Exploring the useful energy implications of the global energy transition: a net energy perspective

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Abstract

A global energy transition is urgently needed to phase out fossil fuels and mitigate climate change. Significant financial and energy investments will be needed to decarbonise the energy system, which may reduce the amount of energy available to the rest of society, i.e. the net energy available. Simultaneously, the ongoing process of mineral depletion may also reduce the net energy available by increasing the energy requirements of mining activities. Considering that energy is fundamental to the functioning of human societies, understanding the net energy implications of the energy transition is crucial.

I argue that the net energy implications of the energy transition should be analysed through the lens of useful energy. Useful energy is the energy valuable for productive and socially beneficial purposes after conversion in an end-use device (e.g. an engine or a light bulb). To conduct such an analysis, I first develop a Multi-Regional Physical Supply Use Table framework to determine the net energy returns of fossil fuels at the useful stage, both at the global and national levels. Then, this newly developed dataset allows me to conduct the first useful stage-based comparison of the net energy returns of fossil fuels and renewable energy systems. Last, I assess the effects of mineral depletion on both the energy consumption of the mining industry, and on the net energy returns of renewable energy technologies.

I find that at the useful stage, the net energy returns of renewable energy systems are likely to be higher than those of fossil fuels, and will only be marginally affected by the effects of mineral depletion. Such results suggest that renewable energy systems have the potential to deliver sufficient net useful energy to provide everyone with decent living standards, provided that net energy is allocated to the appropriate end-uses, and fairly distributed.

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Abbreviations

B2DS	Beyond 2 Degrees Scenario
CDR	Carbon Dioxide Removal
CdTe	Cadmium-Tellurium
CED	Cumulative Energy Demand
CF	Capacity Factor
CIGS	Cadmium-Indium-Galium-Selenium
CSP	Concentrated Solar Power
ECC	Energy Conversion Chain
EDF	Extended Data Figure
EIO	Energy Input Output
EIOU	Energy Industry Own Use
EROI	Energy Return On Investment
ETTs	Energy Transition Technologies
EU	European Union
EU27	European Union 27
EU28	European Union 28
GDP	Gross Domestic Product
GER	Gross Energy Requirements
IAM	Integrated Assessment Model
ICE	Internal Combustion Engine
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LED	Low Energy Demand
MIOT	Monetary Input Output Table
MIOU	Mining Industry Own Use
MR PSUT	Multi-Regional Physical Supply Use Table
PGMs	Platinum Group Metals
PIOT	Physical Input Output Table

PSUT	Physical Supply Use Table
PV	Photovoltaic
R&D	Research and Development
REEs	Rare Earth Elements
SEA	Societal Exergy Analysis
SI	Supplemental Information
SSP	Shared Socioeconomic Pathways
TES	Total Energy Supply
TPES	Total Primary Energy Supply
UK	United Kingdom
US	United States
WEEB	World Energy Extended Balances

Chapter 1

Introduction

Emmanuel Aramendia

In this thesis, I argue the energy that is valuable for productive and socially beneficial purposes is the net useful energy available to society. This introduction presents the key concepts and literature for the thesis, identifies research gaps, and sets out the aims, research questions, and structure of the thesis. Section 1.1 introduces the need for a global energy transition, discusses different levers to quickly reduce greenhouse gas emissions, and argues for the consideration of biophysical limits for planning the energy transition. Section 1.2 introduces the theoretical net useful energy framework, which combines the net energy framework and the useful stage perspective, and which will be the common thread of the thesis. Section 1.3 reviews the different determinants of the net useful energy available to society, their recent trends, and identifies the key gaps that this thesis will attempt to fill. Last, Section 1.4 sets out the aims, research questions, and structure of the thesis, as well as the novelties and contributions of each of the main chapters.

1.1 The global energy transition to come

1.1.1 An urgent need for a global energy transition

Despite the efforts of the fossil fuel industry to hide the dangers of sustained fossil fuel extraction and combustion [1, 2], climate change is now recognised as one of the most serious threats facing humanity, if not the most serious one. While there are numerous sources of greenhouse gas emissions, including deforestation, agriculture, or chemical processes such as cement production, the energy sector, and more specifically fossil fuel extraction and combustion, is responsible for approximately two thirds of anthropogenic greenhouse gas emissions [3]. Average temperatures have already warmed by a 1.1–1.2°C, and recent research raises concerns that cooling effects from aerosols may have been underestimated, so that the extent of actual warming may have been underestimated [4]. While different emission pathways may allow us to reach the 2°C target (ideally 1.5°C), all involve a quick peak in greenhouse gas emissions and a steep decline in emissions thereafter [5] — the lower the reliance on speculative carbon dioxide removal technologies, the steeper the decline will need to be. And yet, the United Nations 2022 Emissions Gap Report finds that 2021 greenhouse gas emissions may "be similar to or even break the record 2019 levels" [6]. Hence, the window of opportunity to respect the 2°C (ideally 1.5°C) target set at the Paris Agreement is thin, and shrinking fast. Eventually, only reaching a net zero greenhouse gas emissions situation,[1] i.e. a situation in which as much greenhouse gas are emitted as are removed from the atmosphere, would stabilise global temperature — a period of net negative emissions may even be needed in case of temporary overshoot of climate targets [7].

Despite the urgency to act, current policies are not aligned with targets, and lead global temperatures towards an average warming in the range 2.4–3.5°C by the end of the century [8], assuming that reinforcing feedbacks, such as emissions from thawing permafrost [9], will not make global temperatures increase further. Indeed, the United Nations 2022 emissions gap report that greenhouse gas emissions must be reduced by 30% in 2030 compared to the current policy projections to stay on a pathway limiting global warming at 2°C by the end of the century [6]. The Production Gap 2021 report reveals the other face of the same coin, by showing that current fossil fuel extraction projections lead to a situation of 45% more extraction that would be required for a 2°C consistent pathway in 2030 — and 89% more than required in 2040 [10] — the IPCC notes the "persistent misallocation of financial global capital," whereby abundant capital flows to fossil fuel-related financing while mitigation investment remains drastically underfunded [8].

While the current energy crisis shows the vulnerability of Western (particularly European) countries to fossil fuel disruption, and provides an additional incentive for a quick phase out of fossil fuels, the policies implemented to face the energy crisis, including the diversification of fossil fuel suppliers, securing of long-term supply contracts, and expansion of new fossil gas infrastructure, such as liquefied gas terminals, creates a risk of carbon lock-in and paradoxically endangers the transition

[1]Strictly speaking, a situation of net zero CO_2 emissions according to the IPCC [7].

to a low-carbon society [11]. Additionally, the recent record profits of oil and gas companies in the context of the energy crisis may encourage further investment in fossil fuel extraction and slow down the shift towards low-carbon energy urgently needed, as evidenced by recent announcements in the oil and gas sector [12].

To summarise, climate change is mostly caused by the emission of greenhouse gas emissions from fossil fuel extraction and combustion, and current policies set the evolution of global temperatures in this century on a very hazardous path. Despite the numerous discourse of climate delay at play [13], recent extreme weather events, such as the 2022 deadly flooding in Pakistan or severe drought in Europe, are compelling: a global energy transition is urgently needed to quickly phase out fossil fuels and cut down greenhouse gas emissions, until reaching net zero emissions.

1.1.2 Levers to reduce greenhouse gas emissions

Traditionally, three main levers have been considered to reach net zero emissions. First, the large upscaling of renewable energy systems to quickly phase-out fossil fuels. Second, increasing energy efficiencies to limit final energy consumption. Third, the use of Carbon Dioxide Removal (CDR) technologies to capture the excess carbon dioxide in the atmosphere. This section discusses further levers and argues for the need for (i) a capped, or even decreasing, final energy consumption, (ii) a transition to a post-growth economic paradigm, and (iii) supplementing supply-side measures with the implementation of demand-side measures to further reduce energy consumption.

(i) The need for a capped, or even decreasing, final energy consumption

An increasing number of mitigation pathways rely on CDR technologies to offset remaining greenhouse gas emissions, or to bring back the global average temperature below 2°C warming after a temporary overshoot [8]. These CDR technologies remain however expensive, and their large scale deployment seems to be a high-risk gamble [14, 15], on which climate policy should not rely. A key lever to limit the reliance on these technologies is to contain future global final energy consumption, as noted by the Intergovernmental Panel On Climate (IPCC) Change when noting in the Sixth Assessment Report that "the scale of energy demand is a critical determinant of the mitigation challenge" [16, p. 692]. Indeed, the higher energy demand is, the larger the uptake of low-carbon energy technologies need to be to reach net zero emissions, or the higher the reliance on CDR technologies is [16]. As a consequence, scenarios consistent with a 2°C average warming by the end of the century stabilise global final energy consumption at levels close to current levels, or even decrease global final energy consumption for those that are least reliant on CDR technologies [17, pp. 337-338], making the case for limiting future global final energy consumption compelling.

(ii) The need to transition to a post-growth economic paradigm

While the dominant economic paradigm remains the pursuit of endless economic growth, there are concerns regarding the feasibility of reconciling economic growth with environmental goals. Indeed, the *green growth* paradigm is based on the idea that environmental impacts, for instance greenhouse gas emissions, can be decoupled from economic growth, i.e. can be reduced while the economy grows (absolute decoupling[2]). The evidence of such an absolute decoupling is thin, particularly when considered at the global level or on a consumption-based perspective [18–20], and basing climate policy on the premise that absolute decoupling will occur, and *will do so at the required pace*, seems to be another high-risk gamble. Particularly, there seems to be a tight coupling between energy consumption and economic output at the global level, as shown in Figure 1.1, which poses a critical issue to the green growth paradigm. Hence, it is increasingly clear that limiting the scale of economic activities under a given threshold (particularly in the case of affluent Western countries), and thereby limiting or even reducing energy consumption, would be highly beneficial for climate change mitigation.

(iii) The need to supplement supply-side with demand-side measures

The last IPCC report presents a new whole chapter on demand-side measures for mitigating climate change [23], due to the increasing consensus that the "potential of demand-side strategies to reduce emissions [...] in three end-use sectors (buildings, land transport, and food) is 40–70% globally by 2050" [8, p.117]. The recent Low Energy Demand scenario shows for instance that global energy demand may be reduced by 40% by changing the quantity and type of energy services demanded,

[2]In opposition to relative decoupling, which refers to a situation in which environmental impacts would continue to increase, albeit at a slower rate than economic output.

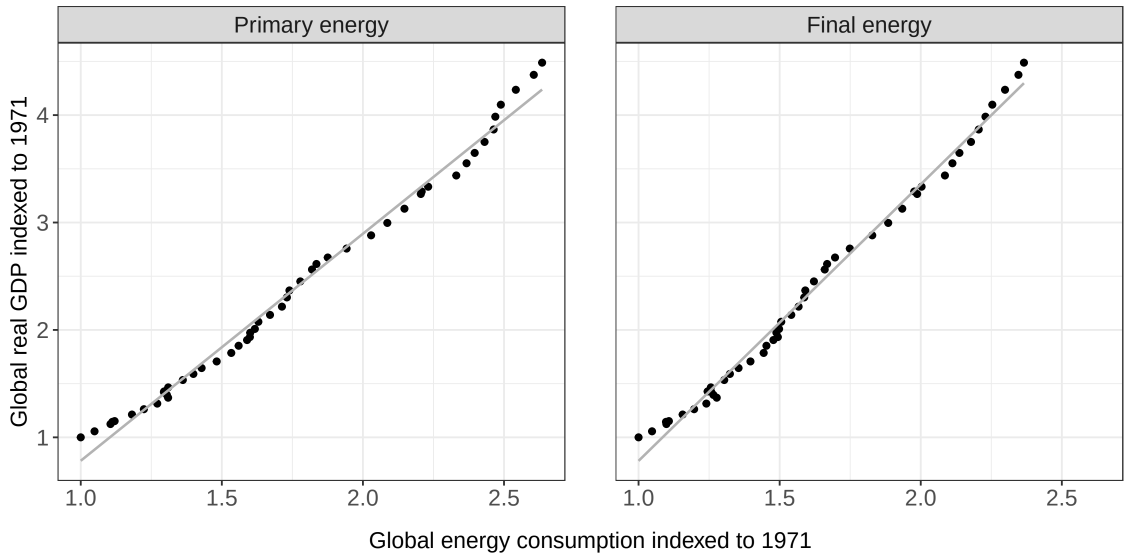

Figure 1.1: Global economic output, measured as real Gross Domestic Product, as function of primary (left) and final (right) energy consumption (1971–2019). Values indexed to 1971. Economic data from the World Bank [21] and energy data from the International Energy Agency [22].

thereby reaching the 1.5°C average warming target without reliance on CDRs [24]. In a similar vein, recent work has shown in the case of the UK that energy demand reduction can have a major role in climate change mitigation, with a possible decrease in energy demand by 52% per capita without compromising quality of life [25]. Further, recent work by Creutzig et al. applying the *avoid, shift, improve* framework shows that demand-side measures can significantly reduce greenhouse gas emissions (by 40–80%) with simultaneously positive outcomes for human well-being [26]. While climate change mitigation has traditionally been focused on the supply side, i.e. on how to switch to low-carbon energy, and how to transform and provide energy more efficiently, the recent literature shows the urgency of moving beyond this traditional approach — which remains pervasive — where energy supply is expected to adapt to society's energy demands, towards demand-side measures, whereby societal energy demand also needs to adjust to facilitate the transition to a low-carbon energy system.

An effective energy transition would result from the combination of a quick up-scale in renewable energy systems to phase out fossil fuels combined with an increase in the efficiencies with which energy is processed and delivered, alongside the implementation of demand-side measures to reduce energy consumption. Although this thesis focuses on the implications of the substitution of fossil fuels with renewable energy systems, setting up the broader context is crucial as additional levers need to be mobilised for a successful energy transition.

1.1.3 Biophysical limits for the energy transition

Following the ecological economics literature, which considers the economy as embedded in the environment [27], I argue in this thesis that the energy transition needs to happen within biophysical limits. An example of critical limit is the land requirements of such a system [28], as land use for energy purposes competes with other crucial uses, such as food production [29, 30]. This section introduces and discusses two limits that this thesis will explore, i.e. the material and energy requirements of the transition to a low-carbon energy system. Recent work shows that the land requirements of renewable energy systems, particularly solar energy, may be considerable [31], and may reach values up to 5% of total land [32].

The material requirements of a low-carbon energy system

One of the challenges facing the energy transition is the high reliance of low-carbon technologies (be it renewable energy generation technologies, passive devices such as electric cars, or batteries for storage) on non-renewable minerals [33–35]. The recent realisation that "a shift to renewable energy will replace one non-renewable resource (fossil fuel) with another (metals and minerals)" [36] has fostered numerous studies exploring the material requirements of the energy transition, both at the global and national levels (see [37] for a review). The surge that can be expected in the demand for specific minerals and metals has been shown to be considerable [34, 38–40], with particularly high requirements in the transportation sector (due to batteries and electric motors for electric mobility) [41, 42] and for the power sector [43, 44]. There is a growing consensus of the crucial role that non-renewable mineral resources will play in the energy transition, with institutions such as the European Union and the United States Geological Survey publishing and analysing a list of critical raw minerals [45–48].[3] While China has had a proactive industrial policy on critical raw

[3] A research group at Yale University US has pioneered these types of criticality analysis, see for instance [49, 50].

materials for years [51, 52], this understanding of criticality increasingly translates into public policy in Western countries, with the recent US Inflation Reduction Act, which includes a component aiming at increasing the share of domestically produced critical raw materials [53], and the EU Critical Raw Materials Act announced in response [54].

Indeed, the high material requirements of the low-carbon transition raises concerns regarding whether geological endowments will be sufficient to cover the requirements, i.e. whether mineral reserves (the amount of minerals identified in the ground for which the extraction is both technically feasible and economically viable[4] — see Section 1.3.2 for further discussion) will be sufficient to supply the required minerals. Watari et al. [55] explores the material implications of the IEA's long term energy scenarios, and finds that material requirements exceed known reserves for several minerals. Moreau et al. [56] conducts a similar analysis for five long-term energy transition scenarios and obtains analogous results. Other studies using simulation models to quantify the material requirements of energy transition scenarios also come to similar conclusions [57–60], hence raising doubts regarding the material feasibility of the energy transition.

