    | -0,29 | 0,45 | 0   | -1,79 |
| A.5.5   | Tetanus                                       | 0,47 | 0    | -1,24 | 0,48 | 0    | -1,29 | 0,54 | 0   | -1,61 |
| A.5.6   | Measles                                       | 0,14 | 0    | -1,26 | 0,14 | 0    | -1,25 | 0,45 | 0   | -2,16 |
| A.5.7   | Varicella and herpes zoster                   | 0,02 | 0    | 0     | 0    | 0    | 0,01  | 0,47 | 0   | -0,82 |
| A.5.8.1 | Acute hepatitis A                             | 0,37 | 0    | -0,16 | 0,01 | 0    | 0,01  | 0,45 | 0   | -1,24 |
| A.5.8.2 | Acute hepatitis B                             | 0,35 | 0    | -0,46 | 0,34 | 0    | -0,45 | 0,39 | 0   | -0,84 |
| A.5.8.3 | Acute hepatitis C                             | 0,23 | 0    | -0,22 | 0,23 | 0    | -0,22 | 0,41 | 0   | -0,85 |
| A.5.8.4 | Acute hepatitis E                             | 0,27 | 0    | -0,2  | 0,27 | 0    | -0,18 | 0,33 | 0   | -0,7  |
| A.6.1.1 | Maternal hemorrhage                           | 0,43 | 0    | -0,33 | 0,51 | 0    | -0,49 | 0,55 | 0   | -1,35 |
| A.6.1.2 | Maternal sepsis and other maternal infections | 0,41 | 0    | -0,26 | 0,43 | 0    | -0,28 | 0,54 | 0   | -1,62 |
| A.6.1.3 | Maternal hypertensive disorders               | 0,45 | 0    | -0,49 | 0,41 | 0    | -0,47 | 0,51 | 0   | -1,08 |
| A.6.1.4 | Maternal obstructed labor and uterine rupture | 0,04 | 0    | -0,08 | 0,35 | 0    | -0,71 | 0,46 | 0   | -1,26 |

|          |  |      |   |       |      |   |       |      |      |       |
|----------|--|------|---|-------|------|---|-------|------|------|-------|
| A.6.1.5  | Maternal abortion and miscarriage                        | 0,21 | 0 | -0,25 | 0,21 | 0 | -0,24 | 0,52 | 0    | -1,43 |
| A.6.1.6  | Ectopic pregnancy  | 0,23 | 0 | -0,19 | 0,23 | 0 | -0,19 | 0,43 | 0    | -1,04 |
| A.6.2.1  | Neonatal preterm birth                                   | 0,31 | 0 | -0,15 | 0,18 | 0 | 0,12  | 0,35 | 0    | -0,42 |
| A.6.2.2  | Neonatal encephalopathy due to birth asphyxia and trauma | 0,35 | 0 | -0,36 | 0,16 | 0 | 0,2   | 0,46 | 0    | -0,59 |
| A.6.2.3  | Neonatal sepsis and other neonatal infections            | 0,25 | 0 | -0,33 | 0,02 | 0 | -0,12 | 0,46 | 0    | -0,74 |
| A.6.2.4  | Hemolytic disease and other neonatal jaundice            | 0,27 | 0 | -0,5  | 0,17 | 0 | -0,27 | 0,44 | 0    | -0,85 |
| A.7.1    | Protein-energy malnutrition                              | 0,09 | 0 | -0,09 | 0,04 | 0 | -0,09 | 0,48 | 0    | -1,23 |
| A.7.2    | Iodine deficiency  | 0,19 | 0 | -0,31 | 0,29 | 0 | -0,47 |      |      |       |
| A.7.3    | Vitamin A deficiency                                     | 0,52 | 0 | -0,75 | 0,52 | 0 | -1,03 |      |      |       |
| B.1.1    | Lip and oral cavity cancer                               | 0,09 | 0 | 0,12  | 0,16 | 0 | 0,18  | 0    | 0,03 | -0,01 |
| B.1.10   | Larynx cancer  | 0,15 | 0 | 0,16  | 0,23 | 0 | 0,21  | 0    | 0    | -0,02 |
| B.1.11   | Tracheal, bronchus, and lung cancer                      | 0,36 | 0 | 0,28  | 0,38 | 0 | 0,29  | 0,3  | 0    | 0,24  |
| B.1.12   | Malignant skin melanoma                                  | 0,32 | 0 | 0,58  | 0,36 | 0 | 0,7   | 0,14 | 0    | 0,25  |
| B.1.13.1 | Non-melanoma skin cancer (squamous-cell carcinoma)       | 0,31 | 0 | 0,52  | 0,34 | 0 | 0,65  | 0,01 | 0    | 0,03  |
| B.1.13.2 | Non-melanoma skin cancer (basal-cell carcinoma)          | 0,22 | 0 | 0,52  | 0,24 | 0 | 0,53  |      |      |       |
| B.1.14   | Breast cancer  | 0,44 | 0 | 0,28  | 0,49 | 0 | 0,34  | 0,04 | 0    | 0,05  |
| B.1.15   | Cervical cancer  | 0,19 | 0 | -0,22 | 0,12 | 0 | -0,16 | 0,32 | 0    | -0,36 |
| B.1.16   | Uterine cancer   | 0,35 | 0 | 0,32  | 0,4  | 0 | 0,39  | 0,01 | 0    | 0,03  |
| B.1.17   | Ovarian cancer   | 0,37 | 0 | 0,26  | 0,4  | 0 | 0,29  | 0,26 | 0    | 0,19  |
| B.1.18   | Prostate cancer  | 0,24 | 0 | 0,26  | 0,35 | 0 | 0,37  | 0    | 0,2  | 0,01  |
| B.1.19   | Testicular cancer  | 0,37 | 0 | 0,64  | 0,42 | 0 | 0,8   | 0,04 | 0    | 0,12  |
| B.1.2    | Nasopharynx cancer                                       | 0,03 | 0 | 0,12  | 0,08 | 0 | 0,2   | 0,03 | 0    | -0,11 |
| B.1.20   | Kidney cancer  | 0,51 | 0 | 0,43  | 0,53 | 0 | 0,47  | 0,38 | 0    | 0,27  |
| B.1.21   | Bladder cancer   | 0,27 | 0 | 0,28  | 0,36 | 0 | 0,38  | 0,04 | 0    | 0,08  |
| B.1.22   | Brain and central nervous system cancer                  | 0,37 | 0 | 0,34  | 0,41 | 0 | 0,42  | 0,21 | 0    | 0,19  |

|          |  |      |      |       |      |      |       |      |      |       |
|----------|--|------|------|-------|------|------|-------|------|------|-------|
| B.1.23   | Thyroid cancer   | 0,3  | 0    | 0,3   | 0,33 | 0    | 0,35  | 0    | 0,2  | 0,01  |
| B.1.24   | Mesothelioma   | 0,21 | 0    | 0,31  | 0,22 | 0    | 0,33  | 0,19 | 0    | 0,27  |
| B.1.25   | Hodgkin lymphoma   | 0,26 | 0    | 0,32  | 0,36 | 0    | 0,47  | 0,02 | 0    | -0,06 |
| B.1.26   | Non-Hodgkin lymphoma   | 0,4  | 0    | 0,34  | 0,48 | 0    | 0,51  | 0,12 | 0    | 0,12  |
| B.1.27   | Multiple myeloma   | 0,36 | 0    | 0,29  | 0,41 | 0    | 0,36  | 0,25 | 0    | 0,19  |
| B.1.28.1 | Acute lymphoid leukemia  | 0,31 | 0    | 0,38  | 0,36 | 0    | 0,5   | 0    | 0    | 0,02  |
| B.1.28.2 | Chronic lymphoid leukemia  | 0,23 | 0    | 0,38  | 0,32 | 0    | 0,5   | 0,06 | 0    | 0,14  |
| B.1.28.3 | Acute myeloid leukemia   | 0,27 | 0    | 0,24  | 0,26 | 0    | 0,23  | 0,19 | 0    | 0,17  |
| B.1.28.4 | Chronic myeloid leukemia   | 0,11 | 0    | 0,2   | 0,15 | 0    | 0,27  | 0,05 | 0    | -0,1  |
| B.1.28.5 | Other leukemia   | 0,02 | 0    | -0,05 | 0,01 | 0    | -0,04 | 0,09 | 0    | -0,15 |
| B.1.29   | Other malignant neoplasms  | 0,24 | 0    | 0,15  | 0,31 | 0    | 0,2   | 0,11 | 0    | -0,08 |
| B.1.3    | Other pharynx cancer   | 0,18 | 0    | 0,26  | 0,23 | 0    | 0,31  | 0,04 | 0    | 0,12  |
| B.1.30.1 | Myelodysplastic, myeloproliferative, and other hematopoietic neoplasms | 0,35 | 0    | 0,38  | 0,39 | 0    | 0,6   | 0,3  | 0    | 0,24  |
| B.1.30.2 | Benign and in situ intestinal neoplasms                                | 0,36 | 0    | 0,38  |      |      |       |      |      |       |
| B.1.30.3 | Benign and in situ cervical and uterine neoplasms                      | 0,15 | 0    | 0,36  |      |      |       |      |      |       |
| B.1.30.4 | Other benign and in situ neoplasms                                     | 0,2  | 0    | 0,15  |      |      |       |      |      |       |
| B.1.4    | Esophageal cancer  | 0,01 | 0    | -0,05 | 0    | 0    | -0,03 | 0,03 | 0    | -0,1  |
| B.1.5    | Stomach cancer   | 0    | 0,09 | 0,01  | 0,01 | 0    | 0,04  | 0,05 | 0    | -0,08 |
| B.1.6    | Colon and rectum cancer  | 0,55 | 0    | 0,39  | 0,56 | 0    | 0,46  | 0,41 | 0    | 0,21  |
| B.1.7.1  | Liver cancer due to hepatitis B  | 0,07 | 0    | -0,18 | 0,06 | 0    | -0,16 | 0,11 | 0    | -0,23 |
| B.1.7.2  | Liver cancer due to hepatitis C  | 0    | 0    | 0,03  | 0,01 | 0    | 0,05  | 0    | 0,36 | -0,01 |
| B.1.7.3  | Liver cancer due to alcohol use  | 0,03 | 0    | 0,09  | 0,03 | 0    | 0,11  | 0,01 | 0    | 0,05  |
| B.1.7.4  | Liver cancer due to NASH   | 0,01 | 0    | -0,06 | 0,01 | 0    | -0,05 | 0,04 | 0    | -0,11 |
| B.1.7.5  | Liver cancer due to other causes                                       | 0,01 | 0    | -0,04 | 0    | 0,03 | -0,02 | 0,11 | 0    | -0,16 |
| B.1.8    | Gallbladder and biliary tract cancer                                   | 0,12 | 0    | 0,14  | 0,14 | 0    | 0,15  | 0,02 | 0    | 0,06  |

|           |   |      |      |       |      |      |       |      |      |       |
|-----------|---|------|------|-------|------|------|-------|------|------|-------|
| B.1.9     | Pancreatic cancer                                   | 0,4  | 0    | 0,29  | 0,4  | 0    | 0,28  | 0,36 | 0    | 0,25  |
| B.11.1    | Rheumatoid arthritis                                | 0,09 | 0    | 0,13  | 0,15 | 0    | 0,15  | 0    | 0,27 | -0,01 |
| B.11.2.1  | Osteoarthritis hip                                  | 0,38 | 0    | 0,18  | 0,38 | 0    | 0,17  |      |      |       |
| B.11.2.2  | Osteoarthritis knee                                 | 0,08 | 0    | 0,03  | 0,07 | 0    | 0,03  |      |      |       |
| B.11.2.3  | Osteoarthritis hand                                 | 0,07 | 0    | 0,15  | 0,06 | 0    | 0,16  |      |      |       |
| B.11.2.4  | Osteoarthritis other                                | 0,12 | 0    | 0,01  | 0,19 | 0    | 0,02  |      |      |       |
| B.11.3    | Low back pain                                       | 0    | 0,02 | 0     | 0,21 | 0    | 0,06  |      |      |       |
| B.11.4    | Neck pain   | 0,1  | 0    | 0,09  | 0,14 | 0    | 0,13  |      |      |       |
| B.11.5    | Gout  | 0    | 0,04 | 0,01  | 0,04 | 0    | 0,06  |      |      |       |
| B.12.1.1  | Neural tube defects                                 | 0,51 | 0    | -0,36 | 0,16 | 0    | -0,13 | 0,49 | 0    | -0,61 |
| B.12.1.10 | Digestive congenital anomalies                      | 0,3  | 0    | 0,39  | 0,37 | 0    | 0,41  | 0,34 | 0    | -0,33 |
| B.12.1.2  | Congenital heart anomalies                          | 0,45 | 0    | -0,21 | 0,17 | 0    | -0,05 | 0,19 | 0    | -0,2  |
| B.12.1.3  | Orofacial clefts                                    | 0,07 | 0    | 0,08  | 0,06 | 0    | -0,08 | 0,34 | 0    | -0,9  |
| B.12.1.4  | Down syndrome                                       | 0,21 | 0    | 0,14  | 0,43 | 0    | 0,31  | 0,12 | 0    | -0,18 |
| B.12.1.5  | Turner syndrome                                     | 0    | 0,28 | -0,01 | 0,14 | 0    | 0,15  |      |      |       |
| B.12.1.6  | Klinefelter syndrome                                | 0,15 | 0    | 0,3   | 0,34 | 0    | 0,57  |      |      |       |
| B.12.1.7  | Other chromosomal abnormalities                     | 0,03 | 0    | 0,04  | 0,4  | 0    | 0,23  | 0    | 0    | -0,02 |
| B.12.1.8  | Congenital musculoskeletal and limb anomalies       | 0,06 | 0    | -0,07 | 0,01 | 0    | 0,02  | 0,09 | 0    | -0,15 |
| B.12.1.9  | Urogenital congenital anomalies                     | 0,02 | 0    | -0,02 | 0    | 0,31 | 0     | 0,07 | 0    | -0,13 |
| B.12.2.1  | Urinary tract infections and interstitial nephritis | 0,19 | 0    | 0,14  | 0,2  | 0    | 0,14  | 0,06 | 0    | -0,14 |
| B.12.2.2  | Urolithiasis  | 0,22 | 0    | 0,16  | 0,22 | 0    | 0,15  | 0,03 | 0    | -0,14 |
| B.12.2.3  | Benign prostatic hyperplasia                        | 0,06 | 0    | 0,09  | 0,05 | 0    | 0,08  |      |      |       |
| B.12.3.1  | Uterine fibroids                                    | 0,02 | 0    | 0,04  | 0,02 | 0    | 0,05  | 0,07 | 0    | -0,37 |
| B.12.3.2  | Polycystic ovarian syndrome                         | 0,15 | 0    | 0,26  | 0,14 | 0    | 0,26  |      |      |       |
| B.12.3.4  | Endometriosis                                       | 0,24 | 0    | -0,09 | 0,23 | 0    | -0,08 | 0,18 | 0    | -0,61 |