Conversely, some authors insist on the fact that reserves are a dynamic concept, at the interplay of geological and economic factors [61], as additional deposits may become profitable to extract with an increase in mineral prices, and as reserves tend to increase over time as new discoveries are made and as technological progress makes the extraction of new mineral deposits technically feasible and economically viable. Such a trend of increasing reserves over time has for instance been clearly shown in the case of copper [62] or zinc [61]. As such, some authors claim that geological endowments should not be regarded as an ultimate constraint on mineral extraction, and that future reserves will be sufficient provided appropriate investment, exploration, and research, is carried out [63–65]. The question of the amount of minerals that will be ultimately extracted, is therefore an extremely complex question involving the interaction of numerous factors [66].

However, and disregarding the size of reserves, there are clear risks related to mineral supply bottlenecks, as a sufficient size of reserves does not ensure that minerals will be extracted and available at the time and location required for meeting demand [45, 57, 67]. Indeed, the current disruption of global supply chains in the

[4]Note that the definition slightly changes from institution to institution, and has many nuances.

context of the ephemeral economic recovery followed by the war in Ukraine is starkly evidencing supply constraints and bottlenecks for some raw minerals (as well as processed materials) [68]. In the case of critical raw minerals, the high geographical concentration of the extracted deposits, and known reserves[5] [69], as well as and the geopolitical tensions surrounding those [70] may exacerbate supply bottlenecks, as exemplified by the Chinese industrial policy on strategic metals [51, 52].

The energy requirements of a low-carbon energy system

Related to the material requirements of the transition to a low-carbon energy system is the energy requirements of manufacturing the low-carbon technologies, and the infrastructure required for the low-carbon energy system. This issue has been explored through the issue of greenhouse gas emissions — which are mostly due to energy consumption — associated with the transition to a low-carbon energy system. Scott et al. [71] explores such emissions for the UK and finds significant emissions from the transition to a low-carbon energy system, although these remain significantly lower than avoided emissions. Recent work by Pehl et al. [72] find that global cumulative emissions for the transition to a low-carbon energy system would be small compared to the carbon budget. Di Felice et al. [73] also find moderate cumulative emissions for the EU energy transition (in the range 21–25 Gt of CO_2 equivalent), although they highlight that the consideration of emissions due to the construction and maintenance of the required infrastructure (particularly those required to increase grid flexibility), gives a less optimistic picture than conventional decarbonisation scenarios.[6] Last, Slameršak et al. [74] recently find that the greenhouse gas emissions associated with the transition to a low-carbon energy system may be very substantial, in the range 70–395 Gt CO_2 equivalent, and in the worst cases, may "take up all remaining emissions available to society under 1.5°C pathways" (approximately 400 Gt CO_2) [74].

Moving to studies looking specifically at the energy requirements of transitioning to a low-carbon energy system, Slameršak et al. [74], find that such energy requirements are large, and may significantly impinge on the energy available for the rest

[5] Note that the high geographical concentration of refining facilities (i.e. metallurgical facilities for metals) can also constitute a significant constraint on supply, even when the primary mineral extraction may be reasonably distributed.

[6] However, both the study of Pehl et al. [72] and Di Felice et al. [73] only account for the greenhouse gas emissions associated with the power sector.

of human activities, which may be reduced by 10 to 34%, depending on the scenario under scrutiny — there are also significant uncertainties on the energy requirements of each low-carbon technology. King and Bergh [75] find a similar likely decrease in the energy available for the rest of activities per capita, by 24 to 31% — which starkly contrasts with recent rising trends by 0.5% annually — due to significant upfront energy investments in the low-carbon energy system. Next, Sgouridis et al. [76] also find significant upfront energy requirements for the build-up of the renewable energy system, and hence advocates for a "sower's strategy" to use available fossil fuels to build the low-carbon energy infrastructure at a much quicker pace than the current one in order to stay within the remaining carbon budget. In a similar vein, Sers and Victor [77] advocate for a large and quick energy investment in the renewable energy system to avoid what the authors refer to as the "energy-emissions trap", i.e. a situation in which either an energy shortfall or an overshoot of the carbon budget is unavoidable. Last, Capellán-Pérez et al. [58] find that current yearly energy investments (approximately 40 EJ/year, ~10% of global final energy consumption) have to increase by respectively 50%, 125%, and 175% to reach a 50%, 75%, and 100% based renewable energy system, which also points to the need to increase the energy investments in the transition to a low-carbon energy system, hence diverting some energy from other societal uses.

Next, Section 1.2 introduces the theoretical framework adopted in this thesis to study the energy and material requirements of the transition to a low-carbon energy system.

1.2 Theoretical framework

1.2.1 The reliance of human societies on energy

Energy and societies through the ages

Human societies have always been heavily reliant on energy for their functioning, and societal evolutions may be interpreted through an energy lens. Hunter-gatherer societies functioned as an "uncontrolled solar energy system" [78], i.e. relied on biomass upon which no control was exerted, which strongly limited the amount of energy available per capita. The Neolithic revolution and the associated transition to an agricultural, sedentary society, marked the evolution to a "controlled solar energy system," whereby control was exerted on the biomass society relied upon, thereby considerably increasing the amount of energy that could be harnessed [78] — see Haberl [79] for a quantification.

Since the Neolithic revolution, and until the industrial revolution, human societies relied mostly on renewable sources of energy, i.e. muscle work, solar energy, wind energy, water energy, and biomass for their functioning, with only anecdotal use of hydrocarbons (oil and gas), for instance the burning of bitumens in the late Roman empire in Constantinople, or the use of gas to evaporate brines and extract salt in China [80, 81].[7] Coal mining and use for thermal purposes started in Europe in the Middle Age in the 12th and 13th century. Britain, partly due to the ability to build a dense network of canals and to the closeness of coal, limestone, and iron deposits, took lead in the extraction and use of coal, with large amounts of coal feeding the growing population of London by the early 1600s [83], and dominated the world's coal extraction until the late 1870s [84]. Besides domestic heating, early industrial applications driving coal consumption were iron-making, glassmaking, and mine draining [85]. Efforts to drain coal mines themselves would lead to the first innovations allowing to convert thermal energy into work; first through the inefficient Newcomen's steam engine (1712), and then, some 60 years later, the Watt steam engine would provide the basis of the Industrial Revolution [83]. Since then, global energy consumption, mostly driven by fossil fuel consumption, has increased at a vertiginous pace, as shown in Figure 1.2.

Such a colossal increase in the supply of fossil fuels has entailed drastic societal changes, although the benefits have been unequally distributed, with some countries, as well as some social groups, remaining at the margins of the material benefits brought about [87]. The recent availability of tremendous amounts of energy has also created new vulnerabilities, as the current organisation of Western societies has become highly dependent on abundant and cheap energy. Whether one thinks of the length and complexity of supply chains, of the high reliance of the agricultural sector on fuels and synthetic fertilizers (often based on fossil gas), of the urban sprawl and planning of Western cities, or of the high dependence on carbon-intensive materials in the construction industry (e.g. steel and concrete), the sectors that rely

[7] Coal is the exception as it was used in substantial quantities well before the Middle Age in specific societies, for instance in the Roman Empire [82], and more remarkably in China, where it was the dominant fuel by the 1000s, used for iron-making, but also for heating buildings [83].

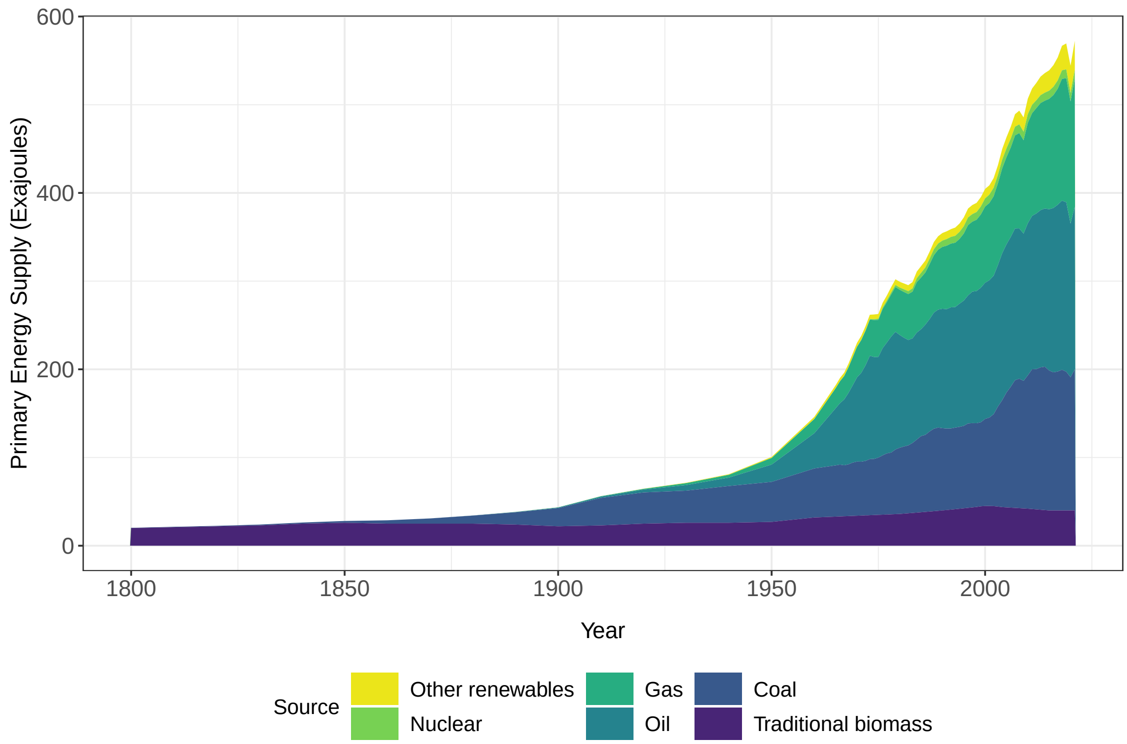

Figure 1.2: Global primary energy supply (1800–2020) by main energy source. Data from Our World In Data, using the "direct method," or "Physical Content Method," in the International Energy Agency's terminology [86].

on enormous amounts of cheap energy are many. The 1970s oil and associated economic crisis were a stark revealer of the vulnerabilities associated with the high reliance of our societies on energy (particularly, fossil fuels), and the present global energy crisis is a bleak remainder that despite the urgency to phase out fossil fuels, the situation has not significantly changed.

Human needs satisfaction and energy use

Acknowledging the strong reliance of society on energy consumption, alongside the threat of climate change and the need to reduce energy consumption, brings about the question of how, and if, energy use can be reduced, or limited, without adversely affecting human well-being. Brand-Correa and Steinberger [88] develop a novel framework to explore this question by bringing together the areas of human well-being and of energy services, i.e. services provided by energy. After noting the limits of a hedonic perspective on human well-being, notably the fact that it may result in ever-growing consumption, Brand-Correa and Steinberger advocate for a eudaimonaic approach to human well-being, which focuses on the possibilities of individuals to flourish, and to take active part within a given society [89].

Further, Brand-Correa and Steinberger [88] adopt a human needs perspective, which “introduce[s] a normative goal of achieving minimally impaired participation in society.” The human needs approach argues that there are basic needs which are universal, objective, non-substitutable, and satiable, the fulfilment of which are prerequisites for living well within society [88, 90, 91]. The means through which those needs are satisfied, i.e. the need satisfiers, are flexible and evolve over time, and depend on the culture and society considered [90]. Needs may then be satisfied through delivered energy services in combination with the needs satisfiers [88]. Energy services are also a flexible concept, as a given energy service may be delivered in different ways, for instance mobility through individual car, public transportation, etc. By recognising the satiable nature of human needs, and the flexibility of energy services and needs satisfiers, the framework introduced by Brand-Correa and Steinberger [88] sheds light on different levers to provide good living standards at low energy use, and can be used as a way to empower local communities through consideration of their specific views of energy services and needs satisfiers [92]. Such a framework opens the way for the quantification of the energy requirements of decent living standards [93–96], and for the exploration of the conditions upon which these may be secured at low energy consumption levels [97–99]. The framework introduced by Brand-Correa and Steinberger [88] is of high value to conceptualise the dependency of human needs on energy use. The next sections will introduce the concepts of net and useful energy, and will argue that the energy valuable for productive and socially beneficial purposes, i.e. to deliver energy services, is the net useful energy available to society.

1.2.2 Harnessing energy takes energy: from gross to net energy

Traditional net energy framework

In the 1970s, in the context of the oil shocks and energy crisis, the high reliance of society on abundant and cheap energy came into the spotlight. In order to identify energy saving opportunities, considerable efforts were made to gain a better understanding of the flows of energy across society and the economy, and particularly, of the energy requirements of goods and services [100–102].[8] This period also saw the emergence of energy input-output analysis as a key method to track energy flows across the economy [106, 107]. This systematic consideration of the energy requirements of goods and services led analysts to study the energy requirements of energy-yielding systems themselves,[9] thereby originating the field of net energy analysis, which distinguishes between *gross* and *net* energy flows. Gross energy refers to the amount of energy supplied by an energy-yielding system, while net energy refers to the remaining energy once the energy required by the energy-yielding system itself has been subtracted. Net energy analysis even reached a prominent place in the the US debate, as shown by the US 1974 Federal Nonnuclear Energy Research and Development Act, which required that "the potential for production of net energy [...] shall be analyzed and considered in evaluating proposals" [109]. Although the field of net energy analysis only took off in the 1970s, it is worth mentioning that the concept of net energy had already been formalised by Cottrell in 1955, (referred to as *energy surplus*), as "the energy available to man in excess of that expended to make energy available" [110].

The Energy Return On Investment (EROI) has emerged as one of the most used metric in net energy analysis. It is simply defined as the energy output of a given energy-yielding system divided by the required energy inputs for the manufacture, operation, maintenance, and decommissioning of the considered system, as simply put in Equation 1.1:

$$\text{EROI} = \frac{\text{Energy output}}{\text{Energy inputs}}. \tag{1.1}$$

It is therefore a metric that represents the efficacy with which a given energy-yielding system delivers energy, and answers the question of how much energy is returned for a unit of energy invested in the considered energy system. This metric is crucial as it defines the scale of the energy system (e.g. the number of oil wells, of solar

[8]These efforts even briefly revived the energy theory of value (see [103]) first developed in the US in the 1920s by the Technocracy movement [104], and according to which the price of products and services should be determined as function of their energy requirements, and which received empirical backing for instance by Costanza [105].

[9]Slesser [100] refers to the Energy Requirement for Energy in 1975, while Hall et al. [108] introduces the now famously known EROI concept in 1979.

panels, etc) required to produce a given flow of net energy to society, as shown in Figure 1.3. When the EROI of the energy system is high, the amount of primary energy that needs to be harnessed to deliver a given amount of net energy to society is only moderately higher than the net energy delivered to society. Conversely, in the case of low EROI energy system, the primary energy that needs to be harnessed is considerably higher than the net energy delivered to society.[10] Section 1.1.3 has argued that the energy transition needs to happen within biophysical limits, hence making the question of the scale of the energy system, and of its EROI, critical.

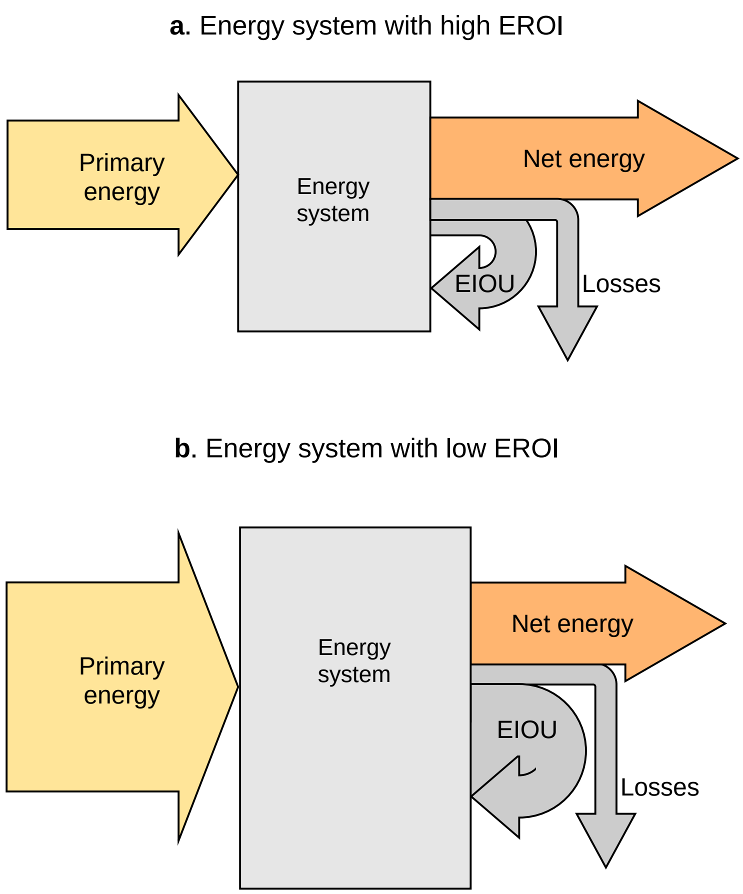

Figure 1.3: Primary energy harvested, net energy delivered to society, energy consumption of the energy system, and size of the energy system, in the case of high and low EROI energy system. EIOU: Energy Industry Own Use.

The EROI metric behaves in a highly non-linear manner, as depicted in Fig-

[10] Strictly speaking, energy losses in the conversion of primary energy to final energy also play a crucial role in defining the size of the energy sector.

ure 1.4, which shows the share of net energy delivered to society as function of the EROI. Such a share only varies moderately at low EROI values, but steeply declines when the EROI decreases to very low values — this abrupt decline has been coined the "net energy cliff" [111]. This dramatic non-linear behaviour has contributed to popularising the EROI concept and net energy analysis, although it makes the EROI a delicate metric to interpret and analyse, as will be further discussed in Chapter 5.

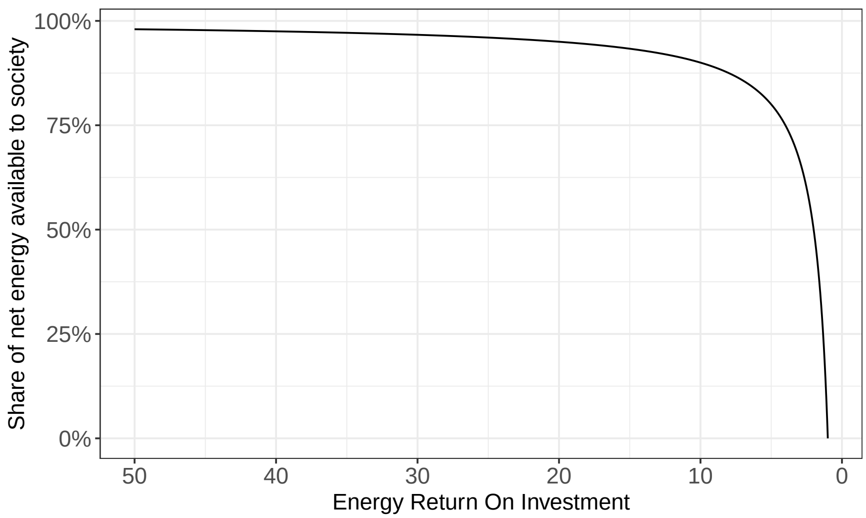

Figure 1.4: Share of net energy available to society as function of the Energy Return On Investment. As the share declines very steeply when the Energy Return On Investment reaches low values, the relationship is also known as the net energy cliff.

Recently, the net energy framework has received considerable attention through the EROI concept for two main reasons. First, authors have highlighted that decreasing net energy returns are a symptom of fossil fuel depletion [111–113], due to the decreasing qualities of the fossil fuel deposits harnessed. When coupling this decrease in net energy returns with the perspective of global oil and gas production potentially peaking in next decades [114, 115], recent studies show that the effects on the future net energy that fossil fuels can deliver to society may be considerable [116–118]. Second, concerns have been raised regarding the net energy implications of the energy transition, as influential studies have claimed that renewable energy systems have much lower net energy returns than conventional fossil fuel energy [119, 120], and questioned whether renewable energy systems may sustain an energy-intensive society [121], or even whether they are net energy yielders [122] (recent works however show that such findings may be misguided, which is further discussed in Section 1.3.1). It is noteworthy that in these two cases, the factor of interest is not so much the absolute value of net energy delivered to society, but rather, the **variation in net energy** that may be expected as a result of either fossil fuel depletion or the energy transition.

Materials also take energy: expanding the framework

The energy analysis community made clear in the context of the 1970s oil crisis that the production of raw materials consumes large amounts of energy [101, 102]. If, following the industrial ecology and ecological economics tradition, the economy is considered as a system that needs energy and raw material inputs for its functioning [123, 124], the energy requirements of producing raw materials could be discounted from the net energy available to society. Indeed, the raw materials are not valuable by themselves, but become valuable once transformed, and embedded in infrastructure, consumable goods, etc. But drawing the line of the quantification of net energy may then become complex: where should one stop? I have argued in the previous section that it is not so much the determination of the net energy available that is crucial, but rather, the determination of its variation over time. Thus, to decide whether the energy requirements of producing raw materials need to be considered in the net energy framework, one needs to answer the following question: *is there evidence to believe that the energy requirements of producing raw materials may increase in the future, hence decreasing the amount of net energy available to society?*

As noted in early studies back in the 1970s, and as will be further discussed in Section 1.3.2, the process of mineral depletion will entail increasing energy requirements of mining minerals, as the mining industry needs to move towards deposits of decreasing qualities [100, 125, 126]. Hence, there is evidence that the energy requirements of *mining* raw materials may have an effect on the net energy available to society. In this thesis, I will therefore expand the traditional net energy framework to account for the energy requirements of mining (see Appendix B for a clear definition of what is understood by *mining*), and of how these may vary as a result of mineral depletion. Figure 1.5 shows the expanded net energy framework.

Figure 1.5: Net energy framework expanded with consideration of energy consumption of mining activities. EIOU: Energy Industry Own Use. MIOU: Mining Industry Own Use.

1.2.3 Not all energy is valuable: from final to useful energy

Energy analysis tracks energy flows accross the Energy Conversion Chain (ECC) from their extraction from the environment to their end-use. Three stages of the ECC need to be clearly differentiated. First, primary energy refers to energy extracted from the environment (e.g. oil extracted from a well, solar radiation captured through solar panels, etc), which usually requires further transformations prior to its utilisation. Second, final energy (or energy at the point of use) refers to energy delivered and used by the end-user (e.g. gasoline used in a vehicle, electricity used in a light bulb, etc). Third, useful energy refers to the energy that is exchanged for energy services after conversion in an end-use device (e.g. the motion of a vehicle, the heat warming up a house, or the light given by a light bulb). The conversion of primary energy into final energy may consist in a more or less complex chain of processes (including the transportation of energy), depending on the conversion chain considered, while the conversion of final energy into useful energy occurs within a single end-use device. Each of these transformations involves losses, so that the useful energy eventually delivered by the ECC is only a fraction of the primary energy extracted from the environment. Indeed, Cullen and Allwood [127] show how the useful energy delivered by end-use devices in 2005 was barely 12% of the primary energy harvested.

Cullen and Allwood [128] further define *passive systems*, to which useful energy is delivered, and within which useful energy provides energy services. Such an expansion of the ECC is crucial, because the same amount of useful energy may deliver a very different energy service depending on the passive system used — one can think of the difference in terms of warmth provided when using the same amount of heat in poorly insulated building versus a newly retrofitted building, or in terms of passenger-kilometers delivered when using a unit of energy with a car versus a bus, or even versus an electric bike. Figure 1.6 shows a graphical representation of the ECC, from primary extraction to the delivery of energy services. This thesis will conduct the analysis until the useful energy stage, as it is the last stage which can be quantified in purely energy units, and which does not involve subjective judgment on the measure of the service delivered — see the recent work of Lawley [129] on the potential of framing energy demand reduction in terms of energy services to reduce energy consumption in the UK.

Expanding energy analysis to the useful stage of energy use was also fostered by the context of the oil and energy crisis in the 1970s, with the aim of identifying energy saving opportunities. The 1975 American Institute of Physics report on "Technical Aspects of the More Efficient Utilization of Energy" was a landmark study for energy analysis at the useful energy stage, which adopted the exergy quantification of energy as measure of energy at the useful stage [131, 132].[11] Also in 1975, Reistad [134] published the first economy-wide analysis of energy flows until the useful stage. This first economy-wide study was inspirational for the field of Societal Exergy Analysis (SEA), which has been at the forefront of economy-wide energy and exergy accounting until the useful stage in recent years — see Brockway et al. [135] for a review.

Considerable efforts have been carried out by the SEA community to develop and refine methods to quantify energy and exergy flows at the useful stage since the

[11] Exergy is a quantification of energy that accounts for the fact that not all energy forms are of the same quality, and measures the amount of physical work that can be done with a given energy flow. In other words, exergy quantifies energy by its work potential, instead of its usual quantification in terms of heat potential [133].

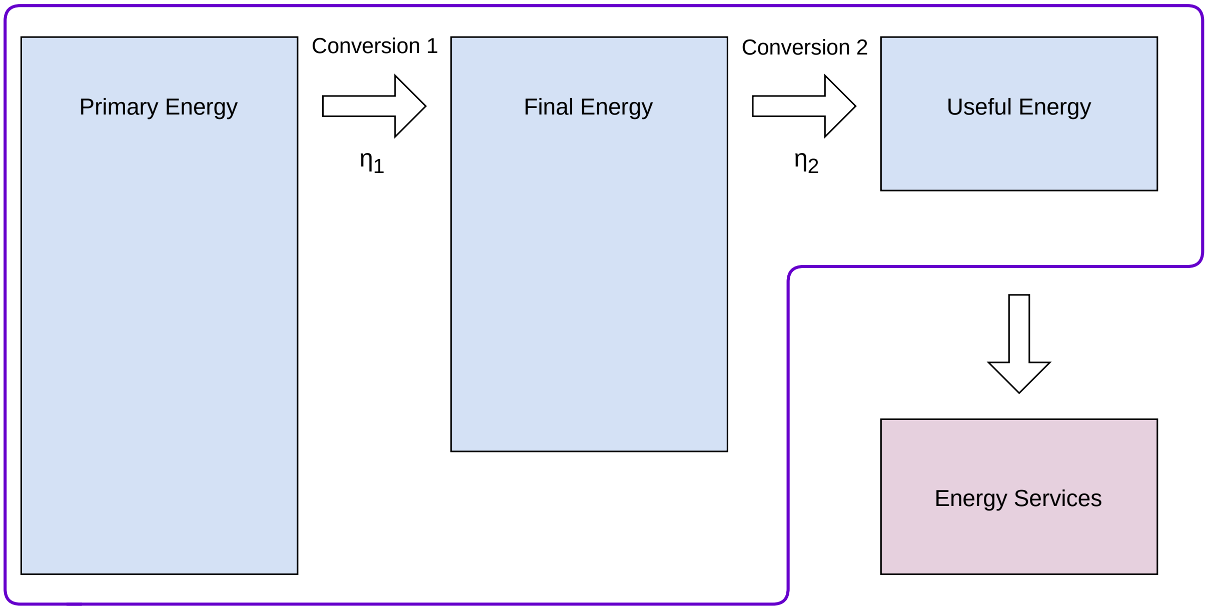

Figure 1.6: Representation of the Energy Conversion Chain, where η_1 and η_2 represent respectively the energy efficiencies of the first and second conversion process. The purple, solid line represents the boundaries of the ECC considered for this thesis. Adapted from Aramendia [130].

seminal work of Ayres and Warr [136] (see for instance [133, 137–140]). The field has then moved on to the study of the role of energy (more specifically, useful exergy) in the economy, originating the novel field of exergy economics. Ayres and Warr [141] first showed that accounting for useful exergy as a factor of production can successfully account for the part of economic growth usually left unexplained (through the Total Factor Productivity) in neoclassical Aggregate Production Functions. Santos et al. [142] recently confirmed this result using a co-integration approach and the most up-to-date econometric techniques, and were able to establish this finding with a more standard form of production function than the one used by Ayres and Warr [141]. The exergy economics literature also showed how the energy intensity of the economy (i.e. energy consumption divided by economic output, usually measured as GDP) tends to be much more stable when computed in terms of useful exergy than when computed in terms of primary or final energy [139, 143], thus suggesting a strong link between energy at the useful stage and economic output. Sakai et al. [144] used an econometric model to show that increasing final-to-useful efficiencies (which cause an increase in the useful exergy available) can account for 25% of economic growth in the UK, for the period 1971–2013.

Considering the fact that it is useful energy that is exchanged for energy services, it seems sensible to consider that useful energy is the energy valuable for productive and socially beneficial purposes. In addition, the recent findings of the exergy economics literature mentioned previously strongly corroborate this premise, as useful exergy, i.e. a particular quantification of energy at the useful stage, has been found to be strongly connected with economic output, i.e. productive activities. This work will however use the conventional quantification of energy in terms of heat potential, with the aim of engaging the broader net energy community. Combining the net energy and the useful stage approaches thus seems crucial to obtain a robust understanding of the flow of energy valuable to society, and leads to the formulation of the *net useful energy* framework, which is represented in Figure 1.7.

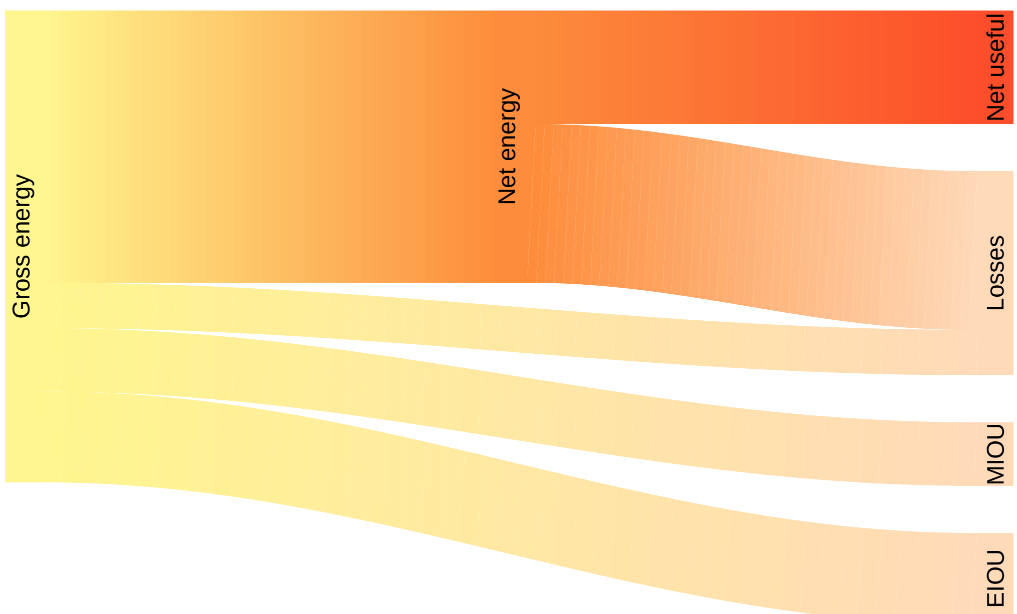

Figure 1.7: Net useful energy framework adopted in this thesis. Net useful stands for net useful energy. EIOU: Energy Industry Own Use. MIOU: Mining Industry Own Use.

1.3 Net useful energy available to society: a review of its determinants

1.3.1 Net energy analysis: the thorny question of boundaries and methodology

The flow of net energy delivered to society is defined as the sum of energy delivered by the energy system, minus the energy invested in the energy system itself, at a given time. Such a flow is therefore intrinsically dynamic, and may vary as a result of the investments in the energy system, and as function of the energy mix. Conducting a static analysis of the energy system is a crucial preliminary step to a dynamic analysis of the evolution of net energy flows. The question of the net energy returns of energy systems has been principally analysed through the EROI metric, already introduced in Section 1.2.2.