S.2. ASSOCI

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|          |   |      |      |       |      |      |       |      |      |       |
|----------|---|------|------|-------|------|------|-------|------|------|-------|
| B.12.3.5 | Genital prolapse                                | 0,12 | 0    | -0,08 | 0,12 | 0    | -0,1  | 0,22 | 0    | -0,54 |
| B.12.3.6 | Premenstrual syndrome                           | 0    | 0,03 | 0     | 0    | 0    | 0     |      | THEI |       |
| B.12.3.7 | Other gynecological diseases                    | 0,02 | 0    | -0,04 | 0,02 | 0    | -0,05 | 0,2  | 0    | -0,54 |
| B.12.4.1 | Thalassemias                                    | 0    | 0    | 0,06  | 0    | 0,4  | 0,02  | 0,05 | 0    | -0,26 |
| B.12.4.2 | Thalassemias trait                              | 0,01 | 0    | -0,06 | 0,17 | 0    | -0,35 |      | IENT |       |
| B.12.4.3 | Sickle cell disorders                           | 0,04 | 0    | -0,38 | 0,02 | 0    | -0,35 | 0,09 | 0    | -0,65 |
| B.12.4.4 | Sickle cell trait                               | 0,03 | 0    | -0,2  | 0,21 | 0    | -0,53 |      | JS   |       |
| B.12.4.5 | G6PD deficiency                                 | 0,15 | 0    | -0,22 | 0,28 | 0    | -0,34 | 0,27 | 0    | -0,48 |
| B.12.4.6 | G6PD trait                                      | 0,15 | 0    | -0,11 | 0,11 | 0    | -0,13 |      |      |       |
| B.12.6.1 | Caries of deciduous teeth                       | 0,06 | 0    | -0,03 | 0,07 | 0    | -0,04 |      |      |       |
| B.12.6.2 | Caries of permanent teeth                       | 0    | 0    | 0     | 0    | 0    | -0,01 |      |      |       |
| B.12.6.3 | Periodontal diseases                            | 0,01 | 0    | -0,03 | 0,03 | 0    | -0,06 |      |      |       |
| B.12.6.4 | Edentulism                                      | 0,2  | 0    | 0,14  | 0,15 | 0    | 0,13  |      |      |       |
| B.2.1    | Rheumatic heart disease                         | 0,4  | 0    | -0,57 | 0,37 | 0    | -0,58 | 0,26 | 0    | -0,35 |
| B.2.10   | Peripheral artery disease                       | 0,28 | 0    | 0,1   | 0,09 | 0    | 0,06  | 0,09 | 0    | 0,24  |
| B.2.11   | Endocarditis                                    | 0,24 | 0    | 0,14  | 0,09 | 0    | 0,17  | 0,08 | 0    | -0,12 |
| B.2.2    | Ischemic heart disease                          | 0,01 | 0    | 0,04  | 0,03 | 0    | 0,04  | 0,01 | 0    | -0,04 |
| B.2.3.1  | Ischemic stroke                                 | 0    | 0,38 | 0     | 0    | 0,05 | -0,01 | 0,03 | 0    | -0,07 |
| B.2.3.2  | Intracerebral hemorrhage                        | 0,36 | 0    | -0,32 | 0,26 | 0    | -0,23 | 0,37 | 0    | -0,4  |
| B.2.3.3  | Subarachnoid hemorrhage                         | 0,07 | 0    | 0,07  | 0,11 | 0    | 0,12  | 0,02 | 0    | -0,06 |
| B.2.5.1  | Non-rheumatic calcific aortic valve disease     | 0,36 | 0    | 0,55  | 0,48 | 0    | 0,97  | 0,17 | 0    | 0,23  |
| B.2.5.2  | Non-rheumatic degenerative mitral valve disease | 0,19 | 0    | 0,43  | 0,21 | 0    | 0,49  | 0    | 0,39 | -0,01 |
| B.2.6.1  | Myocarditis                                     | 0,1  | 0    | 0,03  | 0,05 | 0    | 0,09  | 0    | 0    | 0,03  |
| B.2.8    | Atrial fibrillation and flutter                 | 0,17 | 0    | 0,13  | 0,2  | 0    | 0,16  | 0,08 | 0    | 0,06  |
| B.3.1    | Chronic obstructive pulmonary disease           | 0,06 | 0    | 0,07  | 0,03 | 0    | -0,07 | 0,2  | 0    | -0,21 |

|         |  |      |   |       |      |   |       |      |     |       |
|---------|--|------|---|-------|------|---|-------|------|-----|-------|
| B.3.2.1 | Silicosis  | 0,01 | 0 | -0,11 | 0,01 | 0 | -0,14 | 0,01 | 0   | -0,11 |
| B.3.2.2 | Asbestosis   | 0,08 | 0 | -0,24 | 0,05 | 0 | -0,22 | 0    | 0   | -0,06 |
| B.3.2.3 | Coal workers pneumoconiosis                                    | 0,01 | 0 | -0,15 | 0,01 | 0 | 0,17  | 0,07 | 0   | -0,32 |
| B.3.2.4 | Other pneumoconiosis   | 0,04 | 0 | -0,24 | 0,02 | 0 | -0,18 | 0,2  | 0   | -0,46 |
| B.3.3   | Asthma   | 0,02 | 0 | 0,03  | 0,14 | 0 | 0,13  | 0,4  | 0   | -0,62 |
| B.3.4   | Interstitial lung disease and pulmonary sarcoidosis            | 0,05 | 0 | -0,13 | 0,2  | 0 | 0,17  | 0    | 0   | 0,03  |
| B.4.1.1 | Cirrhosis and other chronic liver diseases due to hepatitis B  | 0,12 | 0 | -0,18 | 0,21 | 0 | -0,29 | 0,34 | 0   | -0,49 |
| B.4.1.2 | Cirrhosis and other chronic liver diseases due to hepatitis C  | 0,01 | 0 | 0,04  | 0,04 | 0 | -0,09 | 0,13 | 0   | -0,22 |
| B.4.1.3 | Cirrhosis and other chronic liver diseases due to alcohol use  | 0,08 | 0 | 0,16  | 0,01 | 0 | 0,05  | 0,08 | 0   | -0,17 |
| B.4.1.4 | Cirrhosis and other chronic liver diseases due to NAFLD        | 0,03 | 0 | 0,07  | 0,01 | 0 | -0,03 | 0,21 | 0   | -0,24 |
| B.4.1.5 | Cirrhosis and other chronic liver diseases due to other causes | 0,11 | 0 | -0,1  | 0,2  | 0 | -0,15 | 0,38 | 0   | -0,37 |
| B.4.2.1 | Peptic ulcer disease   | 0,2  | 0 | -0,18 | 0,22 | 0 | -0,2  | 0,26 | 0   | -0,33 |
| B.4.2.2 | Gastritis and duodenitis                                       | 0,08 | 0 | -0,07 | 0,19 | 0 | -0,12 | 0,25 | 0   | -0,51 |
| B.4.2.3 | Gastroesophageal reflux disease                                | 0,03 | 0 | -0,04 | 0,03 | 0 | -0,04 |      | NON |       |
| B.4.3   | Appendicitis   | 0,1  | 0 | 0,13  | 0,1  | 0 | 0,13  | 0,39 | 0   | -0,53 |
| B.4.4   | Paralytic ileus and intestinal obstruction                     | 0,08 | 0 | 0,08  | 0,06 | 0 | 0,06  | 0,43 | 0   | -0,37 |
| B.4.5   | Inguinal, femoral, and abdominal hernia                        | 0,02 | 0 | 0,04  | 0,05 | 0 | -0,07 | 0,28 | 0   | -0,33 |
| B.4.6   | Inflammatory bowel disease                                     | 0,41 | 0 | 0,52  | 0,44 | 0 | 0,59  | 0,03 | 0   | -0,07 |
| B.4.7   | Vascular intestinal disorders                                  | 0,44 | 0 | 0,3   | 0,47 | 0 | 0,35  | 0,03 | 0   | 0,07  |
| B.4.8   | Gallbladder and biliary diseases                               | 0,38 | 0 | 0,49  | 0,22 | 0 | 0,29  | 0,22 | 0   | -0,23 |
| B.4.9   | Pancreatitis   | 0,03 | 0 | 0,04  | 0,16 | 0 | 0,14  | 0,12 | 0   | -0,17 |
| B.5.1   | Alzheimer's disease and other dementias                        | 0,12 | 0 | 0,03  | 0,18 | 0 | 0,05  | 0,07 | 0   | -0,02 |
| B.5.2   | Parkinson's disease  | 0,22 | 0 | 0,07  | 0,35 | 0 | 0,11  | 0,01 | 0   | -0,02 |
| B.5.3   | Idiopathic epilepsy  | 0,03 | 0 | 0,03  | 0,12 | 0 | -0,09 | 0,22 | 0   | -0,21 |
| B.5.4   | Multiple sclerosis   | 0,27 | 0 | 0,37  | 0,29 | 0 | 0,44  | 0,16 | 0   | 0,21  |

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|         |  |      |   |       |      |      |       |      |      |       |
|---------|--|------|---|-------|------|------|-------|------|------|-------|
| B.5.5   | Motor neuron disease                                   | 0,22 | 0 | 0,18  | 0,5  | 0    | 0,32  | 0,37 | 0    | 0,56  |
| B.5.6.1 | Migraine   | 0,07 | 0 | 0,03  | 0,1  | 0    | 0,04  |      |      |       |
| B.5.6.2 | Tension-type headache                                  | 0,26 | 0 | 0,05  | 0,21 | 0    | 0,05  |      |      |       |
| B.6.1   | Schizophrenia  | 0,22 | 0 | 0,03  | 0,35 | 0    | 0,06  |      |      |       |
| B.6.2.1 | Major depressive disorder                              | 0,02 | 0 | -0,04 | 0,02 | 0    | -0,03 |      |      |       |
| B.6.2.2 | Dysthymia  | 0,21 | 0 | -0,05 | 0,17 | 0    | -0,06 |      |      |       |
| B.6.3   | Bipolar disorder                                       | 0,06 | 0 | 0,05  | 0,17 | 0    | 0,11  |      |      |       |
| B.6.4   | Anxiety disorders                                      | 0,11 | 0 | 0,05  | 0,12 | 0    | 0,07  |      |      |       |
| B.6.5.1 | Anorexia nervosa                                       | 0,54 | 0 | 0,19  | 0,55 | 0    | 0,31  | 0,24 | 0    | 0,55  |
| B.6.5.2 | Bulimia nervosa  | 0,54 | 0 | 0,18  | 0,53 | 0    | 0,34  | 0    | 0,71 | -0,01 |
| B.6.6   | Autism spectrum disorders                              | 0,16 | 0 | 0,06  | 0,24 | 0    | 0,08  |      |      |       |
| B.6.7   | Attention-deficit/hyperactivity disorder               | 0,27 | 0 | 0,18  | 0,25 | 0    | 0,18  |      |      |       |
| B.6.8   | Conduct disorder                                       | 0,07 | 0 | 0,01  | 0,14 | 0    | 0,02  |      |      |       |
| B.7.1   | Alcohol use disorders                                  | 0,11 | 0 | 0,16  | 0,12 | 0    | 0,17  | 0    | 0    | 0,05  |
| B.7.2.1 | Opioid use disorders                                   | 0,05 | 0 | 0,09  | 0,11 | 0    | 0,14  | 0,14 | 0    | 0,32  |
| B.7.2.2 | Cocaine use disorders                                  | 0,41 | 0 | 0,55  | 0,4  | 0    | 0,62  | 0,2  | 0    | 0,48  |
| B.7.2.3 | Amphetamine use disorders                              | 0,19 | 0 | 0,23  | 0,15 | 0    | 0,21  | 0,3  | 0    | 0,62  |
| B.7.2.4 | Cannabis use disorders                                 | 0,23 | 0 | 0,19  | 0,23 | 0    | 0,2   |      |      |       |
| B.7.2.5 | Other drug use disorders                               | 0,47 | 0 | 0,19  | 0,36 | 0    | 0,32  | 0,21 | 0    | 0,36  |
| B.8.1.1 | Diabetes mellitus type 1                               | 0,19 | 0 | 0,18  | 0,19 | 0    | 0,17  | 0,19 | 0    | -0,23 |
| B.8.1.2 | Diabetes mellitus type 2                               | 0,01 | 0 | 0,03  | 0    | 0,08 | 0,01  | 0,14 | 0    | -0,26 |
| B.8.2.1 | Chronic kidney disease due to diabetes mellitus type 1 | 0,03 | 0 | 0,04  | 0,16 | 0    | 0,1   | 0,28 | 0    | -0,46 |
| B.8.2.2 | Chronic kidney disease due to diabetes mellitus type 2 | 0,18 | 0 | 0,14  | 0,01 | 0    | 0,03  | 0,19 | 0    | -0,33 |
| B.8.2.3 | Chronic kidney disease due to hypertension             | 0,22 | 0 | 0,15  | 0    | 0    | 0,02  | 0,24 | 0    | -0,35 |
| B.8.2.4 | Chronic kidney disease due to glomerulonephritis       | 0,01 | 0 | -0,03 | 0,01 | 0    | -0,03 | 0,31 | 0    | -0,38 |

|         |  |      |      |       |      |      |       |      |   |       |
|---------|--|------|------|-------|------|------|-------|------|---|-------|
| B.8.2.5 | Chronic kidney disease due to other and unspecified causes | 0,18 | 0    | 0,12  | 0,03 | 0    | -0,05 | 0,17 | 0 | -0,2  |
| B.8.3   | Acute glomerulonephritis                                   | 0,03 | 0    | -0,09 | 0,02 | 0    | -0,09 | 0,2  | 0 | -0,65 |
| B.9.1.1 | Atopic dermatitis  | 0,18 | 0    | 0,15  | 0,27 | 0    | 0,2   |      |   |       |
| B.9.1.2 | Contact dermatitis   | 0,19 | 0    | -0,17 | 0,17 | 0    | -0,17 |      |   |       |
| B.9.1.3 | Seborrhoeic dermatitis                                     | 0,08 | 0    | -0,05 | 0,08 | 0    | -0,07 |      |   |       |
| B.9.10  | Urticaria  | 0,04 | 0    | -0,03 | 0,04 | 0    | -0,03 |      |   |       |
| B.9.11  | Decubitus ulcer  | 0,24 | 0    | 0,31  | 0,23 | 0    | 0,3   | 0,01 | 0 | 0,14  |
| B.9.12  | Other skin and subcutaneous diseases                       | 0,44 | 0    | 0,07  | 0,46 | 0    | 0,07  | 0,01 | 0 | -0,08 |
| B.9.2   | Psoriasis  | 0,3  | 0    | 0,28  | 0,29 | 0    | 0,33  |      |   |       |
| B.9.3.1 | Cellulitis   | 0,16 | 0    | 0,15  | 0,23 | 0    | 0,14  | 0,03 | 0 | -0,16 |
| B.9.3.2 | Pyoderma   | 0,02 | 0    | 0,05  | 0    | 0    | 0,02  | 0,21 | 0 | -0,4  |
| B.9.4   | Scabies  | 0,22 | 0    | -0,61 | 0,22 | 0    | -0,6  |      |   |       |
| B.9.5   | Fungal skin diseases                                       | 0,12 | 0    | -0,09 | 0,15 | 0    | -0,13 |      |   |       |
| B.9.6   | Viral skin diseases  | 0    | 0,37 | 0     | 0,07 | 0    | 0,07  |      |   |       |
| B.9.7   | Acne vulgaris  | 0,08 | 0    | 0,07  | 0,1  | 0    | 0,08  |      |   |       |
| B.9.8   | Alopecia areata  | 0,18 | 0    | 0,04  | 0,19 | 0    | 0,04  |      |   |       |
| B.9.9   | Pruritus   | 0,13 | 0    | -0,03 | 0,12 | 0    | -0,03 |      |   |       |
| C.1.1.1 | Pedestrian road injuries                                   | 0,22 | 0    | -0,24 | 0,3  | 0    | -0,3  | 0,22 | 0 | -0,3  |
| C.1.1.2 | Cyclist road injuries                                      | 0,02 | 0    | -0,05 | 0,06 | 0    | -0,1  | 0,04 | 0 | -0,11 |
| C.1.1.3 | Motorcyclist road injuries                                 | 0,06 | 0    | -0,11 | 0,11 | 0    | -0,14 | 0,04 | 0 | -0,11 |
| C.1.1.4 | Motor vehicle road injuries                                | 0,01 | 0    | 0,03  | 0    | 0,81 | 0     | 0,03 | 0 | -0,08 |
| C.1.1.5 | Other road injuries  | 0,01 | 0    | 0,03  | 0    | 0    | 0,03  | 0,07 | 0 | -0,21 |
| C.1.2   | Other transport injuries                                   | 0    | 0,01 | 0,01  | 0,05 | 0    | -0,06 | 0,08 | 0 | -0,16 |
| C.2.1   | Falls  | 0,39 | 0    | 0,34  | 0,34 | 0    | 0,27  | 0,05 | 0 | -0,08 |
| C.2.10  | Exposure to forces of nature                               | 0,14 | 0    | -0,53 | 0,17 | 0    | -0,65 | 0,11 | 0 | -0,44 |

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|         |   |      |   |       |      |      |       |      |   |       |
|---------|---|------|---|-------|------|------|-------|------|---|-------|
| C.2.11  | Other unintentional injuries                    | 0,36 | 0 | 0,26  | 0,28 | 0    | 0,28  | 0,28 | 0 | -0,41 |
| C.2.2   | Drowning  | 0,02 | 0 | 0,06  | 0    | 0    | 0,02  | 0,17 | 0 | -0,26 |
| C.2.3   | Fire, heat, and hot substances                  | 0,15 | 0 | 0,19  | 0,02 | 0    | 0,07  | 0,2  | 0 | -0,31 |
| C.2.4.1 | Poisoning by carbon monoxide                    | 0,32 | 0 | 0,33  | 0,23 | 0    | 0,19  | 0,07 | 0 | -0,23 |
| C.2.4.2 | Poisoning by other means                        | 0,27 | 0 | 0,29  | 0,27 | 0    | 0,34  | 0,42 | 0 | -0,65 |
| C.2.5.1 | Unintentional firearm injuries                  | 0,02 | 0 | -0,07 | 0    | 0    | -0,02 | 0,28 | 0 | -0,53 |
| C.2.5.2 | Other exposure to mechanical forces             | 0,3  | 0 | 0,3   | 0,28 | 0    | 0,28  | 0,16 | 0 | -0,23 |
| C.2.6   | Adverse effects of medical treatment            | 0,19 | 0 | 0,18  | 0,19 | 0    | 0,18  | 0,36 | 0 | -0,39 |
| C.2.7.1 | Venomous animal contact                         | 0,06 | 0 | -0,11 | 0,09 | 0    | -0,14 | 0,5  | 0 | -0,98 |
| C.2.7.2 | Non-venomous animal contact                     | 0,24 | 0 | -0,18 | 0,34 | 0    | -0,26 | 0,36 | 0 | -0,69 |
| C.2.8.1 | Pulmonary aspiration and foreign body in airway | 0,17 | 0 | 0,17  | 0,13 | 0    | 0,2   | 0,03 | 0 | -0,1  |
| C.2.8.2 | Foreign body in eyes                            | 0,01 | 0 | -0,02 | 0,07 | 0    | -0,05 |      |   |       |
| C.2.8.3 | Foreign body in other body part                 | 0,01 | 0 | -0,04 | 0,11 | 0    | -0,15 | 0,34 | 0 | -0,57 |
| C.2.9   | Environmental heat and cold exposure            | 0,02 | 0 | 0,06  | 0    | 0,42 | 0,01  | 0,06 | 0 | -0,26 |
| C.3.1.1 | Self-harm by firearm                            | 0,1  | 0 | 0,16  | 0,07 | 0    | 0,14  | 0    | 0 | 0,05  |
| C.3.1.2 | Self-harm by other specified means              | 0,16 | 0 | 0,21  | 0,11 | 0    | 0,19  | 0    | 0 | 0,02  |
| C.3.2.1 | Physical violence by firearm                    | 0,17 | 0 | 0,3   | 0,18 | 0    | 0,31  | 0,08 | 0 | -0,33 |
| C.3.2.2 | Physical violence by sharp object               | 0,01 | 0 | 0,04  | 0    | 0,03 | 0,01  | 0,09 | 0 | -0,27 |
| C.3.2.4 | Physical violence by other means                | 0,13 | 0 | 0,16  | 0,06 | 0    | 0,1   | 0,11 | 0 | -0,25 |
| C.3.3   | Conflict and terrorism                          | 0,1  | 0 | -0,56 | 0,18 | 0    | -0,89 | 0,11 | 0 | -0,6  |
| C.3.4   | Executions and police conflict                  | 0,02 | 0 | -0,14 | 0,08 | 0    | -0,44 | 0    | 0 | -0,06 |

## 5.3. REFERENCES

- Akizu-Gardoki, Ortz, Conrad Kunze, Anthony Coxeter, Gorka Bueno, Thomas Wiedmann, and Jose Manuel Lopez-Guede (Dec. 2020). “Discovery of a possible Well-being Turning Point within energy footprint accounts which may support the degrowth theory”. en. In: *Energy for Sustainable Development* 59, pp. 22–32. ISSN: 0973-0826. DOI: 10.1016/j.esd.2020.09.001. URL: <https://www.sciencedirect.com/science/article/pii/S0973082620302933> (visited on 01/12/2023).
- Allison, Stephen and Tarun Bastiampillai (Feb. 2017). “Bullying and depression at work: prevention starts at the very top”. English. In: *The Lancet Psychiatry* 4.2. Publisher: Elsevier, p. 96. ISSN: 2215-0366, 2215-0374. DOI: 10.1016/S2215-0366(16)30448-5. URL: [https://www.thelancet.com/journals/lanpsy/article/PIIS2215-0366\(16\)30448-5/fulltext](https://www.thelancet.com/journals/lanpsy/article/PIIS2215-0366(16)30448-5/fulltext) (visited on 07/05/2022).
- Andrieu, Baptiste, Laurie Marraud, Olivier Vidal, Mathis Egnell, Laurent Boyer, and Guillaume Fond (2022). “The Exponential Relationship between Healthcare Systems’ Resource Footprints and Their Access and Quality: A Study of 49 Regions between 1995 and 2015”. In: *SSRN Electronic Journal*. DOI: 10.2139/ssrn.4182423.
- Andrieu, Baptiste, Olivier Vidal, Hugo Le Boulzec, Louis Delannoy, and François Verzier (Oct. 2022). “Energy Intensity of Final Consumption: the Richer, the Poorer the Efficiency”. In: *Environmental Science & Technology* 56.19. Publisher: American Chemical Society, pp. 13909–13919. ISSN: 0013-936X. DOI: 10.1021/acs.est.2c03462. URL: <https://doi.org/10.1021/acs.est.2c03462> (visited on 11/08/2022).
- Arto, Iñaki, Iñigo Capellán-Pérez, Rosa Lago, Gorka Bueno, and Roberto Bermejo (Aug. 2016). “The energy requirements of a developed world”. en. In: *Energy for Sustainable Development* 33, pp. 1–13. ISSN: 0973-0826. DOI: 10.1016/j.esd.2016.04.001. URL: <https://www.sciencedirect.com/science/article/pii/S0973082616301892> (visited on 11/01/2022).
- Ashok, Abhishekh H., Yuya Mizuno, Nora D. Volkow, and Oliver D. Howes (May 2017). “Association of Stimulant Use With Dopaminergic Alterations in Users of Cocaine, Amphetamine, or Methamphetamine: A Systematic Review and Meta-analysis”. eng. In: *JAMA psychiatry* 74.5, pp. 511–519. ISSN: 2168-6238. DOI: 10.1001/jamapsychiatry.2017.0135.
- Barber, Ryan M et al. (July 2017). “Healthcare Access and Quality Index based on mortality from causes amenable to personal health care in 195 countries and territories, 1990–2015: a novel analysis from the Global Burden of Disease Study 2015”. en. In: *The Lancet* 390.10091, pp. 231–266. ISSN: 01406736. DOI: 10.1016/S0140-6736(17)30818-8. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0140673617308188> (visited on 04/15/2022).
- Battson, Micah L., Dustin M. Lee, Dillon K. Jarrell, Shuofei Hou, Kayl E. Ecton, Tiffany L. Weir, and Christopher L. Gentile (May 2018). “Suppression of gut dysbiosis reverses Western diet-induced vascular dysfunction”. In: *American Journal of Physiology-Endocrinology and Metabolism* 314.5. Publisher: American Physiological Society, E468–E477. ISSN: 0193-1849. DOI: 10.1152/ajpendo.00187.2017. URL: <https://journals.physiology.org/doi/full/10.1152/ajpendo.00187.2017> (visited on 07/15/2023).
- “Borders and pipelines” (Mar. 2022). en. In: *Nature Energy* 7.3. Number: 3 Publisher: Nature Publishing Group, pp. 213–213. ISSN: 2058-7546. DOI: 10.1038/s41560-022-01009-6. URL: <https://www.nature.com/articles/s41560-022-01009-6> (visited on 01/12/2023).
- Borroni, Elisa, Angela Cecilia Pesatori, Valentina Bollati, Massimiliano Buoli, and Michele Carugno (Jan. 2022). “Air pollution exposure and depression: A comprehensive updated systematic review and meta-analysis”. eng. In: *Environmental Pollution (Barking, Essex: 1987)* 292.Pt A, p. 118245. ISSN: 1873-6424. DOI: 10.1016/j.envpol.2021.118245.
- Brown, Lawrence H., Taha Chaiechi, Petra G. Buettner, Deon V. Canyon, J. Mac Crawford, and Jenni Judd (Feb. 2013). “Higher energy prices are associated with diminished resources, performance and safety in Australian