Boundaries for EROI calculations: inputs and outputs

The most influential study in the definition of standardised boundaries and terminology for EROI calculations is probably the article of Hall et al. [119]. Figure 1.8 illustrates the EROI definitions and associated boundaries introduced by the authors, which can be summarised as:[12]

- The standard EROI, or $EROI_{st}$, which computes the EROI at the primary extraction stage, e.g. at the mine mouth, well head, or farm gate.
- The point-of-use EROI, or $EROI_{pou}$, which includes the energy requirements of refining (when needed) and transporting the energy carrier to the end-user, and is therefore an EROI calculated at the final energy stage.
- The extended EROI, or $EROI_{ext}$, which further expands the boundary of energy inputs to include the energy required to use the energy carrier. For instance, the energy requirements of building the road may be considered, as the road is required to use the gasoline in a car.

[12] In addition, the authors also present the societal EROI, which would be the EROI obtained when summing the energy delivered by all energy carriers in a given society, and dividing by all the energy required to produce these.

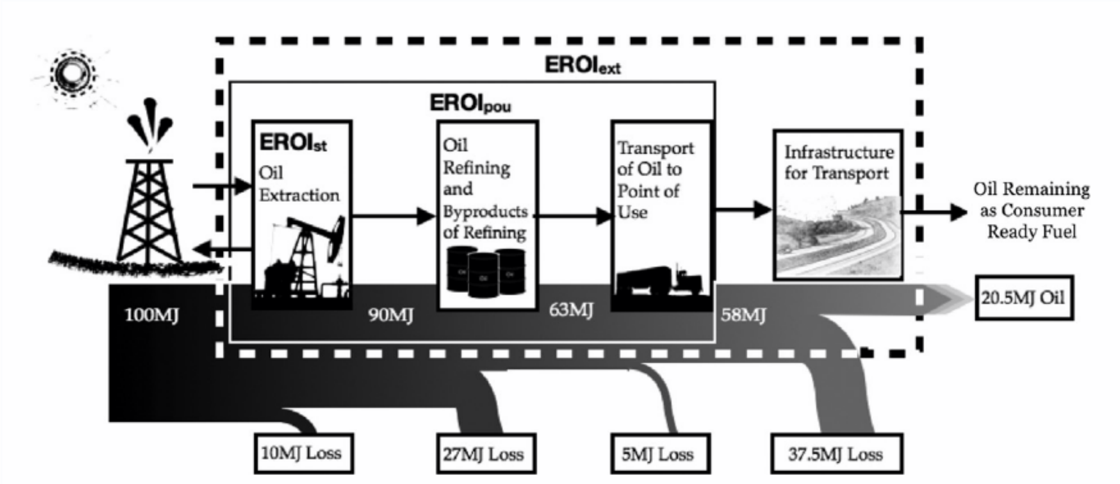

Figure 1.8: Different boundaries for the calculation of Energy Return On Investment, with the example of the oil supply chain. Figure extracted from Lambert et al. [145].

However, the boundaries and terminology introduced by Hall et al. [119] do not explicitly differentiate the different boundaries of EROI calculations. Indeed, two boundaries can (and I argue should, for the sake of clarity) be clearly differentiated: first is the stage at which the energy output is quantified, i.e. primary, final, or useful. Second is the level of energy inputs considered, i.e. which energy requirements are estimated and included in the computation of the EROI, and which are omitted. Murphy et al. [146] suggested a bidimensional framework to explicitly account for these two dimensions, which has recently been adopted for instance by Feng et al. [147]. For the sake of consistency with the view of the ECC introduced in Section 1.2.3, I will refer to EROIs at different output stages as primary stage, final stage, and useful stage EROIs, instead of the standard and point-of-use EROIs terminology. Note that no assumption on the level of energy inputs considered is implied by the primary, final, and useful stage terminology. Figure 1.9 shows the bi-dimensional framework to establish EROI boundaries, with an example of the energy inputs levels that may be considered.[13]

There may also be variations in the convention used to quantify energy flows.

[13]Note that additional levels can be added by the analyst in both dimensions. For instance, the energy output may be quantified after all conversion processes, but prior to transportation to the end-user, or the energy requirements for the decommissioning of facilities may be added as an additional level if those are not included in the other levels — note that the definition of the energy inputs to consider can be particularly cumbersome [148].

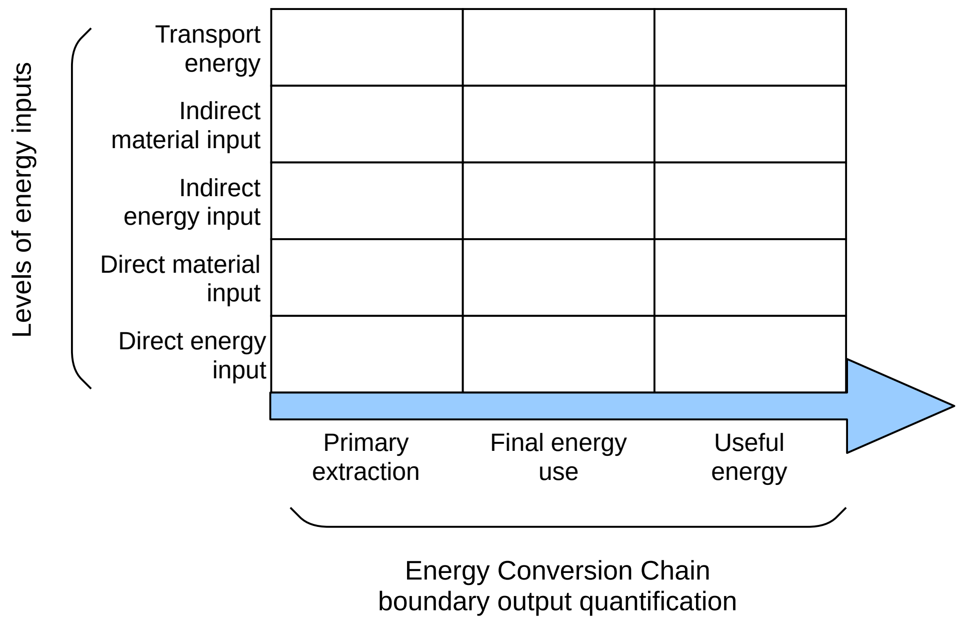

Figure 1.9: Example of bidimensional framework for the calculation of EROIs. On the horizontal axis, the energy stage at which the output is quantified; on the vertical axis, the level of energy inputs considered. Inspired from Murphy et al. [146] and Feng et al. [147].

For instance, some studies may adjust final energy output to calculate a primary energy equivalent (this method has been particularly used for calculating the EROI of electricity from renewable energy origin [149–151]). The fact that many EROI studies are based on process analysis using a Life Cycle Analysis methodology has meant that numerous studies tend to quantify energy inputs in terms of primary energy requirements.[14] Some studies may also adjust energy flows accounting for their quality; for instance, a recent study quantified energy flows in terms of exergy content [153]. These methodological choices, which define how the defined energy flows will be quantified, are essential to take into consideration, particularly when comparing EROI values across different energy systems and methods. However, the definition of boundaries, which define which energy flows will be considered, is even more critical.

[14]Life Cycle Analysis has a standardised approach to calculate the Cumulative Energy Demand (CED) of a given system — in primary energy terms — which give a good basis for computing the EROI. The CED however needs to be adjusted as it includes the primary energy harvested from the environment (for instance, the energy of the oil extracted), while the energy requirements used for EROI calculations exclude these [152].

Last, the temporal profile of energy inputs and outputs are important, even when conducting a static EROI analysis, because temporal aspects will be crucial for a dynamic analysis of the net energy available to society. Energy inputs and outputs are usually computed throughout the whole life cycle of a given project (or of a given functional unit following the Life Cycle Analysis approach, for instance the production of a unit of energy). The energy output will typically be delivered over the operational lifetime of the project, while energy inputs may happen at different times depending on whether they are associated with capital investments, operational requirements, or decommissioning — Figure 1.10 shows a possible profile of energy outputs and inputs. Renewable energy systems tend to have much greater upfront energy requirements, i.e. energy requirements associated with capital investments, than fossil fuel energy, which may be of crucial importance in the context of a large and fast deployment of renewable energy systems.

Criticality of boundaries

Traditionally, renewable energy systems have been considered to have much lower EROIs than fossil fuel energy, due to a handful of particularly influential studies (see e.g. [119, 120]). However, recent work has shown that such an analysis is based on inconsistent comparisons whereby the primary stage EROIs of fossil fuels is compared to the final stage EROI of renewable energy systems [111, 150, 155], at least in the case of solar photovoltaic and wind power energy. Indeed, a very large share of the energy requirements of the fossil fuel industry happens in the conversion of primary energy into final energy, so that conducting the analysis at the primary stage disregards most of the energy requirements [156–158], and invalidates any comparison with renewable energy systems — although it may remain useful to study the effects of fossil fuel depletion on the energy requirements of their extraction [112, 113, 156].

Even though the fact that renewable energy systems have much lower net energy returns than fossil fuels has been seriously questioned recently, numerous energy-economy models adopting a net energy perspective still ascribe much lower EROIs to renewable energy systems than to fossil fuel energy, showing the pervasiveness of the low-EROI renewable energy conception [75, 77, 159]. An additional reason why renewable energy systems have been found to have much lower EROIs than fossil fuel energy has been the energy requirements of dealing with the intermittency associated

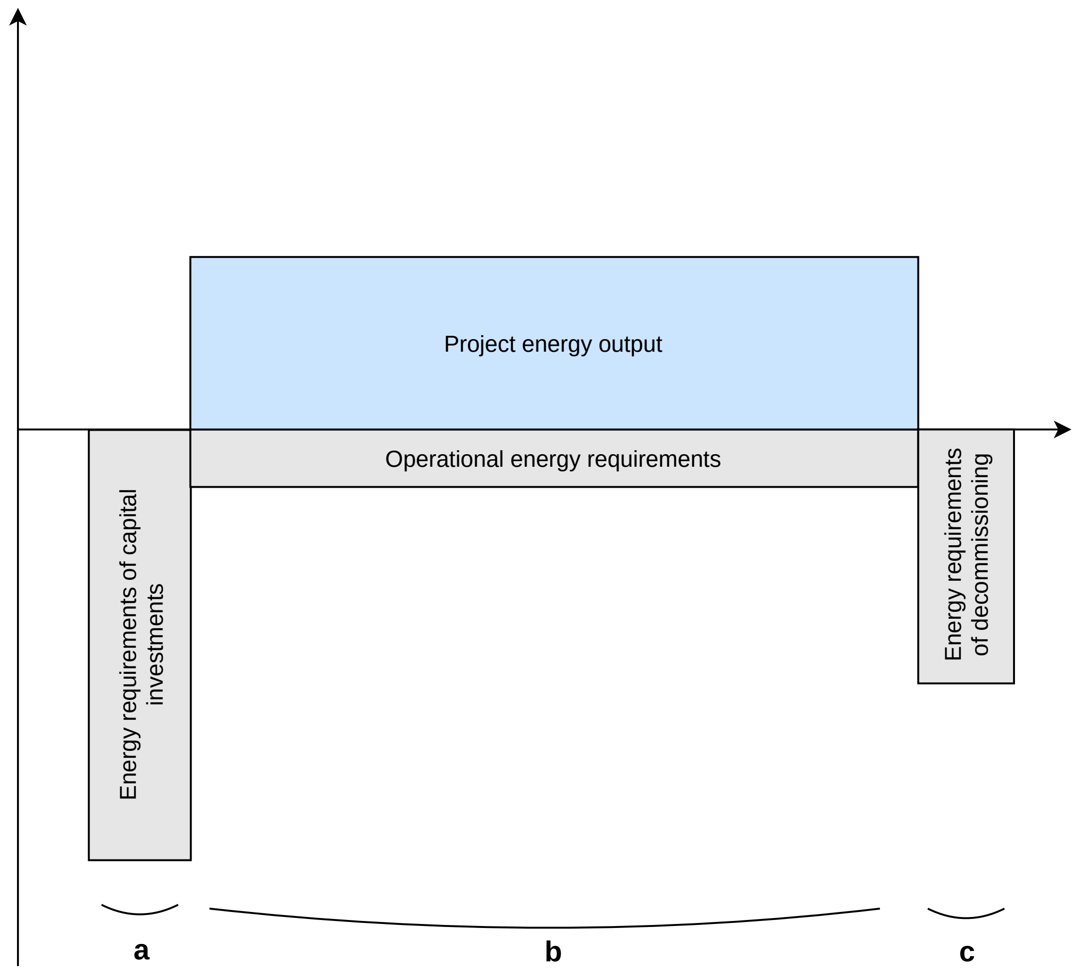

Figure 1.10: Example of profile of energy inputs and outputs for a given project, inspired from [154]. The high energy requirements associated with capital investments and relatively low operational energy requirements would be typical of a renewable energy project such as a solar photovoltaic or wind power farm. **a,** construction phase, **b,** operational lifetime, **c,** decommissioning phase.

with renewable energy systems (solar energy and wind power), which brings back the thorny and crucial of boundaries. Indeed, Weißbach et al. [160] find very low EROIs for renewable energy systems once the effects of intermittency are taken into consideration. However, the energy requirements of dealing with intermittency cannot be ascribed to a specific energy technology, as these are function of the whole energy system (energy mix, technologies chosen, etc) [161, 162], and as these increase in a highly non-linear way, from being insignificant to increasing exponentially at high penetrations of intermittent renewable energy systems [163–165].

Based on this up-to-date review of the literature, a few factors will be of critical importance for the future evolution of the net energy available to society. First, the extent to which the primary stage EROI of fossil fuels will decrease will be an important factor, although the relatively low weight that the primary extraction represents in the energy requirements of the fossil fuel industry will tend to mitigate this effect, particularly considering that there are still significant energy efficiency opportunities in primary-to-final refining processes [166]. Second, the difference in terms of EROIs between fossil fuel energy and renewable energy systems will also be an important factor in the evolution of net energy. Although recent studies tend to find EROIs of similar magnitudes and values, those of renewable energy systems are heavily dependent on methodological choices, as well as, geographical location, and there is no consensus on their values. Third, the dynamic aspects will be crucial too, as renewable energy systems tend to have much more upfront energy requirements than fossil fuel energy. Indeed, most energy requirements for renewable energy systems are associated with capital investments, while most energy requirements for fossil fuels is associated with operational expenditures. This fact, combined with the high pace at which renewable energy technologies need to be deployed, may entail a temporary drop in the net energy available as the transition unfolds [58, 74].

1.3.2 The increasing energy requirements of mining

Conceptualising mineral depletion

Reserves and resources are crucial concepts to discuss mineral depletion. Figure 1.11 shows a graphical representation of reserves and resources, where reserves are a subset of resources. Although the exact definitions vary from institution to institution, "reserves" usually refer to the amount of a given mineral currently identified[15] that

[15] As for resources, note that there are many nuances in reserves. According to the US Geological Survey [167], these can be measured (quantity computed from detailed samplings), indicated (similar to measured, with further apart sampling sites, so that there is more uncertainty), demonstrated (sum of measured and indicated), or inferred (estimates based on an assumed continuity beyond demonstrated reserves), and they can be economic (profitable extraction is demonstrated, or assumed with reasonable certainty), or marginally economic (part of reserves which are at the margins of being profitable to extract) [167]. The reserve base concept is also an important concept that refers to demonstrated reserves, marginally economic reserves, and the share of subeconomic

could be technologically and economically recovered, with current technology and economic conditions. Conversely, "resources" usually refer to the amount of a mineral that could potentially be one day recovered, and includes the amount that presently can be extracted, i.e. reserves.

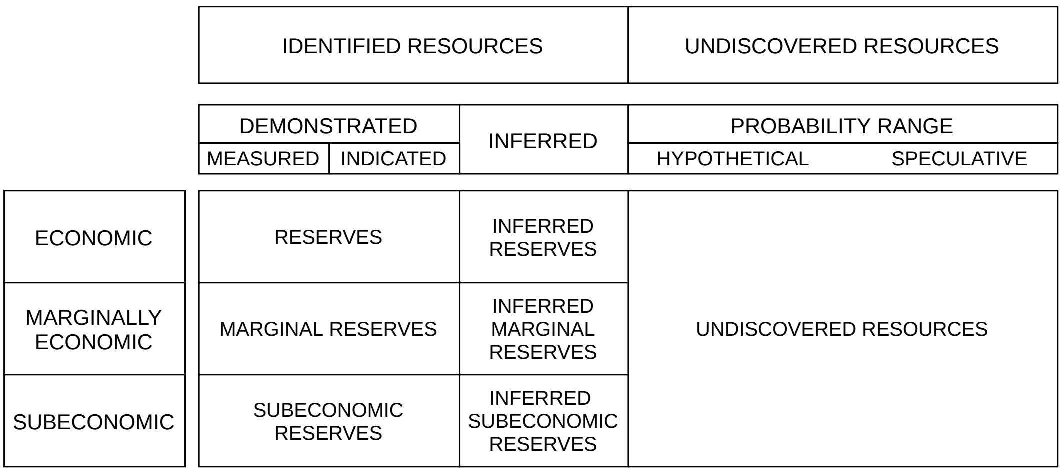

Figure 1.11: Representation of reserves and resources, adapted from the US Geological Survey [167].