- ambulance systems”. eng. In: *Australian and New Zealand Journal of Public Health* 37.1, pp. 83–89. ISSN: 1753-6405. DOI: 10.1111/1753-6405.12015.
- Bygrave, Annie, Kate Whittaker, and Sanchia Aranda AM (Nov. 2020). “Assessing the implementation of interventions addressing socioeconomic inequalities in cancer screening in high-income countries”. In: *Journal of Public Health Research* 9.4, p. 1713. ISSN: 2279-9028. DOI: 10.4081/jphr.2020.1713. URL: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7662454/> (visited on 07/23/2023).
- Christ, Anette, Mario Lauterbach, and Eicke Latz (Nov. 2019). “Western Diet and the Immune System: An Inflammatory Connection”. eng. In: *Immunity* 51.5, pp. 794–811. ISSN: 1097-4180. DOI: 10.1016/j.immuni.2019.09.020.
- Deivanayagam, Thilagawathi Abi, Sonora English, Jason Hickel, Jon Bonifacio, Renzo R Guinto, Kyle X Hill, Mita Huq, Rita Issa, Hans Mulindwa, Heizal Patricia Nagginda, Priscila de Morais Sato, Sujitha Selvarajah, Chetna Sharma, and Delan Devakumar (July 2023). “Envisioning environmental equity: climate change, health, and racial justice”. en. In: *The Lancet* 402.10395, pp. 64–78. ISSN: 0140-6736. DOI: 10.1016/S0140-6736(23)00919-4. URL: <https://www.sciencedirect.com/science/article/pii/S0140673623009194> (visited on 07/02/2023).
- Delannoy, Louis, Pierre-Yves Longaretti, David Murphy, and Emmanuel Prados (Sept. 2021). “Peak oil and the low-carbon energy transition: A net-energy perspective”. In: *Applied Energy* 304. DOI: 10.1016/j.apenergy.2021.117843.
- Drew, Jonathan, Sean D. Christie, Peter Tyedmers, Jenna Smith-Forrester, and Daniel Rainham (July 2021). “Operating in a Climate Crisis: A State-of-the-Science Review of Life Cycle Assessment within Surgical and Anesthetic Care”. In: *Environmental Health Perspectives* 129.7, p. 076001. ISSN: 0091-6765. DOI: 10.1289/EHP8666. URL: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8274692/> (visited on 07/07/2022).
- Eckelman, Matthew J. and Jodi Sherman (June 2016). “Environmental Impacts of the U.S. Health Care System and Effects on Public Health”. en. In: *PLOS ONE* 11.6. Ed. by Shama Ahmad, e0157014. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0157014. URL: <https://dx.plos.org/10.1371/journal.pone.0157014> (visited on 10/01/2021).
- Eckelman, Matthew J., Jodi D. Sherman, and Andrea J. MacNeill (July 2018). “Life cycle environmental emissions and health damages from the Canadian healthcare system: An economic-environmental-epidemiological analysis”. en. In: *PLOS Medicine* 15.7. Ed. by Jonathan Alan Patz, e1002623. ISSN: 1549-1676. DOI: 10.1371/journal.pmed.1002623. URL: <https://dx.plos.org/10.1371/journal.pmed.1002623> (visited on 10/01/2021).
- Eurostat - Data Explorer* (2022). URL: <https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do> (visited on 04/21/2022).
- Farjana, Shahjadi Hisan, Nazmul Huda, M. A. Parvez Mahmud, and R. Saidur (Sept. 2019). “A review on the impact of mining and mineral processing industries through life cycle assessment”. en. In: *Journal of Cleaner Production* 231, pp. 1200–1217. ISSN: 0959-6526. DOI: 10.1016/j.jclepro.2019.05.264. URL: <https://www.sciencedirect.com/science/article/pii/S0959652619318001> (visited on 04/20/2023).
- Fell, Michael James (May 2017). “Energy services: A conceptual review”. en. In: *Energy Research & Social Science* 27, pp. 129–140. ISSN: 2214-6296. DOI: 10.1016/j.erss.2017.02.010. URL: <https://www.sciencedirect.com/science/article/pii/S2214629617300518> (visited on 04/21/2022).
- Figueiredo, Natasha, Junko Kose, Bernard Srour, Chantal Julia, Emmanuelle Kesse-Guyot, Sandrine Péneau, Benjamin Allès, Indira Paz Graniel, Eloi Chazelas, Mélanie Deschasaux-Tanguy, Charlotte Debras, Serge Hercberg, Pilar Galan, Carlos A. Monteiro, Mathilde Touvier, and Valentina A. Andreeva (Apr. 2022). “Ultra-processed food intake and eating disorders: Cross-sectional associations among French adults”. en. In: *Journal of Behavioral Addictions* 11.2. Publisher: Akadémiai Kiadó Section: Journal of Behavioral Addictions, pp. 588–599.

- ISSN: 2063-5303, 2062-5871. DOI: 10 . 1556/2006 . 2022 . 00009. URL: <https://akjournals.com/view/journals/2006/11/2/article-p588.xml> (visited on 07/15/2023).
- Frumkin, Howard, Jeremy Hess, and Stephen Vindigni (Oct. 2007). “Peak Petroleum and Public Health”. In: *JAMA* 298.14, pp. 1688–1690. ISSN: 0098-7484. DOI: 10 . 1001 / jama . 298 . 14 . 1688. URL: <https://doi.org/10.1001/jama.298.14.1688> (visited on 07/07/2022).
- Gambhir, Ajay, Laurent Drouet, David McCollum, Tamaryn Napp, Dan Bernie, Adam Hawkes, Oliver Fricko, Petr Havlik, Keywan Riahi, Valentina Bosetti, and Jason Lowe (Jan. 2017). “Assessing the Feasibility of Global Long-Term Mitigation Scenarios”. en. In: *Energies* 10.1, p. 89. ISSN: 1996-1073. DOI: 10 . 3390/en10010089. URL: <http://www.mdpi.com/1996-1073/10/1/89> (visited on 02/23/2022).
- Graedel, T. E., E. M. Harper, N. T. Nassar, Philip Nuss, and Barbara K. Reck (Apr. 2015). “Criticality of metals and metalloids”. In: *Proceedings of the National Academy of Sciences* 112.14. Publisher: Proceedings of the National Academy of Sciences, pp. 4257–4262. DOI: 10 . 1073/pnas . 1500415112. URL: <https://www.pnas.org/doi/abs/10.1073/pnas.1500415112> (visited on 05/01/2023).
- Grubler, Arnulf, Charlie Wilson, Nuno Bento, Benigna Boza-Kiss, Volker Krey, David L. McCollum, Narasimha D. Rao, Keywan Riahi, Joeri Rogelj, Simon De Stercke, Jonathan Cullen, Stefan Frank, Oliver Fricko, Fei Guo, Matt Gidden, Petr Havlík, Daniel Huppmann, Gregor Kiesewetter, Peter Rafaj, Wolfgang Schoepp, and Hugo Valin (June 2018). “A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies”. en. In: *Nature Energy* 3.6. Number: 6 Publisher: Nature Publishing Group, pp. 515–527. ISSN: 2058-7546. DOI: 10 . 1038 / s41560 - 018 - 0172 - 6. URL: <https://www.nature.com/articles/s41560-018-0172-6> (visited on 03/12/2022).
- Haberl, Helmut, Dominik Wiedenhofer, Doris Virág, Gerald Kalt, Barbara Plank, Paul Brockway, Tomer Fishman, Daniel Hausknost, Fridolin Krausmann, Bartholomäus Leon-Gruchalski, Andreas Mayer, Melanie Pichler, Anke Schaffartzik, Tânia Sousa, Jan Streeck, and Felix Creutzig (June 2020). “A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: synthesizing the insights”. en. In: *Environmental Research Letters* 15.6, p. 065003. ISSN: 1748-9326. DOI: 10 . 1088/1748 - 9326/ab842a. URL: <https://iopscience.iop.org/article/10.1088/1748-9326/ab842a> (visited on 09/13/2021).
- Hanif, Imran (Aug. 2018). “Energy consumption habits and human health nexus in Sub-Saharan Africa”. en. In: *Environmental Science and Pollution Research* 25.22, pp. 21701–21712. ISSN: 1614-7499. DOI: 10 . 1007 / s11356 - 018 - 2336 - 0. URL: <https://doi.org/10.1007/s11356-018-2336-0> (visited on 02/20/2023).
- Harm, Health Care Without (2019). *Health Cares Climate Footprint*. Tech. rep. URL: [https://noharm-global.org/sites/default/files/documents-files/5961/HealthCaresClimateFootprint\\_092319.pdf](https://noharm-global.org/sites/default/files/documents-files/5961/HealthCaresClimateFootprint_092319.pdf) (visited on 10/01/2021).
- Hess, Jeremy, Daniel Bednarz, Jaeyong Bae, and Jessica Pierce (Sept. 2011). “Petroleum and Health Care: Evaluating and Managing Health Care’s Vulnerability to Petroleum Supply Shifts”. In: *American Journal of Public Health* 101.9, pp. 1568–1579. ISSN: 0090-0036. DOI: 10 . 2105 / AJPH . 2011 . 300233. URL: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3154246/> (visited on 07/07/2022).
- Hickel, Jason, Paul Brockway, Giorgos Kallis, Lorenz Keyßer, Manfred Lenzen, Aljoša Slameršak, Julia Steinberger, and Diana Ürge-Vorsatz (Aug. 2021). “Urgent need for post-growth climate mitigation scenarios”. en. In: *Nature Energy* 6.8. Number: 8 Publisher: Nature Publishing Group, pp. 766–768. ISSN: 2058-7546. DOI: 10 . 1038/s41560-021-00884-9. URL: <https://www.nature.com/articles/s41560-021-00884-9> (visited on 03/12/2022).
- Hickel, Jason, Christian Dorninger, Hanspeter Wieland, and Intan Suwandi (Mar. 2022). “Imperialist appropriation in the world economy: Drain from the global South through unequal exchange, 1990–2015”. en. In: *Global Environmental Change* 73, p. 102467. ISSN: 0959-3780. DOI: 10 . 1016 / j . gloenvcha . 2022 . 102467. URL: <https://www.sciencedirect.com/science/article/pii/S095937802200005X> (visited on 04/21/2022).

- Hickel, Jason, Daniel W O'Neill, Andrew L Fanning, and Huzaifa Zoomkawala (Apr. 2022). "National responsibility for ecological breakdown: a fair-shares assessment of resource use, 1970–2017". en. In: *The Lancet Planetary Health* 6.4, e342–e349. ISSN: 25425196. DOI: 10.1016/S2542-5196(22)00044-4. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2542519622000444> (visited on 04/09/2022).
- Hickel, Jason and Aljosa Slamersak (July 2022). "Existing climate mitigation scenarios perpetuate colonial inequalities". en. In: *The Lancet Planetary Health* 6.7, e628–e631. ISSN: 25425196. DOI: 10.1016/S2542-5196(22)00092-4. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2542519622000924> (visited on 11/30/2022).
- Kane, G. M., C. A. Bakker, and A. R. Balkenende (Aug. 2018). "Towards design strategies for circular medical products". en. In: *Resources, Conservation and Recycling*. Sustainable Resource Management and the Circular Economy 135, pp. 38–47. ISSN: 0921-3449. DOI: 10.1016/j.resconrec.2017.07.030. URL: <https://www.sciencedirect.com/science/article/pii/S0921344917302094> (visited on 04/20/2022).
- Katz, Corey (Feb. 2022). "The Ethical Duty to Reduce the Ecological Footprint of Industrialized Healthcare Services and Facilities". In: *The Journal of Medicine and Philosophy: A Forum for Bioethics and Philosophy of Medicine* 47.1, pp. 32–53. ISSN: 0360-5310. DOI: 10.1093/jmp/jhab037. URL: <https://doi.org/10.1093/jmp/jhab037> (visited on 04/20/2023).
- Lassale, Camille, G. David Batty, Amaria Baghdadli, Felice Jacka, Almudena Sánchez-Villegas, Mika Kivimäki, and Tasnime Akbaraly (July 2019). "Healthy dietary indices and risk of depressive outcomes: a systematic review and meta-analysis of observational studies". en. In: *Molecular Psychiatry* 24.7. Number: 7 Publisher: Nature Publishing Group, pp. 965–986. ISSN: 1476-5578. DOI: 10.1038/s41380-018-0237-8. URL: <https://www.nature.com/articles/s41380-018-0237-8> (visited on 07/05/2022).
- Lenzen, Manfred, Keiichiro Kanemoto, Daniel Moran, and Arne Geschke (Aug. 2012). "Mapping the Structure of the World Economy". en. In: *Environmental Science & Technology* 46.15, pp. 8374–8381. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/es300171x. URL: <https://pubs.acs.org/doi/10.1021/es300171x> (visited on 11/08/2022).
- Lenzen, Manfred, Arunima Malik, Mengyu Li, Jacob Fry, Helga Weisz, Peter-Paul Pichler, Leonardo Suveges Moreira Chaves, Anthony Capon, and David Pencheon (July 2020). "The environmental footprint of health care: a global assessment". en. In: *The Lancet Planetary Health* 4.7, e271–e279. ISSN: 25425196. DOI: 10.1016/S2542-5196(20)30121-2. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2542519620301212> (visited on 10/05/2021).
- Lenzen, Manfred, Daniel Moran, Keiichiro Kanemoto, and Arne Geschke (Mar. 2013). "BUILDING EORA: A GLOBAL MULTI-REGION INPUT-OUTPUT DATABASE AT HIGH COUNTRY AND SECTOR RESOLUTION". en. In: *Economic Systems Research* 25.1, pp. 20–49. ISSN: 0953-5314, 1469-5758. DOI: 10.1080/09535314.2013.769938. URL: <http://www.tandfonline.com/doi/abs/10.1080/09535314.2013.769938> (visited on 01/03/2021).
- MacNeill, Andrea J., Forbes McGain, and Jodi D. Sherman (Feb. 2021). "Planetary health care: a framework for sustainable health systems". English. In: *The Lancet Planetary Health* 5.2. Publisher: Elsevier, e66–e68. ISSN: 2542-5196. DOI: 10.1016/S2542-5196(21)00005-X. URL: [https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196\(21\)00005-X/fulltext](https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(21)00005-X/fulltext) (visited on 07/02/2023).
- Malik, Arunima, Manfred Lenzen, Scott McAlister, and Forbes McGain (Jan. 2018). "The carbon footprint of Australian health care". en. In: *The Lancet Planetary Health* 2.1, e27–e35. ISSN: 25425196. DOI: 10.1016/S2542-5196(17)30180-8. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2542519617301808> (visited on 10/19/2021).
- Marx, Wolfgang, Melissa Lane, Meghan Hockey, Hajara Aslam, Michael Berk, Ken Walder, Alessandra Borsini, Joseph Firth, Carmine M. Pariante, Kirsten Berding, John F. Cryan, Gerard Clarke, Jeffrey M. Craig, Kuan-Pin Su, David Mischoulon, Fernando Gomez-Pinilla, Jane A. Foster, Patrice D. Cani, Sandrine Thuret, Heidi M. Staudacher, Almudena Sánchez-Villegas, Husnain Arshad, Tasnime Akbaraly, Adrienne O'Neil, Toby Segasby, and Felice N. Jacka (Jan. 2021). "Diet and depression: exploring the biological mechanisms of action".

- en. In: *Molecular Psychiatry* 26.1. Number: 1 Publisher: Nature Publishing Group, pp. 134–150. ISSN: 1476-5578. DOI: 10.1038/s41380-020-00925-x. URL: <https://www.nature.com/articles/s41380-020-00925-x> (visited on 07/05/2022).
- Mathieu, Patrick and Benoit J. Arsenault (July 2017). “CAVD: civilization aortic valve disease”. eng. In: *European Heart Journal* 38.28, pp. 2198–2200. ISSN: 1522-9645. DOI: 10.1093/eurheartj/ehx219.
- Miller, Ronald E and Peter D Blair (2009a). “Input–Output Analysis: Foundations and Extensions, Second Edition”. en. In: p. 784.
- (July 2009b). *Input-Output Analysis: Foundations and Extensions*. en. Google-Books-ID: viHaAgAAQBAJ. Cambridge University Press. ISBN: 978-1-139-47759-8.
- Nansai, Keisuke, Jacob Fry, Arunima Malik, Wataru Takayanagi, and Naoki Kondo (Jan. 2020). “Carbon footprint of Japanese health care services from 2011 to 2015”. en. In: *Resources, Conservation and Recycling* 152, p. 104525. ISSN: 09213449. DOI: 10.1016/j.resconrec.2019.104525. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344919304318> (visited on 10/01/2021).
- OECD(2022). *Health resources - Health spending - OECD Data*. URL: <https://data.oecd.org/healthres/health-spending.htm> (visited on 04/21/2022).
- Organisation, World Health (2022). *Country Commitments*. en. URL: <https://www.who.int/initiatives/cop26-health-programme/country-commitments> (visited on 04/20/2022).
- Organization, World Health (2022). *Global Health Expenditure Database*. URL: <https://apps.who.int/nha/database> (visited on 04/21/2022).
- Orhan, Rana, John Middleton, Thomas Krafft, and Katarzyna Czabanowska (Jan. 2021). “Climate Action at Public Health Schools in the European Region”. en. In: *International Journal of Environmental Research and Public Health* 18.4. Number: 4 Publisher: Multidisciplinary Digital Publishing Institute, p. 1518. ISSN: 1660-4601. DOI: 10.3390/ijerph18041518. URL: <https://www.mdpi.com/1660-4601/18/4/1518> (visited on 07/05/2022).
- Ostertag, Katrin, Tanja Bratan, Carsten Gandenberger, Bärbel Hüsing, and Matthias Pfaff (2021). *Sustainable resource use in the health care sector – exploiting synergies between the policy fields of resource conservation and health care*. Tech. rep. German Environment Agency. URL: [https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2021-08-04\\_texte\\_15-2021\\_health-sector-resources\\_summary.pdf](https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2021-08-04_texte_15-2021_health-sector-resources_summary.pdf) (visited on 05/01/2023).
- Panel, Manager International Resource (Dec. 2018). “Global Resources Outlook”. en. In: URL: <https://www.resourcepanel.org/reports/global-resources-outlook> (visited on 04/21/2022).
- Pichler, Peter-Paul, Ingram S Jaccard, Ulli Weisz, and Helga Weisz (May 2019). “International comparison of health care carbon footprints”. en. In: *Environmental Research Letters* 14.6, p. 064004. ISSN: 1748-9326. DOI: 10.1088/1748-9326/ab19e1. URL: <https://iopscience.iop.org/article/10.1088/1748-9326/ab19e1> (visited on 10/01/2021).
- Population, total | Data* (2022). URL: <https://data.worldbank.org/indicator/SP.POP.TOTL> (visited on 11/08/2022).
- Rahman, Mohammad Mafizur and Khosrul Alam (Sept. 2021). “The nexus between health status and health expenditure, energy consumption and environmental pollution: empirical evidence from SAARC-BIMSTEC regions”. eng. In: *BMC public health* 21.1, p. 1694. ISSN: 1471-2458. DOI: 10.1186/s12889-021-11534-w.
- Rockström, Johan, Joyeeta Gupta, Dahe Qin, Steven J. Lade, Jesse F. Abrams, Lauren S. Andersen, David I. Armstrong McKay, Xuemei Bai, Govindasamy Bala, Stuart E. Bunn, Daniel Ciobanu, Fabrice DeClerck, Kristie Ebi, Lauren Gifford, Christopher Gordon, Syezlin Hasan, Norichika Kanie, Timothy M. Lenton, Sina Lori-ani, Diana M. Liverman, Awaz Mohamed, Nebojsa Nakicenovic, David Obura, Daniel Ospina, Klaudia Prodani, Crelis Rammelt, Boris Sakschewski, Joeri Scholtens, Ben Stewart-Koster, Thejna Tharammal, Detlef van Vuuren, Peter H. Verburg, Ricarda Winkelmann, Caroline Zimm, Elena M. Bennett, Stefan Bringezu, Wendy Broadgate, Pamela A. Green, Lei Huang, Lisa Jacobson, Christopher Ndehedehe, Simona Pedde, Juan Rocha,

- Marten Scheffer, Lena Schulte-Uebbing, Wim de Vries, Cunde Xiao, Chi Xu, Xinwu Xu, Noelia Zafra-Calvo, and Xin Zhang (May 2023). "Safe and just Earth system boundaries". en. In: *Nature*. Publisher: Nature Publishing Group, pp. 1–10. ISSN: 1476-4687. DOI: 10.1038/s41586-023-06083-8. URL: <https://www.nature.com/articles/s41586-023-06083-8> (visited on 07/02/2023).
- Romanello, Marina, Claudia Di Napoli, Paul Drummond, Carole Green, Harry Kennard, Pete Lampard, Daniel Scamman, Nigel Arnell, Sonja Ayeb-Karlsson, Lea Berrang Ford, Kristine Belesova, Kathryn Bowen, Wenjia Cai, Max Callaghan, Diarmid Campbell-Lendrum, Jonathan Chambers, Kim R. van Daalen, Carole Dalin, Niheer Dasandi, Shouro Dasgupta, Michael Davies, Paula Dominguez-Salas, Robert Dubrow, Kristie L. Ebi, Matthew Eckelman, Paul Ekins, Luis E. Escobar, Lucien Georgeson, Hilary Graham, Samuel H. Gunther, Ian Hamilton, Yun Hang, Risto Hänninen, Stella Hartinger, Kehan He, Jeremy J. Hess, Shih-Che Hsu, Slava Jankin, Louis Jamart, Ollie Jay, Ilan Kelman, Gregor Kiesewetter, Patrick Kinney, Tord Kjellstrom, Dominic Kniveton, Jason K. W. Lee, Bruno Lemke, Yang Liu, Zhao Liu, Melissa Lott, Martin Lotto Batista, Rachel Lowe, Frances MacGuire, Maquins Odhiambo Sewe, Jaime Martinez-Urtaza, Mark Maslin, Lucy McAllister, Alice McGushin, Celia McMichael, Zhifu Mi, James Milner, Kelton Minor, Jan C. Minx, Nahid Mohajeri, Maziar Moradi-Lakeh, Karyn Morrissey, Simon Munzert, Kris A. Murray, Tara Neville, Maria Nilsson, Nick Obradovich, Megan B. O'Hare, Tadj Oreszczyn, Matthias Otto, Fereidoon Owfi, Olivia Pearman, Mahnaz Rabbaniha, Elizabeth J. Z. Robinson, Joacim Rocklöv, Renee N. Salas, Jan C. Semenza, Jodi D. Sherman, Liuhua Shi, Joy Shumake-Guillemot, Grant Silbert, Mikhail Sofiev, Marco Springmann, Jennifer Stowell, Meisam Tabatabaei, Jonathon Taylor, Joaquin Triñanes, Fabian Wagner, Paul Wilkinson, Matthew Winning, Marisol Yglesias-González, Shihui Zhang, Peng Gong, Hugh Montgomery, and Anthony Costello (Nov. 2022). "The 2022 report of the Lancet Countdown on health and climate change: health at the mercy of fossil fuels". English. In: *The Lancet* 400.10363. Publisher: Elsevier, pp. 1619–1654. ISSN: 0140-6736, 1474-547X. DOI: 10.1016/S0140-6736(22)01540-9. URL: [https://www.thelancet.com/journals/lancet/article/PIIS0140-6736\(22\)01540-9/fulltext](https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(22)01540-9/fulltext) (visited on 02/20/2023).
- Roser, Max and Hannah Ritchie (Sept. 2021). "Burden of Disease". In: *Our World in Data*. URL: <https://ourworldindata.org/burden-of-disease> (visited on 06/12/2022).
- Sabel, Clive E., John F. Pearson, Deborah F. Mason, Ernest Willoughby, David A. Abernethy, and Bruce V. Taylor (Aug. 2021). "The latitude gradient for multiple sclerosis prevalence is established in the early life course". eng. In: *Brain: A Journal of Neurology* 144.7, pp. 2038–2046. ISSN: 1460-2156. DOI: 10.1093/brain/awab104.
- Sarfati, M., L. Marraud, E. Baurès, C. Harpet, and L. Marraud (June 2022). "Transdisciplinary Training as a Lever for Organizational Change in Health Sector: Towards a sustainable healthcare leadership". In: Brussels.
- Shiri, Rahman and Kobra Falah-Hassani (Oct. 2017). "Does leisure time physical activity protect against low back pain? Systematic review and meta-analysis of 36 prospective cohort studies". eng. In: *British Journal of Sports Medicine* 51.19, pp. 1410–1418. ISSN: 1473-0480. DOI: 10.1136/bjsports-2016-097352.
- Shobande, Olatunji Abdul (Feb. 2020). "The effects of energy use on infant mortality rates in Africa". en. In: *Environmental and Sustainability Indicators* 5, p. 100015. ISSN: 2665-9727. DOI: 10.1016/j.indic.2019.100015. URL: <https://www.sciencedirect.com/science/article/pii/S2665972719300157> (visited on 02/20/2023).
- Smil, Vaclav (n.d.). *Energy and Civilization*. 2018/11/13. MIT Press. URL: <https://mitpress.mit.edu/9780262536165/energy-and-civilization/>.
- Södersten, Carl-Johan, Richard Wood, and Edgar G. Hertwich (Feb. 2018). "Environmental Impacts of Capital Formation: Environmental Impacts of Capital Formation". en. In: *Journal of Industrial Ecology* 22.1, pp. 55–67. ISSN: 10881980. DOI: 10.1111/jiec.12532. URL: <https://onlinelibrary.wiley.com/doi/10.1111/jiec.12532> (visited on 07/08/2021).
- Södersten, Carl-Johan H., Richard Wood, and Edgar G. Hertwich (Nov. 2018a). "Endogenizing Capital in MRIO Models: The Implications for Consumption-Based Accounting". en. In: *Environmental Science & Technology* 52.22, pp. 13250–13259. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/acs.est.8b02791. URL: <https://pubs.acs.org/doi/10.1021/acs.est.8b02791> (visited on 07/07/2021).