The fixed-stock paradigm. A first way to conceptualise mineral depletion, and referred by Northey et al. [66] as the "fixed-stock paradigm," is to consider that reserves and resources are fixed, and that the tonnage of a mineral that will ultimately be extracted are comprised between the reported values of reserves and resources. Approaches aiming at determining the remaining years of supply by estimating the ratio of extractable mineral over the current extraction are a good example of this static conception of reserves and resources [168]. By comparing the required cumulative extraction to reserves and resources, the majority of studies exploring future material requirements implicitly adopt this approach, often because modelling future supply and availability is extremely complex and uncertain [66], and because current reserves and resources may be used as non-speculative indicator of the amount of minerals that there is currently knowledge of, and to which material requirements may be compared. The view of a fixed, deterministic, and *a priori* defined level of Ultimately Recoverable Resources (URR) has motivated

resources for which the potential to become economically available is reasonable.

studies to project the extraction of different minerals over time following the Hubbert's peak approach[16] [171–174], although the forecasts are highly sensitive to the URR adopted [173–175].

The opportunity cost paradigm. However, it has been argued that as reserves and resources are dynamic concepts at the intersection of geological, technological, and economic factors, considering the URR as fixed, and *a priori* determined, is neither appropriate nor realistic [61, 176], as reserves and resources are "only a small subset of "all there is"" [64]. The "opportunity cost pardigm" defends that there is no fixed limit to the amount of extractable minerals, as "once cheaper to develop resources are depleted then any unmet demand will result in an increase in market prices, thereby making marginally higher-cost resources still economic to develop and extract" [66]. The opportunity cost paradigm is therefore a market-based approach, according to which the determining factor for the amount of minerals that will be ultimately extracted is the opportunity cost of extraction, i.e. what society is willing to give up to extract an additional unit mass of a mineral. Proponents of the opportunity cost paradigm define "cumulative availability curves," which represent the opportunity cost, expressed in monetary unit, as function of the cumulative extraction of a given mineral, to represent the fact that the opportunity cost of mineral extraction will increase as a result of mineral depletion [65]. Hence, according to the "opportunity cost paradigm," what will define the eventual quantity of mineral extracted (or URR) is not purely physical availability, but the interaction of geological, economic, social, and political factors, and of the opportunity cost that society is willing to pay to carry on extracting.

Combining perspectives: declining returns of mining, and increasing energy requirements. Although the opportunity cost paradigm perspective seems sensible, it often leads to a techno-optimistic perspective, where technology will allow the mining industry to keep extracting amounts virtually infinite, and where physical constraints only play a marginal role, i.e. moderately increasing extraction costs before technological improvements offset these effects. Indeed, by considering

[16] Hubbert [169] proposed a model to forecast future oil production following a symmetric, or bell-shaped curve. He successfully forecasted the US oil production to peak around 1970, although his predictions were not as accurate at the global level. His work inspired numerous authors and studies, see for instance the very famous "The End of Cheap Oil" paper [170].

the whole crust as a potential resource, the opportunity cost paradigm considers the geological endowments as virtually infinite, but disregards the consequences of extracting deposits of decreasing qualities. Conversely, a physical view of depletion emphasises that extracting minerals from deposits of decreasing qualities will considerably increase the energy requirements of extraction. Pioneers of this perspective defended in the 1970s that such increasing energy requirements will determine the ultimate limit to the amount of minerals that can eventually be extracted [125, 126]. In other words, "the discussion about mineral resource depletion is as much about falling resource quality and accessibility as it is about a reduction in resource quantity and availability" [177], and about the energy implications of such falling quality and accessibility. In a more recent study, Bardi [178] defends that energy is a fundamental factor for mining, and that due to future energy constraints and increasing energy requirements of mining, "the production of mineral commodities is destined to decline in the future." More recently, Pigneur [179], broadens this conceptualisation: "the depletion of metallic resources, beyond the questions of economic limits of extraction, is a multiplier of the social and environmental costs generated by our current ways of production and consumption" [179].[17]

Following this perspective, I argue that the issue of mineral depletion is better understood as an issue of declining returns in the mining sector, i.e. a process whereby the required inputs (water, energy, chemicals) — as well as environmental damage and externalities caused — per unit mass of valuable mineral extracted tend to increase over time. And particularly, mineral depletion and decreasing deposit qualities can be expected to increase the energy requirements of mineral extraction through different mechanisms. Decreasing ore grades have a direct effect on the quantity of ore that needs to be extracted, moved, hauled, and crushed to obtain the same amount of valuable mineral, and hence increase the energy requirements of mining [67]. Decreasing deposit qualities may also translate in decreasing grinding sizes, i.e. the size to which the mineral particles need to be reduced to liberate valuable minerals from the rest of the ore, which considerably increases the requirements of milling and grinding [180]. Other factors related to decreasing qualities of mineral deposits that may increase the energy requirements of mining include increasing mine depths reducing the accessibility of deposits [181], or increasing rock hardness [126].

[17] Own translation. By *costs*; understand non-monetary costs.

The increasing energy requirements of mining

A trend of decreasing ore grades has been shown both at the level of individual mines and companies [182], and whole countries [183], for a wide range of metals, including copper [182], nickel [184], gold [185], zinc-lead ores [186], or platinum group metals [187]. Accordingly, Topp et al. [188] identifies the decline in mineral deposit qualities (e.g. in ore grades) as a factor hampering the productivity of the mining sector in Australia. The quantifications of the corresponding increasing energy requirements of mining remain however scarce, although a clear trend can be identified from the literature. Calvo et al. [182] uses company and mine level data to show that the average energy intensity of copper mining, in the analysed mines, has increased by 12% from 2003 to 2013, representing an average yearly increase of 1.1%. Calculating the yearly energy intensity of copper mining from the data provided by the Chilean Copper Commission [189] yields an increase of 66% from 2001 to 2019, representing an average yearly increase of 3.0%. Last, Rötzer and Schmidt [190] explore the effect of technological improvements on the energy intensities of copper mining over time with a process-based approach. The authors find that although energy intensities of copper mining significantly decreased from the 1930s to the 1970s as a result of technological improvements, copper mining intensities increased by approximately 30% from the 1970s to the 2010s, and that the effects of technological improvements have been much more moderate.

Overall, the literature shows that in recent years, and in the case of copper, the influence of geological factors and of mineral depletion have been dominant over those of technological progress. This trend of increasing energy intensities of mining can be expected to persist, as technological improvements are ultimately limited by thermodynamic and practical limits, for instance in terms of energy efficiency [191, 192]. The extent and pace at which the energy intensities of mining will increase depend on the ore grade-tonnage distributions[18] of each mineral [193], for which the uncertainty is considerable — see further discussion in Appendix B — but will be much more significant for minerals mined at low concentrations, as the energy consumption of comminution (ore milling and grinding) evolves as a function of the inverse of ore grade [67].

[18] A distribution, or function, representing the tonnage available of a given mineral at a given ore grade.

1.3.3 Energy at the useful stage: the key role, and yet uncertain future, of final-to-useful efficiencies

As discussed in Section 1.2.3, the energy efficiencies of processes and devices are key to determine the energy ultimately valuable to society, i.e. useful energy. Although these have increased significantly in the past as a result of technological progress, there are theoretical (thermodynamic) limits [127], as well as technical limits [192], to the energy efficiency of processes. The US Department of Energy has also highlighted the existence of such limits in a series of energy bandwidth studies (see for instance [194, 195]). The remaining scope for improvement is highly variable from process to process; whereas there are still some large energy efficiency improvements possible in the metallurgical sector [194, 195], these seem to be much more limited in the automotive sector, as the efficiency of an Internal Combustion Engine (ICE) is relatively close to its technical efficiency limit [192]. We note however, that a more *effective* use of energy may still be possible with more effective passive devices [128] (see Section 1.2.3), for instance using smaller, lighter cars, which would consume less energy per passenger kilometre.

Equally insightful can be the study of the evolution of aggregate efficiencies at the country level. The SEA community has put significant efforts in tracking energy and exergy flows across energy stages, from primary to useful, at the national level, and hence offers valuable insights on the evolution of these aggregated efficiencies at national levels.[19] Williams et al. [196] first identified a trend of stagnating aggregate efficiency for the case of Japan in recent years, and coined this trend the *dilution effect,* whereby "successive adoption of less efficient technologies led to dramatically reduced improvements in net efficiency, in some cases even an overall decline." In other words, even if the efficiency of individual devices keeps increasing, the penetration of less efficient technologies constrains, or even decreases, the aggregate efficiency of conversion processes. Warr et al. [197] confirmed this trend for Japan and further identified it for the US. Brockway et al. [137] also identified this effect for the US and the UK, with aggregate primary-to-useful (exergy) efficiencies levelling off at approximately 11% and 15% for respectively the US and the UK.

[19] We note that the definition of efficiency, e.g. whether it is an energy or exergy efficiency, and whether it is a primary-to-useful, or final-to-useful efficiency, differs from study to study. For the sake of simplicity, in the remaining of this section I use the general term "efficiency" to include all these nuances, which are not essential for the point I make.

Guevara et al. [198] also identified this trend of stagnating efficiencies in Mexico, in the 2003–2009 time period (the study only covers data until 2009). Such a trend has however not been identified in the case of China [199] or Ghana [200], pointing to significant divergence in trends across countries.

The existence of technical limits for energy efficiency, and the trends of stagnating aggregate efficiencies in a range of countries suggest that efficiencies may not increase significantly in the future, and may not be a critical determinant of the future evolution of the useful energy delivered to society. However, there are also reasons to believe that efficiencies may have the potential to significantly increase in the future. First, and as pointed out, there are still significant efficiency gains possible in many sectors and processes, such as the metallurgical sector. In addition, and as increasing energy efficiencies is a key lever in the conventional approach to reduce greenhouse gas emissions, significant improvements in specific end-use efficiencies may be expected as climate change mitigation becomes a priority — the evolution of the economy-wide efficiency will however heavily depend on the mix of end-uses, as evidenced by Pinto et al. [201] in the case of electricity.

Second, the process of electrification may cause energy efficiencies of given end-uses to significantly increase, which is the thesis defended by Eyre [202] when they advocate for reconceptualising the energy transition as the transition from an energy system based on heat to an energy system based on work. If we take the example of the automotive sector, while the standard energy efficiency of an ICE is in the range 21–35%, the one of an electric motor is in the range 86–96% [192]. Similarly, the large expected uptake of heat pumps, which could be used for low and medium temperature (up to 160°C [203]) heating, may significantly drive upwards average final-to-useful energy efficiencies, as such devices would usually yield around four times more heat than the electricity input, "because most of the heat is transferred rather than generated" [204].[20] To conclude, although current trends show a slow-down in the evolution of energy efficiencies, there are reasons to believe that these may considerably increase as a result of the energy transition.

[20] The ratio of useful heat to electricity is called a coefficient of performance in the case of a heat pump, but is akin to a final-to-useful energy efficiency, if the useful energy is considered to be the heat delivered.

1.3.4 Gaps addressed by this thesis

In the previous sections, I have shown that energy is key to human societies. Particularly, energy is a key driver of growth, and a key enabler of development as well as human well-being in human societies. More specifically, it is the net useful energy available to society that is ultimately valuable for productive and socially beneficial purposes, i.e. the net energy, to which the energy required for mining raw materials is subtracted, quantified at the useful stage. In this section, I identify and discuss three key gaps regarding the future evolution of the net useful energy available to society in the context of the global energy transition and of mineral depletion:

- the lack of assessment of future pathways for the mining industry's energy consumption;
- the lack of comparison of the net energy returns of fossil fuel-based carriers with those of renewable energy technologies at the useful stage of energy use;
- and the lack of assessment of the effects of mineral depletion on the net energy returns of renewable energy technologies.

Gap 1: The unknown future energy consumption of the mining industry

As discussed in Section 1.1.3, low-carbon technologies are heavily reliant on a wide range of minerals, and the material requirements of the energy transition will be considerable. In addition, economic growth has been to date strongly correlated to resource use and extraction, and the evidence of decoupling materials use from GDP growth at the global level remains to date very thin [18, 205, 206]. Future economic growth can therefore be expected to further exacerbate mineral demand and extraction. Increasing mineral demand due to the energy transition and economic growth, combined with increasing energy intensities of mining (Section 1.3.2), suggests that the mining industry energy consumption will significantly increase in the future. However, energy consumption in a low-carbon future is supposed to remain at close to current levels (Section 1.1.2). A surge in the energy requirements of mining activities may therefore either jeopardise climate targets, or decrease the net useful energy available for society. Understanding the magnitude of these threats requires an understanding of the current scale of the mining industry energy consumption, and of the possible future pathways for such energy consumption.

There are so far few estimations of the current global energy consumption of the mining industry. The International Energy Agency provides an estimate of such energy consumption (slightly below 1% of global final energy consumption) in the World Energy Extended Balances (WEEB) [207]. However, such an estimate only accounts for the direct energy requirements of the mining industry (i.e. energy consumption *in-situ*), and excludes the indirect energy requirements of the mining industry (energy consumption embodied in the industry's supply chain). Holmberg et al. [208] attempted an estimation of the global energy consumption of the mining industry using a top-down approach based on the IEA dataset (hence also excluding indirect energy requirements), and found the global energy consumption of the mining industry to be approximately 3–4% of global final energy consumption. However, I have argued in Section 1.3.2 that a feature of mineral depletion is the increase in inputs required per extracted unit mass of valuable mineral, so that the embodied energy requirements can also be expected to increase as a consequence of mineral depletion. Hence, I argue that the quantification of indirect energy requirements is crucial to estimate the future energy consumption that may be diverted from other societal uses by the mining industry as a result of mineral depletion.

Other studies have quantified the global energy consumption of primary metal production, using a supply chain perspective, which accounts for both direct and indirect energy requirements. For instance, Bardi [178] estimates that primary metal production accounts for 5–10% of the total primary energy consumption; Bihouix and De Guillebon [209] estimates the value to be in the range 8–10% of total primary energy consumption; and Nuss and Eckelman [210] finds primary metal production to be responsible for approximately 10% of global primary energy consumption in 2008. All these studies, however, do not differentiate energy requirements for mining activities and downstream metallurgical processes,[21] which is crucial to understand the impacts of increasing energy intensities on the net useful energy available to society.

Last, a series of studies have attempted to quantify the future energy consumption and environmental impacts of primary metal production, and to do so, have accounted for the effects of increasing energy intensities of mining. A first set of studies have quantified such effects using exogenous projections for the ore grades of

[21] This explains the large difference with the IEA estimates mentioned above. Nuss and Eckelman [210] also differentiates when doing the Life Cycle Analysis of each mineral where possible.

mined deposits, and have then linked ore grades with energy intensities of mining using Life Cycle Analysis data. For instance, Van der Voet et al. [211] has assessed the energy consumption of primary metal production for a seven major metals. Kuipers et al. [212] and Dong et al. [213] used a similar method to estimate the future environmental impacts of copper production, respectively globally, and in China. A second set of studies have estimated the environmental impacts of copper production by constructing ore grade-tonnage distributions, whereby the cumulative extraction copper is linked to the ore grade of the mined deposit. The energy intensities of mining are then derived as function of cumulative extraction using a relationship between ore grade and energy intensity established from Life Cycle Analysis data. Elshkaki et al. [214] and Ciacci et al. [215] have done so respectively globally and for the EU28. Last, Harmsen et al. [216] has sought to determine the impacts of mineral depletion on the net energy returns of renewable energy technologies using this methodology, which is further discussed in the next section.