- (2018b). “Endogenizing Capital in MRIO Models: The Implications for Consumption-Based Accounting”. In: *Environmental Science & Technology* 52.22, pp. 13250–13259. DOI: 10.1021/acs.est.8b02791.
- Stadler, Konstantin (2015). “Pymrio - a Python module for automating input output calculations and generating reports”. en. In: *EnviroInfo & ICT4S-Adjunct Proceedings (Part 2)*, p. 1.
- Stadler, Konstantin, Richard Wood, Tatyana Bulavskaya, Carl-Johan Södersten, Moana Simas, Sarah Schmidt, Arkaitz Usubiaga, José Acosta-Fernández, Jeroen Kuenen, Martin Bruckner, Stefan Giljum, Stephan Lutter, Stefano Merciai, Jannick H Schmidt, Michaela C Theurl, Christoph Plutzar, Thomas Kastner, Nina Eisenmenger, Karl-Heinz Erb, Arjan Koning, and Arnold Tukker (Oct. 2021). *EXIOBASE 3*. DOI: 10.5281/zenodo.5589597. URL: <https://zenodo.org/record/5589597> (visited on 04/21/2022).
- Stadler, Konstantin, Richard Wood, Tatyana Bulavskaya, Carl-Johan Södersten, Moana Simas, Sarah Schmidt, Arkaitz Usubiaga, José Acosta-Fernández, Jeroen Kuenen, Martin Bruckner, Stefan Giljum, Stephan Lutter, Stefano Merciai, Jannick H. Schmidt, Michaela C. Theurl, Christoph Plutzar, Thomas Kastner, Nina Eisenmenger, Karl-Heinz Erb, Arjan de Koning, and Arnold Tukker (June 2018). “EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables: EXIOBASE 3”. en. In: *Journal of Industrial Ecology* 22.3, pp. 502–515. ISSN: 10881980. DOI: 10.1111/jiec.12715. URL: <http://doi.wiley.com/10.1111/jiec.12715> (visited on 11/05/2020).
- “Statistical Review of World Energy 2022” (2022). en. In: p. 60.
- Steenmeijer, Michelle A, João F D Rodrigues, Michiel C Zijp, and Susanne L Waaijers-van der Loop (Dec. 2022). “The environmental impact of the Dutch health-care sector beyond climate change: an input–output analysis”. en. In: *The Lancet Planetary Health* 6.12, e949–e957. ISSN: 25425196. DOI: 10.1016/S2542-5196(22)00244-3. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2542519622002443> (visited on 04/16/2023).
- Steffen, Will, Katherine Richardson, Johan Rockström, Sarah E. Cornell, Ingo Fetzer, Elena M. Bennett, Reinette Biggs, Stephen R. Carpenter, Wim de Vries, Cynthia A. de Wit, Carl Folke, Dieter Gerten, Jens Heinke, Georgina M. Mace, Linn M. Persson, Veerabhadran Ramanathan, Belinda Reyers, and Sverker Sörlin (Feb. 2015). “Planetary boundaries: Guiding human development on a changing planet”. In: *Science* 347.6223. Publisher: American Association for the Advancement of Science, p. 1259855. DOI: 10.1126/science.1259855. URL: <https://www.science.org/doi/10.1126/science.1259855> (visited on 04/10/2023).
- Steinmann, Zoran J. N., Aafke M. Schipper, Mara Hauck, Stefan Giljum, Gregor Wernet, and Mark A. J. Huijbregts (June 2017). “Resource Footprints are Good Proxies of Environmental Damage”. In: *Environmental Science & Technology* 51.11. Publisher: American Chemical Society, pp. 6360–6366. ISSN: 0013-936X. DOI: 10.1021/acs.est.7b00698. URL: <https://doi.org/10.1021/acs.est.7b00698> (visited on 04/21/2022).
- Sterck, Olivier, Max Roser, Mthuli Ncube, and Stefan Thewissen (Feb. 2018). “Allocation of development assistance for health: is the predominance of national income justified?” In: *Health Policy and Planning* 33.Supp1, pp. i14–i23. ISSN: 0268-1080. DOI: 10.1093/heapol/czw173. URL: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5886300/> (visited on 06/12/2022).
- Stern, David I. (2019). “Energy and economic growth”. In: *Routledge Handbook of Energy Economics*. Num Pages: 19. Routledge. ISBN: 978-1-315-45965-3.
- Tennison, Imogen, Sonia Roschnik, Ben Ashby, Richard Boyd, Ian Hamilton, Tadj Oreszczyn, Anne Owen, Marina Romanello, Paul Ruyssevelt, Jodi D. Sherman, Andrew Z. P. Smith, Kristian Steele, Nicholas Watts, and Matthew J. Eckelman (Feb. 2021). “Health care’s response to climate change: a carbon footprint assessment of the NHS in England”. English. In: *The Lancet Planetary Health* 5.2. Publisher: Elsevier, e84–e92. ISSN: 2542-5196. DOI: 10.1016/S2542-5196(20)30271-0. URL: [https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196\(20\)30271-0/fulltext](https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(20)30271-0/fulltext) (visited on 04/05/2022).
- Thiel, Cassandra L., Andy Cassels-Brown, Hena Goel, Rachel Stancliffe, Ingeborg Steinbach, Peter Thomas, and Jorge Vendries (July 2020). “Utilizing off-the-shelf LCA methods to develop a ‘triple bottom line’ auditing

- tool for global cataract surgical services”. en. In: *Resources, Conservation and Recycling* 158, p. 104805. ISSN: 0921-3449. DOI: 10.1016/j.resconrec.2020.104805. URL: <https://www.sciencedirect.com/science/article/pii/S0921344920301269> (visited on 07/07/2022).
- Thiel, Cassandra L., Emily Schehlein, Thulasiraj Ravilla, R. D. Ravindran, Alan L. Robin, Osamah J. Saeedi, Joel S. Schuman, and Rengaraj Venkatesh (Nov. 2017). “Cataract surgery and environmental sustainability: Waste and lifecycle assessment of phacoemulsification at a private healthcare facility”. eng. In: *Journal of Cataract and Refractive Surgery* 43.11, pp. 1391–1398. ISSN: 1873-4502. DOI: 10.1016/j.jcrs.2017.08.017.
- Torre, Jorge Arias-de la, Gemma Vilagut, Amy Ronaldson, Antoni Serrano-Blanco, Vicente Martín, Michele Peters, Jose M. Valderas, Alex Dregan, and Jordi Alonso (Oct. 2021). “Prevalence and variability of current depressive disorder in 27 European countries: a population-based study”. English. In: *The Lancet Public Health* 6.10. Publisher: Elsevier, e729–e738. ISSN: 2468-2667. DOI: 10.1016/S2468-2667(21)00047-5. URL: [https://www.thelancet.com/journals/lanpub/article/PIIS2468-2667\(21\)00047-5/fulltext](https://www.thelancet.com/journals/lanpub/article/PIIS2468-2667(21)00047-5/fulltext) (visited on 07/05/2022).
- Usubiaga, Arkaitz and José Acosta-Fernández (2018). “SI\_energy Supporting Information for energy accounts”. en. In: *Journal of Industrial Ecology*.
- Vidal, Olivier, Hugo Le Boulzec, Baptiste Andrieu, and François Verzier (Jan. 2022). “Modelling the Demand and Access of Mineral Resources in a Changing World”. en. In: *Sustainability* 14.1. Number: 1 Publisher: Multidisciplinary Digital Publishing Institute, p. 11. ISSN: 2071-1050. DOI: 10.3390/su14010011. URL: <https://www.mdpi.com/2071-1050/14/1/11> (visited on 07/05/2022).
- VizHub - GBD Results* (2023). URL: <https://vizhub.healthdata.org/gbd-results/> (visited on 02/08/2023).
- Vos, Theo et al. (Oct. 2020). “Global burden of 369 diseases and injuries in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019”. English. In: *The Lancet* 396.10258. Publisher: Elsevier, pp. 1204–1222. ISSN: 0140-6736, 1474-547X. DOI: 10.1016/S0140-6736(20)30925-9. URL: [https://www.thelancet.com/journals/lancet/article/PIIS0140-6736\(20\)30925-9/fulltext](https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(20)30925-9/fulltext) (visited on 07/06/2022).
- Wang, Zhaohua, Muhammad Mansoor Asghar, Syed Anees Haider Zaidi, Kishwar Nawaz, Bo Wang, Wehui Zhao, and Fengxing Xu (June 2020). “The dynamic relationship between economic growth and life expectancy: Contradictory role of energy consumption and financial development in Pakistan”. en. In: *Structural Change and Economic Dynamics* 53, pp. 257–266. ISSN: 0954-349X. DOI: 10.1016/j.strueco.2020.03.004. URL: <https://www.sciencedirect.com/science/article/pii/S0954349X20300084> (visited on 02/20/2023).
- Watson, Robert T, Ivar A Baste, Anne Larigauderie, Paul Leadley, Unai Pascual, Brigitte Baptiste, Sebsebe Demissew, Luthando Dziba, Gunay Erpul, Asghar M Fazel, Markus Fischer, Ana Maria Hernández, Madhav Karki, Vinod Mathur, Tamar Pataridze, Isabel Sousa Pinto, Marie Stenseke, Katalin Török, and Bibiana Vilá (n.d.). “MEMBERS OF THE MANAGEMENT COMMITTEE WHO PROVIDED GUIDANCE FOR THE PRODUCTION OF THIS ASSESSMENT:” en. In: ().
- Weisz, Ulli, Peter-Paul Pichler, Ingram S. Jaccard, Willi Haas, Sarah Matej, Florian Bachner, Peter Nowak, and Helga Weisz (Sept. 2020). “Carbon emission trends and sustainability options in Austrian health care”. en. In: *Resources, Conservation and Recycling* 160, p. 104862. ISSN: 09213449. DOI: 10.1016/j.resconrec.2020.104862. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0921344920301828> (visited on 04/04/2022).
- Wiedenhofer, Dominik, Doris Virág, Gerald Kalt, Barbara Plank, Jan Streeck, Melanie Pichler, Andreas Mayer, Fridolin Krausmann, Paul Brockway, Anke Schaffartzik, Tomer Fishman, Daniel Hausknost, Bartholomäus Leon-Gruchalski, Tânia Sousa, Felix Creutzig, and Helmut Haberl (June 2020). “A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: bibliometric and conceptual mapping”. en. In: *Environmental Research Letters* 15.6, p. 063002. ISSN: 1748-9326. DOI: 10.1088/1748-

- 9326/ab8429. URL: <https://iopscience.iop.org/article/10.1088/1748-9326/ab8429> (visited on 09/13/2021).
- Woodcock, James, Phil Edwards, Cathryn Tonne, Ben G. Armstrong, Olu Ashiru, David Banister, Sean Beevers, Zaid Chalabi, Zohir Chowdhury, Aaron Cohen, Oscar H. Franco, Andy Haines, Robin Hickman, Graeme Lindsay, Ishaan Mittal, Dinesh Mohan, Geetam Tiwari, Alistair Woodward, and Ian Roberts (Dec. 2009). “Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport”. English. In: *The Lancet* 374.9705. Publisher: Elsevier, pp. 1930–1943. ISSN: 0140-6736, 1474-547X. DOI: 10.1016/S0140-6736(09)61714-1. URL: [https://www.thelancet.com/journals/lancet/article/PIIS0140-6736\(09\)61714-1/fulltext](https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(09)61714-1/fulltext) (visited on 04/21/2022).
- Wootton, Robyn E., Rebecca C. Richmond, Bobby G. Stuijzand, Rebecca B. Lawn, Hannah M. Sallis, Gemma M. J. Taylor, Gibran Hemani, Hannah J. Jones, Stanley Zammit, George Davey Smith, and Marcus R. Munafò (Oct. 2020). “Evidence for causal effects of lifetime smoking on risk for depression and schizophrenia: a Mendelian randomisation study”. eng. In: *Psychological Medicine* 50.14, pp. 2435–2443. ISSN: 1469-8978. DOI: 10.1017/S0033291719002678.
- Wu, Rui (Oct. 2019). “The carbon footprint of the Chinese health-care system: an environmentally extended input–output and structural path analysis study”. en. In: *The Lancet Planetary Health* 3.10, e413–e419. ISSN: 25425196. DOI: 10.1016/S2542-5196(19)30192-5. URL: <https://linkinghub.elsevier.com/retrieve/pii/S2542519619301925> (visited on 10/01/2021).
- Wu, Xudong, Chaohui Li, Jinlan Guo, Xiaofang Wu, Jing Meng, and Guoqian Chen (2021). “Extended carbon footprint and emission transfer of world regions: With both primary and intermediate inputs into account”. In: *Science of The Total Environment* 775, p. 145578. DOI: 10.1016/j.scitotenv.2021.145578.
- Xu, Tianwei, Linda L. Magnusson Hanson, Theis Lange, Liis Starkopf, Hugo Westerlund, Ida E. H. Madsen, Reiner Rugulies, Jaana Pentti, Sari Stenholm, Jussi Vahtera, Åse M. Hansen, Marianna Virtanen, Mika Kivimäki, and Naja H. Rod (Apr. 2019). “Workplace bullying and workplace violence as risk factors for cardiovascular disease: a multi-cohort study”. eng. In: *European Heart Journal* 40.14, pp. 1124–1134. ISSN: 1522-9645. DOI: 10.1093/eurheartj/ehy683.
- Yach, Derek, Corinna Hawkes, C. Linn Gould, and Karen J. Hofman (June 2004). “The global burden of chronic diseases: overcoming impediments to prevention and control”. eng. In: *JAMA* 291.21, pp. 2616–2622. ISSN: 1538-3598. DOI: 10.1001/jama.291.21.2616.
- Yan, Shijiao, Yong Gan, Xingyue Song, Yunqiang Chen, Na Liao, Song Chen, and Chuanzhu Lv (Aug. 2018). “Association between refrigerator use and the risk of gastric cancer: A systematic review and meta-analysis of observational studies”. en. In: *PLOS ONE* 13.8. Publisher: Public Library of Science, e0203120. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0203120. URL: <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0203120> (visited on 11/08/2022).
- Youssef, Adel Ben, Laurence Lannes, Christophe Rault, and Agnès Soucat (Sept. 2016). “Energy Consumption and Health Outcomes in Africa”. en. In: *Post-Print*. Number: halshs-01384730 Publisher: HAL. URL: <https://ideas.repec.org/p/hal/journal/halshs-01384730.html> (visited on 02/20/2023).



## CHAPTER 6 | CONCLUSION

### 6.1. CONTRIBUTION OF THIS THESIS

#### 6.1.1. RESEARCH OBJECTIVE A

Research objective A was to contribute to the development of MATER in terms of stocks and flows of energy and raw materials to build and maintain infrastructures for major world regions over the period 1900-2100, with a particular focus on the transport sector.

Chapter 2.1 presented the DyMEMDS (Dynamic Modelling of Energy and Matter Demand and Supply) model, which is the ancestor of MATER. DyMEMDS is a stock and flow model that links the energy consumption, GDP, and population with raw materials consumption, greenhouse gases emissions, global warming, and additional environmental impacts such as the consumption of water and used land for mining. It includes about 50 technologies of transportation, construction, and energy; 10 metals, cement, and gravel; and 9 geographical regions covering the world. From the evolution of infrastructure calculated for imposed future GDP and population evolutions, the stocks of materials by technologies are estimated using dynamic raw material intensities in kg of material per technological unit.

This full bottom-up approach starting from regional GDP and population evolutions makes it possible to link the global raw material consumption with the economic development and the population and technological evolutions of each geographical region. It reproduces the incremental increase in demand for base metals, cement, and gravels observed since World War II. The period 1950–1970 was marked by a strong increase in global consumption driven by the construction of the infrastructure of currently developed countries. Consumption growth declined during the 1970–2000 period, as saturation thresholds were approached in rich countries, and no poor country was economically emerging. Then the rapid economic emergence of China in the late 1990s led to a second period of increase in global consumption. China's consumption is expected to level off over the next decade, and then decline between 2030 and 2050. After 2050, the need for new infrastructure in this country is no longer controlled by the evolution of GDP/capita because the saturation thresholds are reached. Moreover, the amount of recyclable material that was negligible before 2030 increases after 2030 as fast as the increase

in consumption observed between 2000 and 2025. The amount of steel available for recycling between 2050 and 2075 is even higher than the apparent consumption. A peak in steel consumption was also observed in the US in the 1970s, although less pronounced than in China in 2030 because previous growth was slower. Since then, the US steel consumption has remained relatively constant, which is a common observation made for all rich countries, as well as in China after 2050. An incremental evolution of demand is also observed for Ni, Cr, and Mn, which are mainly used as alloying elements of steel. The incremental evolution is less clear for other base metals such as copper and aluminium involved in a variety of new applications with lower lifetimes than steel since the 1950s. The decrease in Chinese consumption in 2030–2050 is likely to be compensated by the increase due to the economic emergence of India and African countries. Assuming that these countries will achieve their economic development within the century, the Indian peak of cement and steel consumption might occur in 2050 and 2100, and those of copper and aluminium one- or two-decades latter. The African consumption peaks are expected to occur 15 years later. In this scenario, the yearly global demand for steel and cement in 2100 is fourfold the present value and sixfold the present consumption for aluminium and copper.

The DyMEMDS model was coded in Vensim. To allow for more collaborative work, we re-coded it in python as MATER (Multi-regional Assesment of Technologies, Energy and Resources), presented in Chapter 2.2. One of the main strengths of MATER is the fact that the industrial energy consumption is endogenized, meaning that feedback loops allow to calculate the energy and raw materials needed to build the infrastructure needed to build and operate existing stocks.

One of the main inputs of MATER is trajectories in stocks. The third part of chapter 3 demonstrates that utilizing a single S-curve (as a function of GDP per capita) equation precisely replicates historical personal light-duty vehicles stocks in every country worldwide, thus enabling accurate predictions of future stock levels in business-as-usual scenarios. In MATER and DyMEMDS, we built such curves for every major infrastructure sector. In these equations, it is essential to physically explain the regional differences within this equation; failing to do so could yield unreliable results. For instance, it is likely that the GCAM model underestimates the number of cars needing to be built by 2100 in a business-as-usual scenario by 10 billion.

### 6.1.2. RESEARCH OBJECTIVE B

Research objective B was to study the contribution of technological progress and resource dilution on the energy intensity of production of metals in order to incorporate the dynamics into MATER.

Chapter 2 explored this relationship between technological progress and thermodynamic limits. The first paper of the chapter presents a model that uses ore grade, technology improvement, energy prices, and thermodynamic limits to predict the long-term costs and prices of metals. This model accurately reproduces the historical evolution of metal prices since 1900 and predicts that the trend of declining costs will eventually reverse as production energy ap-

proaches thermodynamic limits. This has already happened for precious metals and will occur before the end of the century for other metals. The model built has allowed to improve the calculation of raw materials production energy consumption in MATER. A module was added in MATER to calculate the energy per kg of metal as a function of technological progress (time dependent) and resource quality (inversely proportional to the integral of historical production).

The second paper explores the energy efficiency of the overall economy. We calculated the energy necessary to produce households and governments' final consumption in 49 world regions in 2017. Energy intensities (energy use per dollar of final consumption) were then studied as a function of affluence. We found that high-income regions used more energy per unit of final consumption than low-income ones. This result contradicts the common belief that a higher GDP is correlated with a better efficiency and questions the feasibility of mainstream energy transition scenarios based on universal GDP growth.

This second study was performed only for year 2017. To improve the modelling in MATER, energy intensities would need to be calculated as a function of time and be incorporated in a model similar to that of this chapter's first paper. To do so would require to know the thermodynamic minimum of energy intensities. This could be done by using exergy. Exergy is a measure of the maximum useful work that can be extracted from a system or a flow of matter or energy as it comes into equilibrium with a reference environment. It is a thermodynamic property that quantifies the usefulness or quality of energy. However, exergy is not yet incorporated into EXIOBASE, the input-output database used in the second paper. Researchers are currently working on building exergy extensions for EXIOBASE. Building a model of energy intensity similar to that of paper 1 will therefore soon be possible.

### 6.1.3. RESEARCH OBJECTIVE C

Research objective C was to regionalize the impacts of production and consumption in MATER using input-output modelling.

In the first version of MATER, we considered that there were no exchanges in between regions, which is an obvious limitation. The first part of chapter 4 presents how input output databases can be used to analyze economic and ecological exchanges in between regions. Results from carbon footprint assessments vary greatly depending on the calculation perimeter chosen, making them confusing to non-expert readers and hindering their use for policymaking. Sankey diagrams are a type of flow diagram where the thickness of a flow is proportional to its value. They are powerful visual representation tools that would allow to shed light on the various ways to calculate carbon footprints and on the implications of choosing one method over another. Although several multi-regional input-output databases allow for the calculation of footprints, none of them has been systematically represented as Sankey diagrams. To fill this gap, we built an open access web application to represent carbon footprints for 49 world regions between 1995 and 2019 based on EXIOBASE data ([sankey.theshiftproject.org](http://sankey.theshiftproject.org)). We included production-based, consumption-based and consumption-based with capital endogenized accounts. We then provided examples of the insights gained with such diagrams.

Based on the insights and the experience gained by building these Sankey diagrams, we used EXIOBASE data to regionalize impacts in MATER in the second part of chapter 4. This enabled us to align the model with historical trade dynamics and economic activities. Looking towards long-term scenario analysis, we could adjust the proportions of import and export components at every stage to suit the conditions under investigation. This opens the possibility to construct a variety of scenarios such as 'Business as Usual,' where current trends continue unabated, 'Delocalization,' which explores the effects of increased offshoring and outsourcing, and 'Relocalization,' that considers the impacts of bringing production processes closer to the point of consumption. The adaptability of MATER in accommodating these various scenario constructions provides an exciting avenue for future research.

#### 6.1.4. RESEARCH OBJECTIVE D

Research objective D was to explore the energy-health nexus.

The healthcare sector presents considerably more complex modelling challenges than other sectors (such as transport or building) due to the inherent complexities of the health systems and their multitude of feedback loops and indirect effects. Healthcare systems are multi-faceted, integrating a vast array of services, technologies, and human interactions. These can range from primary care consultations to complex surgical interventions, all of which require diverse inputs and generate different types of outputs. Moreover, the demand for healthcare is influenced not only by demographic and economic factors but also by health status, health behaviours, and policies, among other things. This makes the prediction of demand and the associated resource flows considerably more challenging.

Chapter 5 therefore explored the nexus between health and the environment, through two studies, to pave the way for future integration of the healthcare sector in MATER. The first study of chapter 5 advances existing research by assessing over 1000 environmental and social impacts of healthcare systems in 49 world regions between 1995 and 2015, across the whole value chain, including infrastructures. We find that an exponential link exists between healthcare systems' resources footprint and their healthcare access and quality (HAQ) index. Both prevention and efficiency measures will be needed to change this relationship. If it is not enough, high-income countries will have to choose between further reducing the resource consumption of their healthcare systems or shifting the efforts to other sectors, health being considered an incompressible need. We call for the creation of a "HAQE" (healthcare access, quality, and efficiency) index that would add resource efficiency to access and quality when ranking healthcare systems.

The second study takes a completely different point of view to examine the relationship between the energy footprint per capita (EFC) (which measures the amount of energy required to sustain an individual's lifestyle) and diseases. We find that high EFC is correlated to low rates of enteric infections, maternal and neonatal disorders, nutritional deficiencies and sexually transmissible infections. However, high EFC is also correlated to high rates of substance use disorders, neoplasms, neurological, mental and musculoskeletal disorders, and diabetes and kidney

diseases. These are only correlations and causality is of course not implied. However, the fact that high EFC is not correlated to low rates of non-communicable diseases shows that there is no causality between high EFC and low rates of non-communicable diseases. This evidence questions the narrative that economic growth and technological innovation (which are the source of increased energy use) inherently contribute positively to health. It suggests that while they may provide solutions to certain health problems, they might simultaneously introduce new health challenges, directly or indirectly, through changes in lifestyle and environmental degradation.

Though these two articles provide useful insights to understand the health-environment nexus, they are not yet sufficient to model properly the healthcare sector using the stock-flow approach of MATER. More research is needed using systems thinking to model the dynamics of healthcare.

### 6.1.5. CONTRIBUTIONS FROM PAPERS NOT IN THE THESIS

#### 6.1.5.1. DYNAMIC MODELING OF GLOBAL FOSSIL FUEL INFRASTRUCTURE AND MATERIALS NEEDS: OVERCOMING A LACK OF AVAILABLE DATA

Hugo Le Boulzec, Louis Delannoy, Baptiste Andrieu, François Verzier, Olivier Vidal, and Sandrine Mathy (2022). “Dynamic modeling of global fossil fuel infrastructure and materials needs: Overcoming a lack of available data”. In: *Applied Energy* 326, p. 119871. DOI: 10.1016/j.apenergy.2022.119871

**Abstract** The low-carbon energy transition requires a widespread change in global energy infrastructures which in turn calls for important inputs of energy and materials. While the transport and electricity sectors have been thoroughly analyzed in this regard, that of the hydrocarbon industry has not received the same attention, maybe in part due to the difficulty of access to the necessary data. To fill this gap, we assemble public-domain data from a wide variety of sources to present a stock-flow dynamic model of the fossil fuels supply chain. It is conducted from 1950 to 2050 and along scenarios from the International Energy Agency. We estimate the concrete, steel, aluminum and copper requirements for each segment, as well as the embedded energy and CO<sub>2</sub> emissions through a dynamic material flow analysis (MFA) model. We find that (i) the material intensities of oil, gas and coal supply chains have stagnated for more than 30 years; (ii) gas is the main driver of current and future material consumption; and (iii) recycled steel from decommissioned fossil fuels infrastructures could meet the cumulative need of future low-carbon technologies and reduce its energy and environmental toll. Furthermore, we highlight that regional decommissioning strategies significantly affect the potential of material recycling and reuse. In this context, ambitious decommissioning strategies could drive a symbolic move to build future renewable technologies from past fossil fuel structures.

#### 6.1.5.2. ASSESSING THE ECONOMIC CONSEQUENCES OF AN ENERGY TRANSITION THROUGH A BIOPHYSICAL STOCK-FLOW CONSISTENT MODEL

Pierre Jacques, Louis Delannoy, Baptiste Andrieu, Devrim Yilmaz, Hervé Jeanmart, and Antoine Godin (2023). “Assessing the Economic Consequences of an Energy Transition Through a Biophysical Stock-Flow Consistent Model”. In: *Ecological Economics* 209, p. 107832. DOI: 10.1016/j.ecolecon.2023.107832

**Abstract** The biophysical foundations of socio-economic systems are underrepresented in the vast majority of macroeconomic models. This lack is particularly troublesome when considering the links between energy, matter and the economy in the context of the energy transition. As a remedy, we present here a biophysical stock-flow consistent macroeconomic model calibrated at the global scale, that combines detailed bottom-up estimates for the high capital intensity of renewable energies and the decreasing energy return on investment (EROI) of fossil fuels. We find that the completion of a global energy transition scenario compatible with the 1.5 °C objective of the Paris Agreement leads to a decrease of the system’s EROI and to high investment share, employment and inflation trends, characteristic of a “war economy”. Our results further indicate that a slower growth rate eases the transition, and call for further work on post-growth scenarios studies.