Hence, there is currently **no estimation of future pathways for the mining industry energy consumption that simultaneously takes into consideration (i) the wide range of minerals currently mined, (ii) the mineral requirements of the energy transition, and (iii) the effects of mineral depletion on the energy intensities of mining**, although such estimation would be crucial to assess the extent to which mining activities can be expected to divert energy from the net energy available to society. This is the first gap this thesis will attempt to address.

Gap 2: The missing comparison of the net energy returns of fossil fuels and renewable energy technologies at the useful stage of energy use

I have argued in Section 1.2.1 that the energy ultimately valuable for productive and socially beneficial purposes is not directly the net energy available, but the downstream net useful energy available, i.e. energy after conversion in its useful form in an end-use device. It is crucial to note that different energy carriers are converted into useful energy with different final-to-useful efficiencies, depending on the end-use considered and on the end-use device utilised. As the energy transition will entail a transition from a dominant use of fossil fuel-based energy carriers (mostly fuels) to a much larger use of electricity, capturing the effects of the final-to-useful efficiencies of energy carriers is crucial to understand the net useful energy dynamics of the transition, particularly as electricity is generally used with much higher final-to-useful efficiencies than fuels.

As discussed in Section 1.3.1, the comparison of the net energy returns of fossil fuels and renewable energy technologies has been extensively conducted using the EROI concept, but at best, at the final stage of energy use (and often, comparing primary stage energy returns for fossil fuels with final stage energy returns for renewable energy technologies, leading to biased and inconsistent results). However, even conducting the analysis at the final stage omits the key influence of final-to-useful efficiencies, which favours the net energy returns of renewable energy technologies, and thereby provides overly pessimistic comparisons of renewable energy technologies versus fossil fuels. An important implication is that most energy-economy models including a net energy perspective tend to omit as well the effect of final-to-useful efficiencies (when they do not altogether mix primary stage energy returns for fossil fuels with final stage energy returns for renewable energy technologies), which would somewhat ease the net energy constraints identified.

Raugei [155] correctly identifies the issue of the difference in final-to-useful efficiencies, and argues that comparisons should only be conducted between supply chains delivering the same, or comparable, energy carriers, which are hence available for the same end-uses with the same efficiencies: "it would be recommendable for all comparative studies to always ensure that the calculation boundaries are consistently extended to arrive at a common energy carrier delivered to the end-user [...] by duly accounting for all the necessary supply chain processes and the associated energy losses and investments." While such an approach is indeed appropriate, I argue here that expanding the analysis to the useful stage of analysis allows analysts to compare equivalent outputs, or in Life Cycle Analysis terminology, to adopt an equivalent *functional unit*, hence removing the "apples-to-oranges" comparison issue [155] when comparing the net energy returns of supply chains delivering different energy carriers.[22]

To date, the only study performing an EROI at the useful stage is the pioneering work of Ecclesia et al. [153], which estimates the useful stage societal EROI

[22]Note however that results still need to be analysed with a grain of salt, as not all end-uses may be delivered with any energy carrier (for instance, there is currently no viable option to deliver air transportation with electricity), or as delivering an end-use with a different energy carrier may imply a significant change in the infrastructure and end-use devices utilised (for instance, charging spots as well as electric vehicles for electric mobility).

(see Section 1.2.2) for Portugal, considering the energy flows embodied in capital, imports, and exports, and adopting an exergy metric for the quantification of energy flows (see Section 1.2.3), which allows to deal with the issue of energy quality. The authors find a relatively constant useful stage societal EROI of approximately 3 for the period 1960–2014. Such a result suggests that increasing final-to-useful efficiencies have historically offset the declining primary and final stage net energy returns of fossil fuels, and confirms that conducting the analysis at the primary, or final energy stage, may hide important dynamics in regards to the net energy delivered to society in a valuable form (i.e. useful energy). The study constitutes an important contribution to the literature, but does not differentiate useful stage net energy returns by primary energy source, and therefore does not allow a comparison of different energy supply chains. However, recent advances in the exergy economics literature now provide the research community with a wide range of final-to-useful energy (and exergy) efficiencies for different regions, in the same veins than those used for Portugal by Ecclesia et al. [153]. Particularly, a global primary-final-useful database recently developed at the University of Leeds [217] presents the potential to conduct global, as well as national level analysis, at the useful stage of energy use, differentiating primary energy sources.

Hence, there is currently **no assessment of how the net energy returns of fossil fuel-based carriers compare to those of renewable energy technologies at the useful stage of energy use**, although such a comparison is crucial to understand the dynamics of the net useful energy as the energy transition unfolds. Recent developments in the field however allow me to conduct such an analysis, which is the second gap that this thesis will attempt to fill.

Gap 3: The extent to which the increasing energy requirements of mining can affect the net energy returns of renewable energy technologies

As argued in Section 1.3.2, mineral depletion can be seen as the process whereby mineral deposits of decreasing qualities (in terms of ore grades, accessibility, grinding size, etc.) need to be extracted, thereby entailing an increase of the inputs required for the extraction of valuable minerals (be it capital, labour, energy, or materials), as well as of the environmental damage caused [179, 218]. In this thesis, I am primarily concerned with the increasing energy requirements of mining, represented through the increasing energy intensities of mining introduced in Section 1.3.2. Taking together the high material requirements of renewable energy technologies and of the energy transition (Section 1.1.3) with the increasing energy intensities of mining raises the question of the impacts that mineral depletion may have on the net energy returns of renewable energy technologies.

Estimates of the impacts of increasing energy intensities of mining on the net energy returns of renewable energy technologies remain scarce. First, Harmsen et al. [216] use a geological model estimating copper distribution as a function of ore grade and deposit depth, and thereby link the cumulative extraction of copper to the mineral deposit ore grade and depth. The authors then derive a relationship using Life Cycle Analysis data to determine the energy requirements of copper mining as function of the deposit ore grade and depth. The study finds a marginal impact of declining copper deposit qualities on the net energy returns of wind turbines (decline in EROI from 25.2 in 2010 to 24.4 in 2050). This study is a noteworthy attempt to build, for a given mineral, a mechanistic model to derive the future energy intensities of mining as function of the mineral cumulative production, but fails to quantify the impacts of mineral depletion on the net energy technologies returns of wind turbines taking into consideration the whole range of minerals upon which the technology relies.

Second, Fizaine and Court [219] estimate the impacts of mineral depletion on the net energy returns of renewable energy technologies by modelling the evolution of their EROI for (solar photovoltaic, wind power, and hydro power) as function of the decrease in ore grade for the relevant minerals. The study finds that the effects of mineral depletion on the net energy returns of renewable energy technologies may be significant when the effects of mineral depletion are considered simultaneously for all minerals, and when ore grades decrease to very low concentrations. Although the study also presents an important contribution to the field of study, it presents two key limitations. First, the energy consumption of mining processes is not differentiated from the one of downstream metallurgical processes, and increasing energy intensities are applied to the whole metal production process (both to mining and metallurgical processes). As only the energy requirements of mining are affected by these dynamics, the effects of mineral depletion are likely to be overestimated. Second, the study provides a sensitivity assessment of the impacts of decreasing ore grades on the net energy returns of renewable energy technologies, but does not provide a range of plausible evolutions, or plausible scenarios, for future ore grades (and hence energy intensities).

Hence, although these two studies provide significant advances to the scientific literature, there is currently **no comprehensive assessment of the effects of mineral depletion on the net energy returns of renewable energy technologies that simultaneously (i) takes into consideration the whole range of required minerals, (ii) differentiates the energy consumption of mining processes from the one of downstream metallurgical processes, and (iii) uses plausible future scenarios for the increasing energy intensities of mining**, which is the third research gap identified that this thesis will aim to address.

1.4 Aims, research questions, and approach

1.4.1 Aims and research questions

This thesis attempts to fill the gaps identified in the literature by expanding the net energy framework to (i) consider the energy requirements of mining activities, and (ii) expand the analysis to the useful stage of energy use, hence looking at the net useful energy available to society. The overarching aim of this thesis is **to gain a better understanding of the net useful energy implications of the global energy transition, in the context of mineral depletion.** Each of the identified research gaps maps respectively to the following research questions:

1. (Gap 1) Q1: What will be the future energy consumption of the mining industry as a result of the energy transition, in the context of mineral depletion?

2. (Gap 2) Q2: What are the useful stage energy returns of fossil fuel-based energy carriers, and how do these relate to those of renewable energy technologies?

3. (Gap 3) Q3: How will the energy returns of renewable energy technologies evolve in the context of mineral depletion?

To answer these research questions, I set five intermediary research objectives, which are introduced below, and which will be addressed by each chapter as shown in Figure 1.12.

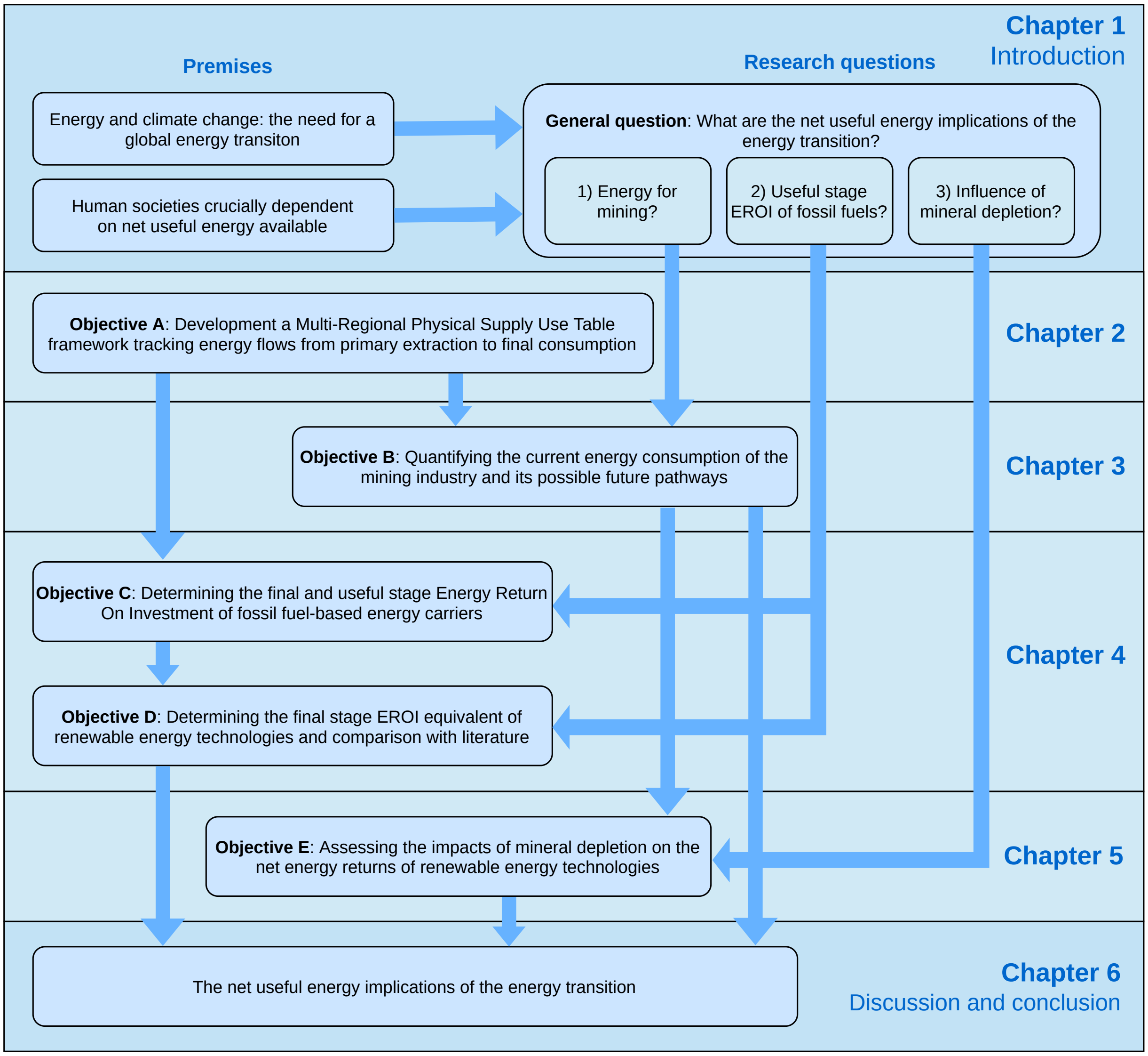

Figure 1.12: Overview of the thesis' chapters, research objectives, research questions, and of their interactions.

A. To develop a framework allowing analysts to track energy flows from primary energy extraction to final consumption, as well as energy flows across regions. Objective **A** can be thought of as an enabler objective, as the developed theoretical model and associated tool to track energy flows, from primary energy extraction to final consumption, as well as energy flows across regions, is a cornerstone of this thesis. Indeed, the developed model allows me to (i) to determine the sector-level factors to convert primary energy requirements in terms of final energy use, which I determine for the mining industry, thereby contributing to answer the first and third research questions (Q1–Q3), and (ii) most importantly, to determine the useful stage EROI of fossil fuel-based energy carriers, both at the global and regional level, thereby contributing to answer the second research question (Q2).

B. To quantify the current energy consumption of the mining industry, as well as its possible future evolutions. This research objective is directly concerned with answering the first research question (Q1) of the thesis, and will provide an understanding of the possible future magnitude of the mining industry energy consumption, in the context of the energy transition and of mineral depletion.

C. To determine the final and useful stage Energy Return On Investment of fossil fuel-based energy carriers. This research objective addresses the first part of the second research question (Q2), and can be considered a research objective on its own as it significantly expands current knowledge on the energy returns of fossil fuel-based energy carriers.

D. To determine the final stage Energy Return On Investment equivalent for which renewable energy technologies would deliver the same amount of net useful energy as fossil fuels, and to compare it with the renewable energy Energy Return On Investment values published in the literature. This research objective addresses the second part of the second research question (Q2), and will provide the thesis with an understanding of how the consideration of the final-to-useful efficiencies of different energy carriers (particularly, fossil fuel-based energy carriers versus electricity) modify the performance of renewable energy technologies versus fossil fuels.

E. To assess the magnitude of the impacts of mineral depletion on the net energy returns of renewable energy technologies. This research objective addresses the third research question (Q3), and assesses the extent to which the results obtained when answering the second research question (Q2) are affected when taking into consideration mineral depletion dynamics.

1.4.2 Thesis approach and structure

The thesis is structured as an introduction, four core chapters, and a discussion and conclusion chapter. The four core chapters are written in a journal article format (see Intellectual property and publication statements for publication details) and are highly interdependent, as the results and outputs of some chapters are important inputs to chapters (see Figure 1.12 for the contribution of each chapter to research objectives, as well as how each chapter interacts with one another).

In the rest of this section, I introduce each chapter and its contribution towards the main objectives of the thesis and towards the other chapters, as well as the contribution of each chapter to the broader scientific literature.

Chapter 2: Developing a Multi-Regional Physical Supply Use Table framework to improve the accuracy and reliability of energy analysis

This chapter directly addresses research objective **A** by introducing a Multi-Regional Physical Supply Use Table (MR-PSUT) framework based on recent work by Heun et al. [220], as well as the associated open source `R` packages [221–223] (see Intellectual property and publication statements for the contributions of the candidate to the packages). Such packages allow analysts to build a MR-PSUT from the WEEB dataset from the International Energy Agency [224] and to conduct thereafter physical energy input-output analyses. The chapter then demonstrates the framework with two applications; first, energy security analysis, and second, the accounting of energy-related greenhouse gas emissions. This chapter is a cornerstone of the thesis for different reasons. First, the MR-PSUT framework is the backbone of the calculations I conduct to determine the useful stage EROI of fossil fuels and subsequent determination of final stage EROI equivalent for renewable energy technologies (Chapter 4). Second, the MR-PSUT framework is used to calculate the sector-specific final-to-primary energy ratios that I use for the mining industry in Chapters 3 and 5.

Contributions to the literature. This chapter presents both important theoretical and practical contributions to the literature. On the theoretical side, the introduced framework expands the existing Physical Supply Use Table framework with a resource matrix, thereby explicitly representing energy flows from primary extraction to final consumption. Such a development provides the mathematical structure with symmetry, thereby enabling reverse Input-Output calculations. In addition, the framework allows analysts to take into consideration the trade in energy products and to track energy flows across regions. On the practical side, the open source `R` packages introduced provide the scientific community with powerful analysis tools fully compatible with the IEA's WEEB dataset, which is the most comprehensive energy database available to date.

Chapter 3: Global energy consumption of the mineral mining industry: exploring the historical perspective and future pathways to 2060

The chapter addresses research objective **B** by (i) providing the first bottom-up assessment of the mining industry's final energy consumption globally (1971–2015), and (ii) using 1.5°C consistent socio-economic scenarios to conduct an exploratory study of future possible pathways for the mining industry's final energy consumption. To do so, typical final energy requirements by unit mass of mineral mined (energy intensities of mining) are estimated for a wide range of minerals from the literature and using the MR-PSUT framework developed in Chapter 2. Plausible evolutions of the energy intensities of mining are then defined reviewing and extrapolating current trends observed in the mining sector. Future mineral demand for the energy transition is estimated based on recent studies analysing the mineral requirements of the energy transition, and mineral demand for the rest economic activities is determined using a stylised approach linking global GDP to mineral demand. Different scenarios regarding the evolution of recycling rates are used to determine the required mineral extraction, and thereafter the mining industry's final energy consumption.

Contributions to the literature. This chapter is the first study estimating the mining industry's final energy consumption globally from a bottom-up perspective, and the first study attempting to determine future plausible pathways for the mining industry's final energy consumption, considering the mineral requirements of the global energy transition, the dynamics of mineral depletion, and the future evolution of recycling rates. In addition, this work provides the scientific community with a set of typical primary and final energy requirements by unit mass of mineral extracted for a wide range of minerals. Last, the chapter reviews the consideration of the energy consumption of the mining industry in energy-economy models and critically discusses it in the light of the results.

Chapter 4: Estimation of fossil fuels useful stage Energy Return On Investment and implications for renewable energy systems

This chapter addresses research objective **C** by calculating the useful stage EROI of fossil fuels based on the MR-PSUT framework developed in Chapter 2 as well as the International Energy Agency's WEEB. In addition, the indirect energy requirements of fossil fuels based energy carriers are determined using the Exiobase MRIO [225, 226], and developing further the method introduced by Brockway et al. [111]. The fossil fuels useful stage EROIs are determined both at the global and national levels, and both at the economy-wide as well as for different end-use level. The obtained values are then used to determine the final stage EROI equivalent for which renewable energy technologies would deliver the same amount of net useful energy as fossil fuels (objective **D**), both globally and at the national level, and for different end-uses. Such EROI equivalent values are then compared with recent estimates of renewable energy technologies (solar photovoltaic and wind power).

Contributions to the literature. This chapter is the first estimation of the useful stage EROI of fossil fuels, both at the global and national level. Further, the study estimates the useful stage EROI of fossil fuels by end-use (as well as by final demand sector in Appendix C). Then, the chapter uses such values as well as the final-to-useful efficiencies of electricity to determine for the first time the final stage EROI equivalent for which renewable energy technologies would deliver the same amount of net useful energy as fossil fuels. Last, the final stage EROI equivalent is compared with recent final stage estimates of EROIs for renewable energy technologies. The obtained results are of high significance and constitute an important contribution to the net energy analysis community.

Chapter 5: Exploring the effects of mineral depletion on renewable energy technologies net energy returns

This chapter directly addresses research objective **E** by exploring the effects of mineral depletion, quantified through the dynamic of increasing energy intensities of mining, on the net energy returns of four renewable energy technologies: solar photovoltaic, concentrated solar power, onshore wind, and offshore wind. To do so, the chapter reuses the typical final energy intensities of mining each mineral as well as the scenarios on their evolutions developed in Chapter 3. In addition, the chapter investigates the potential of technological factors, such as improvements in metallurgical energy efficiencies, material intensities of manufacturing, and recycled input rates, to offset the negative effects of mineral depletion on the net energy returns of renewable energy technologies.

Contributions to the literature. This chapter provides the first estimation of the impacts of mineral depletion on the net energy requirements of renewable energy technologies which (i) clearly differentiates the mining and metallurgical stages of the metal production process, (ii) covers a wide range of minerals and metals, and (iii) considers plausible scenarios for the future evolution of the energy intensities of mining. Indeed, while some previous studies considered some of these aspects, none addressed all of them simultaneously — see Section 1.3.4 for more details.

Chapter 6: Discussion and conclusion

Last, Chapter 6 summarises the main findings of each chapter as well as its contributions to the literature, and discusses the answers to the research questions introduced in Section 1.4. The chapter then discusses the findings in relation to the broader question of the net useful energy implications of the energy transition, and states the main limitations of the thesis, which point to directions for further research. Last, the chapter discusses the findings in relation to the transition to a post-growth and well-being economy.

1.5 References

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Chapter 2

Developing a Multi-Regional Physical Supply Use Table framework to improve the accuracy and reliability of energy analysis

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Physical Supply Use Tables overcome some of the main limitations of the commonly used Energy Extended Input Output Analysis by describing the Energy Conversion Chain in energy terms only. In this paper, we build on recent advances in the field to construct a Multi-Regional Physical Supply Use Table framework. We use data from the International Energy Agency and have developed open source `R` packages, thereby enabling easy adoption of the present work. The new framework enables analysts to take into consideration the trade in energy products and to track energy flows across regions. In addition, we expand the existing Physical Supply Use Table framework to provide the mathematical structure with symmetry, by adding a resource extraction matrix at the upstream end of the Energy Conversion Chain, thereby enabling reverse Input-Output calculations.

Then, we demonstrate two important applications of the new multi-regional framework. First, we show how the framework can be used for energy security analysis, how the primary energy supply can be broken down by region of origin, and how the exposure to overseas suppliers can be quantified by energy product, and final demand sector. Second, we show how energy-related greenhouse gas emissions can be accounted for and disaggregated in terms of energy use by the energy industry, downstream energy use by final demand sectors, and methane leakages and flaring. The framework, which consistently binds energy products supplied to the economy to the Energy Conversion Chain, may be helpful for numerous subfields of energy analysis and modelling.

2.1 Introduction

2.1.1 Energy analysis: a crucial tool for current challenges

Energy analysis is an essential tool to study some of the large and current energy challenges. Indeed, as fossil fuel-based energy consumption is responsible for most greenhouse gas emissions and therefore is a key driver of anthropogenic climate change [1], energy analysis has a crucial informative role to play in climate change mitigation. First, energy analysis can inform the discussion of whether absolute energy-GDP decoupling is possible or not [2] — and assess the role of different factors in the evolution of the energy-GDP relationship [3] — as well as explore the magnitude of the energy rebound induced by energy efficiency improvements, either at the sectoral level [4], or at the economy-wide level [5]. Second, energy analysis can help identify options for reducing energy consumption, be it through increases in efficiency [6], or through the development of alternative provisioning systems to satisfy needs and provide material well-being [7]. Third, energy analysis can help with planning the transition to a renewable energy system, raising important issues regarding the intermittency of renewable electricity production [8] and the influence of climate change on that intermittency [9], the critical minerals required for the development of renewable energy technologies [10], and the land use requirements of such technologies [11]. Fourth, current concerns regarding the exhaustion of non-renewable natural resources [12], as well as to the structural decline of fossil fuel extraction returns — measured in terms of Energy Return On Energy Investment — can be assessed through energy analysis methods, both at the primary [13] and final [14] energy stages.

2.1.2 Physical Supply Use Tables for energy analysis

A widely used tool for energy analysis is Energy Input Output (EIO) analysis; of which Miller and Blair [15] provide a very comprehensive summary. Following Miller and Blair, it is possible to distinguish between (i) the traditional approach to EIO, more commonly known as Energy Extended Input Output (EEIO) analysis,[1] (ii) hybrid EIO analysis, and (iii) physical EIO analysis [16]. When using traditional

[1]Energy Extended Input Output analysis is akin to Environmentally Extended Input Output analysis, and it may sometimes be referred to as such. Environmentally Extended Input Output analysis may however apply to other types of environmental analysis.

EEIO, energy footprints are calculated by pre-multiplying the total requirement matrix (i.e. the Leontief inverse, calculated in monetary terms) by a direct energy intensity vector, or by a matrix of direct energy coefficients [15]. The traditional EEIO approach is widely used for a broad set of applications, for instance to assess production-based and consumption-based national energy accounts [17], to analyse energy flows embodied in global trade [18, 19], or to understand the drivers of energy consumption reduction [20].[2]

However, although the traditional EEIO approach comes with some important advantages, mainly its simplicity and the availability of data, it comes with serious limitations. Indeed, the traditional EEIO approach fails to (i) conform to the principle of energy conservation, (ii) consistently capture the interdependence between energy products demanded by economic activities and the energy industry. Alternatively, one may adopt a physical description of energy flows, which observes the energy conservation condition and can be used to formulate a hybrid EIO model, describing energy flows in physical units, and representing the rest of the economy in monetary terms.[3] However, to formulate such a hybrid EIO model, it is necessary to formulate first a purely physical EIO model, to which we now turn.

Recently, Heun et al. [28] argued for a "unifying energy analysis framework," based on Physical Supply Use Tables (PSUTs). The authors demonstrated how such tables may be used to construct, from a "Make and Use" approach [29], Physical Input Output Tables (PIOTs). From these PIOTs, a wide range of physical EIO analyses can then be performed, hence avoiding the issues inherent to traditional EEIO analysis. A recent example is the work of King [30], who describes a physical EIO method to calculate energy returns of an Energy Conversion Chain (ECC).[4] Noteworthy features of the PSUT framework introduced by Heun et al. [28] are that it allows analysts to perform both energy and exergy analysis across the primary, final, and useful stages of the ECC — as well as across the energy services stage — even in the case of inhomogeneous units. The PSUT framework therefore enables a

[2]The EEIO approach has been used for a long time, and the seminal works Bullard and Herendeen [21], Bullard et al. [22], and Costanza [23] in the context of the development of a normative energy theory of value (see [24, 25]) are worth noting here.

[3]The hybrid approach has for instance been used in the Life Cycle Assessment literature [26], or to assess the economic effects of a carbon tax [27].

[4]The Energy Conversion Chain is defined here as the chain of processes whereby energy is extracted in its primary form, then transformed in final energy carriers, and eventually consumed in end-use devices.

physical representation of energy flows, from the primary extraction to the end-use conversion of energy, thereby enabling incorporation of physical end-use efficiencies. PSUTs have also been used by Guevara [31] to construct PIOTs representing the energy industry. Guevara and co-authors formulated the multi-factor energy input-output model by coupling such PIOTs with Monetary Input Output Tables (MIOTs) [16], which were used to conductstructural decomposition of primary energy consumption in Portugal [32] and to analyse potential drivers of energy-GDP decoupling [33]. These recent applications of a PSUT framework show its potential for enhancing energy analysis.[5]

In this paper, we acknowledge the diversity of methods and tools available for energy analysis, and at the same time, recognise the additional value that PSUTs can bring to the field. A current limitation of the PSUT framework presented in Heun et al. [28] is that its scope remains national, meaning that import flows are represented as part of the supply mix, and that export flows are represented as part of the national final demand. Such a description remains incomplete, for it hides flows across countries and prevents identification of the upstream supply chain related to energy imports by a given country. This is particularly problematic for those countries that import a significant portion of their energy supply; for instance fossil fuel importing countries. A solution is to expand the national PSUT framework into a Multi-Regional Physical Supply Use Table (MR-PSUT) framework, so that imports and exports are explicitly linked to other regions' supply and uses. Such work has for instance been conducted for agricultural products by Bruckner et al. [38], who developed the Food and Agriculture Biomass Input-Output (FABIO) Model to describe agricultural flows across countries. Regarding the energy industry, it is noteworthy to refer to the studies by Guevara et al. [39] and Rocco et al. [40], in which a three region MR-PSUT framework is used to describe the energy industry. The gap that this paper attempts to fill is to provide a clear description of the methodology and process to develop an energy MR-PSUT framework in a fully reproducible way, as well as to showcase applications of the framework.

[5] It is worth noting that PSUT and PIOT frameworks have also gained recent interest outside the field of energy analysis [34]. Examples include the study of paper and wood flows across Germany [35], the estimation of economy-wide material flow indicators using PSUTs of the Czech Republic [36], the estimation of energy-related ecological footprint of Galicia, Spain [37], as well as the calculation of cropland footprints embodied in agricultural products trade [38].

2.1.3 Aim, contribution, and content

The aim of this paper is threefold: first, to provide a clear description of how a MR-PSUT framework can be constructed in a fully reproducible and adaptable way; second, to expand the usual PSUT formulation to take account of energy resources extraction and alteration of the supply mix; third, to demonstrate the framework with two simple applications: energy security analysis, and the accounting of greenhouse gas emissions from the energy industry. Section 2.2 introduces the structure of the expanded PSUT framework, and explains how the MR-PSUT framework is constructed from International Energy Agency (IEA) data. This work contains three key contributions: first, the PSUT structure introduced by Heun et al. [28] is expanded to facilitate the accounting of energy resources extraction on the upstream end of the ECC, and the modelling of a change in the supply mix (Section 2.2.1). Second, the construction of a MR-PSUT framework, based exclusively on IEA data is detailed (Section 2.2.2). Third, the new MR-PSUT framework is built using two open source R packages developed by the authors, IEATools [41] and ECCTools [42], therefore enabling full reproducibility of the work, and straightforward adaptation of the new framework to any further work. Section 2.3 presents and discusses the application of the framework to energy security, and Section 2.4 presents and discusses the application of the framework to the accounting of energy-related greenhouses gas emissions. Then, Section 2.5 provides the conclusions.

2.2 The Multi-Regional Physical Supply Use Table framework

In this section, we (i) introduce the expansion of the PSUT framework originally presented by Heun et al. [28], and (ii) present the methodology applied to construct the MR-PSUT used in this paper.

2.2.1 Description of the expanded PSUT framework

Expanded PSUT framework matrices

Matrix dimension notations Following Heun et al. [28], Table 2.1 presents the matrix dimension notations that will be used when introducing matrices. Products (i.e. energy carriers — gasoline, electricity, etc.), are denoted by p, industries (i.e.

any installation or device transforming one energy product into another energy product — oil refinery, gas heater, etc.) by i, resource stocks by r, and final demand sectors by s. Note that a diagonalised vector (matrix with vector coefficients in the diagonal and zeros off the diagonal) is noted with a hat, e.g. $\widehat{\mathbf{g}}$. See Appendix A.1 for a comprehensive nomenclature table.

Table 2.1: Matrix dimensions notations. Adapted from Heun et al. [28].

Notation	Meaning
p × p	Products in both rows and columns, for instance $\underset{p\times p}{\mathbf{A}}$.
i × i	Industries in both rows and columns, for instance $\widehat{\mathbf{g}}$.
p × i	Products in rows, and industries in columns, for instance $\underset{p\times i}{\mathbf{U}}$.
i × p	Industries in rows, and products in columns, for instance $\underset{i\times p}{\mathbf{V}}$.
p × s	Products in rows, and sectors in columns, for instance $\underset{p\times s}{\mathbf{Y}}$.
p × u	Products in rows, and units in columns, for instance $\underset{p\times u}{\mathbf{S}_{\text{units}}}$.
r × p	Resource stocks in rows, and products in columns, for instance $\underset{r\times p}{\mathbf{R}}$.
p × r	Products in rows, and resource stocks in columns, for instance $\mathbf{R}^{\text{T}}$.

Original PSUT framework Original PSUT framework. The original PSUT framework by Heun et al. [28] consists of four basic matrices. First is the $\underset{p\times i}{\mathbf{U}}$ matrix, or "use" matrix, a product-by-industry matrix representing intermediary uses of products, by industry. Second is the $\underset{i\times p}{\mathbf{V}}$ matrix, or "make" matrix, an industry-by-product matrix representing the products supplied, by industry. Third is the $\underset{p\times s}{\mathbf{Y}}$ matrix, or "final demand" matrix, a product-by-sector matrix which describes the final use of products by final demand sector. Fourth is the auxiliary product-by-unit $\underset{p\times u}{\mathbf{S}_{\text{units}}}$ matrix, which deals with inhomogeneous units in the framework. For the sake of simplicity, and because the examples presented in Sections 2.3 and 2.4 only deal with homogeneous units, the $\underset{p\times u}{\mathbf{S}_{\text{units}}}$ matrix is not further included in this paper. In addition, the $\underset{p\times i}{\mathbf{W}}$ matrix, or "value added" matrix, may be derived from $\mathbf{V}$ and $\mathbf{U}$, to represent the difference between supplied and used products for each industry.