#### 6.1.5.3. “STRONG” TRANSDISCIPLINARITY IN THE ANTHROPOCENE: LESSONS FROM A CROSS DIALOGUE BETWEEN SOCIAL AND MODELING SCIENCES

Louis Delannoy, Angélique Palle, Noémie Rebière, and Baptiste Andrieu (2023). “Strong transdisciplinarity in the Anthropocene: lessons from a cross dialogue between social and modeling sciences”. In: *Hérodote* 188. DOI: 10.3917/her.188.0041

**Abstract** By establishing a causality between the activities of human societies and the transformation of global biophysical processes, the notion of the Anthropocene has imposed systemic and transdisciplinary approaches, the only ones capable of grasping the magnitude of the issues raised. The dialogue proposed in this article is in line with this recent work. It brings together two groups of young researchers, one in the social sciences and the other in modelling sciences, who, through cross interaction, explore the practical challenges of global systemic risk analysis. The exchanges highlight the mutual contributions of hard and social sciences and illustrate the relevance of numerical models to test or validate ecological transition trajectories, while exposing its own epistemological and methodological limitations. Finally, this dialogue extends the notion of “strong” transdisciplinarity, in which interactions between disciplines would take place at every stage of the scientific creation process, as opposed to “weak” transdisciplinarity, in which exchanges would be compartmentalized at certain specific times.

#### 6.1.5.4. GASOLINE PRICE AND THE EFFECTIVENESS OF INTERVENTIONS TARGETING HEALTHIER TRANSPORT MODES: A META-ANALYSIS

Guillaume Chevance, Baptiste Andrieu, Nicolas Koch, Cathryn Tonne, Mark Nieuwenhuijsen, and Paquito Bernard (Apr. 2023). *Gasoline Price and the Effectiveness of Interventions Targeting Healthier Transport Modes: A Meta-Analysis*. en. SSRN Scholarly Paper. Rochester, NY. DOI: 10.2139/ssrn.4429015. URL: <https://papers.ssrn.com/abstract=4429015> (visited on 07/20/2023)

**Abstract** Promoting active and public transportation is beneficial for both public health and the environment. However, evidence about the structural factors that can moderate interventions' effectiveness is limited. The current study aims to quantify the moderating role of gasoline price on the effectiveness of interventions targeting healthier transport modes. This meta-analysis provides an analysis of 59 interventions targeting a change in driving, public and active transportation across four continents. Outcomes were converted into standardized mean differences and multi-level meta-analyses were conducted. We tested the moderating role of relative gasoline price, as a ratio of purchasing power, on interventions' effectiveness. Then, we tested potential interactions between relative gasoline price and access to public transportation, private motor vehicle ownership and access to streets and open spaces. Relative gasoline price significantly moderates the effectiveness of interventions targeting healthier transport modes in Europe (standardized mean difference 4.43, 95% CI 1.11 to 7.74). Interventions were more effective with higher relative gasoline price. Relative gasoline price also significantly interacted with access to public transport in the four continents, with the moderating role of relative gasoline price on interventions' effectiveness being stronger in places with higher access to public transport. Relative gasoline price is a significant moderator of interventions' effectiveness but mostly in context where infrastructures are available. We interpret this result through a conditional effect where gasoline price interacts with the availability of infrastructures supporting a modal shift from car to active and public transportation.

#### 6.1.5.5. EMERGING CONSENSUS ON NET ENERGY PAVES THE WAY FOR IMPROVED INTEGRATED ASSESSMENT MODELING

L. Delannoy, M. Auzanneau, B. Andrieu, O. Vidal, P.-Y. Longaretti, E. Prados, D.J. Murphy, R.W. Bentley, M. Carbajales-Dale, M. Raugei, M. Höök, V. Court, C.W. King, F. Fizaine., P. Jacques., M.K. Heun, A. Jackson, C. Guay-Boutet, E. Aramendia, J. Wang, Hugo Le Boulzec, and CAS Hall (2023). "Emerging consensus on net energy paves the way for improved integrated assessment modeling". In: *Submitted to Energy and Environmental Science*

**Abstract** Extracting, processing, and delivering energy requires energy itself, which reduces the net energy available to the rest of society. We believe that most mitigation pathways and transition models overlook important net energy aspects related to the decline of the qualities of fossil fuel deposits qualities, as well as energy requirements of the energy transition. These will have considerable socioeconomic implications. Here, we summarize our agreement across 8 key

points that should be considered while assessing future energy plans, identify areas of investigation by the net energy analysis community, discuss the implications of net energy constraints in the context of the energy transition, and identify issues of overlooking these. Particularly, we discuss how reductions in net energy available can hinder the transition if demand-side measures are not enabled to limit energy consumption. We also discuss the risks posed for the energy transition in the Global South, which, while being the least responsible for climate change may be amongst the most impacted by both the climate crisis and net energy constraints. Last, we discuss avenues to further consider net energy aspects in mitigation pathways and Integrated Assessment Models.

#### 6.1.5.6. MATERIAL REQUIREMENTS AND IMPACTS OF THE BUILDING SECTOR IN THE SHARED SOCIOECONOMIC PATHWAYS

Hugo Le Boulzec, Sandrine Mathy, François Verzier, Baptiste Andrieu, Daniel Monfort-Climent, and Olivier Vidal (2023). “Material requirements and impacts of the building sector in the Shared Socioeconomic Pathways”. In: *Cleaner Production*

**Abstract** The significant weight of the building sector in global material demand has been addressed in several publications, but a lack of consideration of renovation and energy-materials nexus dimension was identified. To fill these gaps, we developed a stock-flow dynamic model from 1950 to 2100, using scenarios of the International Energy Agency and the Shared Socioeconomic Pathways of the academic literature. We find that (i) the combined increasing stocks in the less developed countries and the development of renovation strategies in the most developed countries results in a rise of the inflows; (ii) it induces a large energy demand and environmental impacts, which could question the feasibility of some low-energy demand scenarios; (iii) the large-scale use of recycled concrete aggregates and green concrete<sup>1</sup> displays a significant potential to enhance the reduction of energy and GHG impacts of concrete. We furthermore highlight the crucial temporal aspect of policies to successfully implement these solutions, as long lifetimes are observed in the building sector.

## 6.2. REFERENCES

- Chevance, Guillaume, Baptiste Andrieu, Nicolas Koch, Cathryn Tonne, Mark Nieuwenhuijsen, and Paquito Bernard (Apr. 2023). *Gasoline Price and the Effectiveness of Interventions Targeting Healthier Transport Modes: A Meta-Analysis*. en. SSRN Scholarly Paper. Rochester, NY. DOI: 10.2139/ssrn.4429015. URL: <https://papers.ssrn.com/abstract=4429015> (visited on 07/20/2023).
- Delannoy, L., M. Auzanneau, B. Andrieu, O. Vidal, P.-Y. Longaretti, E. Prados, D.J. Murphy, R.W. Bentley, M. Carbajales-Dale, M. Raugé, M. Höök, V. Court, C.W. King, F. Fizaine., P. Jacques., M.K. Heun, A. Jackson, C. Guay-Boutet, E. Aramendia, J. Wang, Hugo Le Boulzec, and CAS Hall (2023). “Emerging consensus on net energy paves the way for improved integrated assessment modeling”. In: *Submitted to Energy and Environmental Science*.
- Delannoy, Louis, Angélique Palle, Noémie Rebière, and Baptiste Andrieu (2023). “‘Strong’ transdisciplinarity in the Anthropocene: lessons from a cross dialogue between social and modeling sciences”. In: *Hérodote* 188. DOI: 10.3917/her.188.0041.
- Jacques, Pierre, Louis Delannoy, Baptiste Andrieu, Devrim Yilmaz, Hervé Jeanmart, and Antoine Godin (2023). “Assessing the Economic Consequences of an Energy Transition Through a Biophysical Stock-Flow Consistent Model”. In: *Ecological Economics* 209, p. 107832. DOI: 10.1016/j.ecolecon.2023.107832.
- Le Boulzec, Hugo, Louis Delannoy, Baptiste Andrieu, François Verzier, Olivier Vidal, and Sandrine Mathy (2022). “Dynamic modeling of global fossil fuel infrastructure and materials needs: Overcoming a lack of available data”. In: *Applied Energy* 326, p. 119871. DOI: 10.1016/j.apenergy.2022.119871.
- Le Boulzec, Hugo, Sandrine Mathy, François Verzier, Baptiste Andrieu, Daniel Monfort-Climont, and Olivier Vidal (2023). “Material requirements and impacts of the building sector in the Shared Socioeconomic Pathways”. In: *Cleaner Production*.



## CHAPTER 7 | FINAL THOUGHTS

### 7.1. THE SHIFT PROJECT

This thesis has been funded by The Shift Project. The Shift Project is a French think tank advocating the shift to a post carbon economy. Our strategy is to inform the public debate by (i) setting up working groups on the most sensitive and decisive issues of the transition to a post-carbon economy, (ii) producing robust and quantified statements on key aspects of the transition, and (iii) bringing forward innovative proposals, and we pay particular attention to appropriately-scaled solutions. We then try to influence the public debate by (i) launching lobbying campaigns targeting political and economic decision-makers to promote the recommendations made by our working groups, (ii) hosting events designed to encourage discussion among the different stakeholders concerned with climate and energy issues, and (iii) building partnerships with both professional organisations and academic players.

A recent objective of The Shift Project has been to better understand the raw materials-energy nexus. Participating to the construction of the MATER model emerged as a natural strategy to achieve this. Embarking on a PhD journey with The Shift Project was an exceptional opportunity for me, allowing the research produced to directly influence public discourse. The dissemination of my research to diverse audiences has occurred through conferences, podcasts, YouTube videos, interviews, and radio appearances, reaching scientists, students, NGOs, ministries, public and private companies.

### 7.2. FREEDOM IN RESEARCH

The aim set at the beginning of the thesis was broad and I was given total freedom to explore the subjects I was truly interested in - yes, I genuinely have a passion for Sankey diagrams. My advisors, always ready to guide and mentor me, never imposed anything on me. I believe that such freedom is an essential precondition for producing good research during a PhD journey and beyond.

## 7.3. FUTURE RESEARCH

Models are potent tools that shape public discourse and policy direction. It is astonishing that all technology-rich IAMs are still based on exogenous economic growth with markets and technology being in charge of achieving the various climate targets. Transitioning towards models embedded in physical truths, free of paradoxical directives, and capable of contemplating both growth and post-growth scenarios, would provide more credible and realistic pathways. With this ambitious goal in mind, there are numerous research ideas I am eager to explore in the coming years:

### 7.3.1. EXERGY IN MATER

Technological progress in MATER is well calibrated for raw materials production (chapter 3.1). For other processes, historical progress rates are extrapolated into the future. However, to be more precise, we would need to include thermodynamic limits for each process. This could be done using exergy data.

### 7.3.2. NEW SSPs AND NEW SSP NARRATIVES

Most technology-rich IAM runs are based on the Shared Socioeconomic Pathways (SSPs). Before entering the models, SSPs are translated into economic growth pathways. It is these economic growth trajectories that enter into IAMs. This is an obvious limit and new post-growth trajectories and post-growth compatible IAMs must therefore be built.

### 7.3.3. TURNING MATER INTO AN IAM

MATER allows for really precise modelling of socioeconomic metabolism. Its main advantage compared to other models is that the industrial energy and infrastructure needs are calculated endogenously to fit the demands in services. MATER could now be coupled with other models to be more systemic and have a scope larger than existing IAMs.

### 7.3.4. CRISES, CONTAGION RISKS

MATER, akin to all technology-rich IAMs, operates under a continuity assumption, excluding potential crises. However, real-world scenarios are prone to various crises. Consequently, research is essential to examine and prepare for potential risks and disruptions.

### 7.3.5. A SYSTEMS DYNAMIC APPROACH OF HEALTHCARE

The second article of Chapter 5 identified correlations between per capita energy footprint and disease prevalence, with an inverse relationship found for communicable diseases and a di-

rect one for non-communicable diseases. Incorporating these insights into a dynamic model would require a more nuanced understanding of lifestyle factors and causative dynamics (such as physical activity levels, dietary habits, pollutant exposure, etc.). This approach could potentially unveil the interdependencies between socio-economic and health-related factors, providing valuable insights for public health interventions, policy planning, and strategic decision-making.

#### 7.3.6. GAMIFICATION

Modelling inherently illustrates the dynamic nature of the variables involved, emphasizing the uncertainty of long-term projections. To make this complexity more tangible to a wider audience, transforming MATER into an interactive, educational game could be beneficial. This could enhance awareness of the complexities of socio-economic and environmental systems, and help individuals understand how subtle changes can have far-reaching effects. Additionally, the game could function as a tool for policy makers and researchers, enabling them to test different scenarios and investigate their potential outcomes in a risk-free, simulated environment.

## 7.4. OPEN SCIENCE

I want to close by acknowledging the immense value of open science, which made this research possible. I am very grateful to the EXIOBASE, eora, GBD, GCAM, and all the other teams whose models or data I used. In my own small way, I have put all my code in open-access on my github account, in the hope that it might save other researchers some precious time. MATER, upon completion, will also be open-source and open-access. May the ongoing efforts to make science more collaborative continue (Pauliuk, 2020).

## 7.5. REFERENCES

Pauliuk, Stefan (Jan. 2020). “Making sustainability science a cumulative effort”. en. In: *Nature Sustainability* 3.1. Number: 1 Publisher: Nature Publishing Group, pp. 2–4. ISSN: 2398-9629. DOI: 10.1038/s41893-019-0443-7. URL: <https://www.nature.com/articles/s41893-019-0443-7> (visited on 04/07/2023).