Decomposition of the U matrix To formulate the MR-PSUT framework, we decompose the $\mathbf{U}$ matrix in two complementary matrices, each with product-by-industry dimensions. The $\mathbf{U}_{\text{feed}}$ matrix (where *feed* stands for feedstock) includes those products that are consumed by a given industry to be transformed into other energy products, i.e. what may be referred to as feedstock products (for instance, crude oil in a refinery). In complement, the $\mathbf{U}_{\text{eiou}}$ matrix (where *eiou* stands for energy industry own use) represents those products that are used by a given industry to provide the necessary energy to operate the industrial process (for instance, high temperature heat used to distil crude oil in a refinery).

Addition of the resource matrix A "resource" matrix, noted $\underset{\text{r×p}}{\mathbf{R}}$, of resource-stocks-by-product dimensions, representing products extracted from resource stocks, is added to the basic matrix structure. In the rest of the article, we designate as "resource products" those products that are extracted from resource stocks, and for which the coefficients of the resource matrix may be different from zero. Adding the $\mathbf{R}$ matrix provides the framework with symmetry, with now two end-points; the upstream $\mathbf{R}$ matrix, as well as the downstream $\mathbf{Y}$ matrix. The symmetry enables both upstream analysis (i.e. finding the upstream effects of changes in final demand), as well as downstream analysis (i.e. finding the downstream effects of changes in resource extraction levels). (See an example in Appendix A.2.)

Addition of the balancing matrix A "balancing" matrix, noted $\mathbf{B}$, of flexible column size and product row size, is also added. The balancing matrix fundamentally enables three things: first, dealing with potential imbalances in the ECC (Section 2.2.1); second, modifying the supply structure of the ECC to answer specific research questions, thereby allowing the simulation of different supply scenarios; third, altering the final demand matrix, while conserving energy balance. To modify the supply structure in such a way that the supply of a given industry i is upscaled or downscaled by a factor λ, one can proceed according to Table 2.2. To modify the final demand matrix, one simply has to relocate columns of the $\mathbf{Y}$ matrix to the balancing matrix.

Graphical representation A graphical representation of the expanded PSUT framework is presented in Figure 2.1. The representation elucidates some useful aggregation vectors, found in Table 2.3. It is important to note that the vector $\mathbf{q}$ may be calculated from either a supply side perspective (noted $\mathbf{q}_{\text{s}}$), or from a consumption side perspective (noted $\mathbf{q}_{\text{c}}$). Both formulations are equivalent when

Table 2.2: Changes to do on matrices, **V**, **U**, and **B** when the supply mix needs to be altered so that the output of an industry i is upscaled (case where $\lambda > 1$), or downscaled (case with $0 \leq \lambda < 1$), by a factor λ. Note that the process is valid with $\lambda = 0$, i.e. when industry i is altogether removed from the supply mix.

Value of λ	Changes to matrix **V**	Changes to matrix **U**	Changes to matrix **B**
$0 \leq \lambda < 1$	Row corresponding to industry i is multiplied by λ.	Column corresponding to industry i is multiplied by λ.	First, the column of **U** corresponding to industry i needs to be multiplied by $(1 - \lambda)$ and then to be added to matrix **B**. Second, the row of **V** corresponding to matrix **V** needs to be transposed, multiplied by $(\lambda - 1)$, and added to the matrix **B**.
$\lambda > 1$	Row corresponding to industry i is multiplied by λ.	Column corresponding to industry i is multiplied by λ.	First, the column of **U** corresponding to industry i needs to be multiplied by $(\lambda - 1)$ and added to the **B** matrix. Second, the column of **V** corresponding to industry i needs to be transposed, multiplied by $(1 - \lambda)$, and added to matrix **B**.
$\lambda = 1$	The case is trivial and no change needs to be made.	The case is trivial and no change needs to be made.	The case is trivial and no change is needed.

the balancing matrix is the **0** matrix, but differ when any flows are redirected to the balancing matrix. In what follows, $\mathbf{q}$ will be used in situations where both vectors are equivalent (**0** balancing matrix), $\mathbf{q}_\mathrm{c}$ when the consumption side vector should be used, and $\mathbf{q}_\mathrm{s}$ where the supply side vector should be used.

Energy conservation Before carrying on with the formulation of the Input Output structure, the energy conservation conditions should be verified. Observing such conditions, which are akin to observing the first law of thermodynamics, ensures that physical flows in the PSUT framework are consistent. Two equations should be verified; first, the use and supply of all products must be balanced:

$$\mathbf{R}^\mathrm{T}\mathbf{i} + \mathbf{W}\mathbf{i} - (\mathbf{y} + \mathbf{B}\mathbf{i}) = \mathbf{0}, \tag{2.1}$$

and second, the total output of each industry should equal the total industry input, minus energy losses within each industry:

$$\mathbf{g} - \mathbf{W}^\mathrm{T}\mathbf{i} - \mathbf{U}^\mathrm{T}\mathbf{i} = \mathbf{0}. \tag{2.2}$$

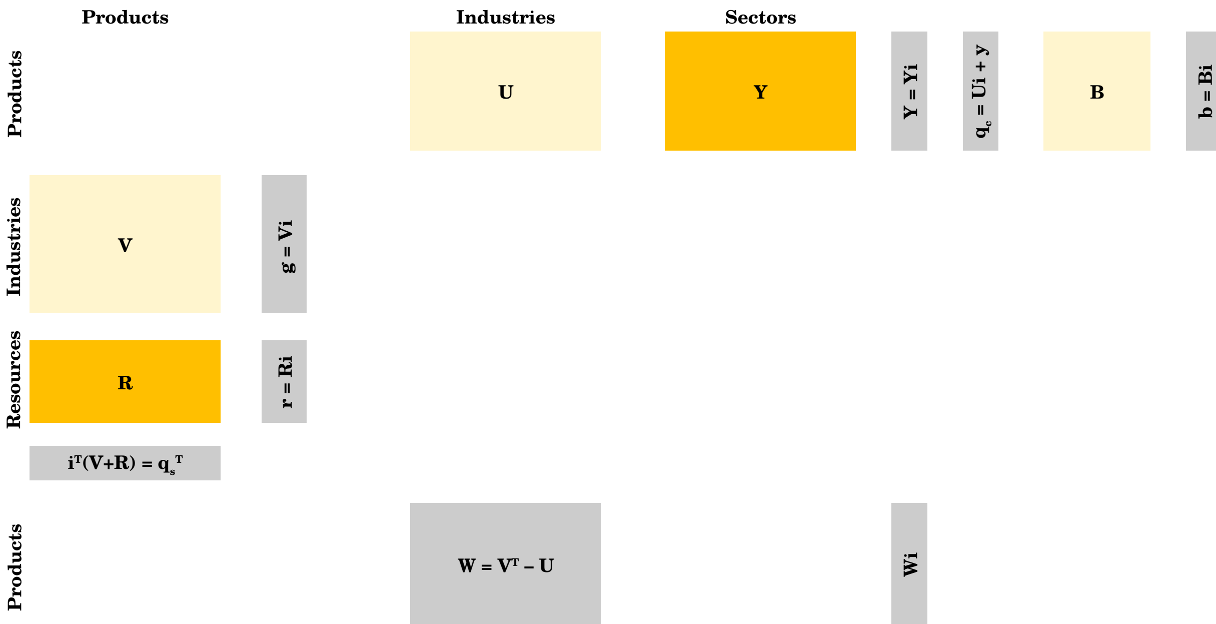

Figure 2.1: Graphical representation of the expanded PSUT framework. Adapted from Heun et al. [28]. See Table 2.3 for matrix and vector definitions. Matrices **R** and **B** are expansions of the original framework.

Table 2.3: Useful aggregation vectors in the PSUT framework; mathematical definition and description. Adapted from Heun et al. [28].

Aggregation vector	Description
$\mathbf{y} = \mathbf{Yi}$	Final demand by product.
$\mathbf{i}^{\mathrm{T}}\mathbf{Y}$	Final demand by sector.
$\mathbf{g} = \mathbf{Vi}$	Total output by industry.
$\mathbf{q}_{\mathrm{c}} = \mathbf{Ui} + \mathbf{y}$	Total output by product, calculated from a consumption-side perspective.
$\mathbf{q}_{\mathrm{s}} = (\mathbf{R} + \mathbf{V})^{\mathrm{T}}\mathbf{i}$	Total output by product, calculated from a supply-side perspective.
$\mathbf{f} = \mathbf{U}^{\mathrm{T}}\mathbf{i}$	Total input by industry.
$\mathbf{U}_{\mathrm{eiou}}^{\mathrm{T}}\mathbf{i}$	Energy consumption by industry, for own use.
$\mathbf{U}_{\mathrm{feed}}^{\mathrm{T}}\mathbf{i}$	Feedstock consumption by industry, for transformation purposes.
$\mathbf{r} = \mathbf{Ri}$	Total resources output, by resource stock type.
$\mathbf{h} = \mathbf{R}^{\mathrm{T}}\mathbf{i}$	Total resources output, by resource products type.
$\mathbf{W}^{\mathrm{T}}\mathbf{i}$	Value added, in energy terms, by industry. Values ought to be zero or negative.
$\mathbf{Wi}$	Value added, in energy terms, by product. Negative values represent resource products extracted from resource stocks, and positive value represent energy products available to final demand.

Once these conditions are verified, one may carry on with the formulation of the PIOT structure.

PIOT structure

IO Model selection First, an IO model should be chosen [43, 44]. Appendix A.3 presents the different IO models described by Eurostat [43], and discusses their validity focusing on the case of an energy PSUT framework. Following Heun et al. [28], we select the Industry Technology Assumption model as the most accurate description of the energy industry. Indeed, the Industry Technology Assumption considers that "all products produced by an industry are produced by the same input structure" [43, p. 309], and is most appropriate for describing numerous cases of joint and by-products (see the Eurostat manual for an extensive discussion [43]), which is the case when describing the energy industry.

IO matrices formulation Now that the IO model has been selected, the IO structure is formulated in Table 2.4. Matrix definitions and notations follow Eurostat guidelines where possible [43].

Estimating the effects of a change in final demand Based on the IO structure, one can estimate the upstream effects of a change in final demand in all PSUT framework matrices. The new matrices are noted with a prime (e.g. $\mathbf{Y}'$, $\mathbf{U}'$, $\mathbf{V}'$) and presented in Table 2.5.

Estimating the effects of a change in primary energy extraction from resource stocks Similarly, one can exploit the symmetry of the expanded PSUT framework to estimate the downstream effects of a change in the level of extracted, or available resources. To do so, a symmetric IO structure has to be constructed, which is described in Table 2.6 — symmetric matrices are noted with a star (*).

The downstream changes induced by a new resource matrix $\mathbf{R}''$ are shown in Table 2.7 and noted with two primes (e.g. $\mathbf{U}''$, $\mathbf{V}''$, $\mathbf{Y}''$). Note that the subsequent calculations rely on the perfect substitution assumption, according to which an industry producing outputs from a given combination of input products will be equally capable of producing the outputs from any of the input products, with no limiting inputs.

Table 2.4: Physical Input-Output matrices definition, and matrix coefficients meaning. Adapted from Heun et al. [28].

Matrix definition	Matrix name	Matrix coefficients meaning
$\underset{p\times i}{\mathbf{Z}} = \mathbf{U}\widehat{\mathbf{g}}^{-1}$	Direct requirement matrix (product-by-industry)	Coefficient (k, l) represents the needed input of product k to produce one unit of output of industry l. Note: replacing the $\mathbf{U}$ matrix by respectively $\mathbf{U}_{\text{eiou}}$ and $\mathbf{U}_{\text{feed}}$ gives the decomposition of $\mathbf{Z}$ in respectively $\mathbf{Z}_{\text{eiou}}$ and $\mathbf{Z}_{\text{feed}}$, which may assist in conducting different types of supply chain analysis.
$\underset{p\times i}{\mathbf{C}} = \mathbf{V}^{\mathrm{T}}\widehat{\mathbf{g}}^{-1}$	Product shares matrix	Coefficient (k, l) represents the share of product k in the production of industry l.
$\underset{i\times p}{\mathbf{D}} = \mathbf{V}\widehat{\mathbf{q}_{\mathrm{s}}}^{-1}$	Market shares matrix	Coefficient (k, l) represents the share of product l by industry k in total supply of product l.
$\underset{r\times p}{\mathbf{O}} = \mathbf{R}\widehat{\mathbf{h}}^{-1}$	Resource shares matrix	Coefficient (k, l) represents the share of the resource product l extracted from the resource stock k.
$\underset{p\times p}{\mathbf{A}} = \mathbf{Z}\mathbf{D}$	Direct requirement matrix (product-by-product)	Coefficient (k, l) represents the directly (excluding supply chain) needed input of product k to produce one unit of product l. Note: replacing the $\mathbf{Z}$ matrix by respectively $\mathbf{Z}_{\text{eiou}}$ and $\mathbf{Z}_{\text{feed}}$ gives the decomposition of $\mathbf{A}$ in respectively $\mathbf{A}_{\text{eiou}}$ and $\mathbf{A}_{\text{feed}}$.
$\underset{p\times p}{\mathbf{L}} = (\mathbf{I} - \mathbf{A})^{-1}$	Total requirement matrix (product-by-product)	Coefficient (k, l) represents the total (including whole supply chain) needed input of product k to produce one unit of product l. Note: replacing the $\mathbf{A}$ matrix by respectively $\mathbf{A}_{\text{eiou}}$ and $\mathbf{A}_{\text{feed}}$ gives the decomposition of $\underset{p\times p}{\mathbf{L}}$ in respectively $\underset{p\times p}{\mathbf{L}_{\text{eiou}}}$ and $\underset{p\times p}{\mathbf{L}_{\text{feed}}}$.
$\underset{i\times p}{\mathbf{L}} = \mathbf{D}(\mathbf{I} - \mathbf{A})^{-1}$	Total requirement matrix (industry-by-product)	Coefficient (k, l) represents the total (including whole supply chain) needed output of industry k to produce one unit of product l. Note: replacing the $\mathbf{A}$ matrix by respectively $\mathbf{A}_{\text{eiou}}$ and $\mathbf{A}_{\text{feed}}$ gives the decomposition of $\underset{i\times p}{\mathbf{L}}$ in respectively $\underset{i\times p}{\mathbf{L}_{\text{eiou}}}$ and $\underset{i\times p}{\mathbf{L}_{\text{feed}}}$.

Finally, we note that everything presented and discussed in Sections 2.2.1 and 2.2.1 remains valid when working with a MR-PSUT framework, the only difference comes from the matrices dimensions. If we are working with i industries, p products, s final demand sectors, and n regions, then the MR-PSUT framework will comprise $n \times i$ industries, $n \times p$ products, and $n \times s$ final demand sectors. Matrix sizes will be accordingly scaled.

Table 2.5: Estimating the effects of a change in the final demand matrix. The new final demand is noted $\mathbf{Y'}$, and induced matrices by the new final demand are noted with a prime.

New matrix	Description
$\mathbf{y'} = \mathbf{Y'i}$	New final demand by product.
$\mathbf{g'} = \underset{\text{i×p}}{\mathbf{L}}\,\mathbf{y'}$	New total output by industry.
$\mathbf{q'} = \underset{\text{p×p}}{\mathbf{L}}\,\mathbf{y'}$	New total output by product.
$\mathbf{U'} = \mathbf{Z}\widehat{\mathbf{g'}}$	New "use" matrix to fulfil $\mathbf{Y'}$.
$\mathbf{V'} = \mathbf{D}\widehat{\mathbf{q'}}$	New "make" matrix to fulfil $\mathbf{Y'}$.
$\mathbf{W'} = \mathbf{V'}^{\mathrm{T}} - \mathbf{U'}$	New value added matrix.
$\mathbf{R'}^{\mathrm{T}}\mathbf{i} = \mathbf{y'} - \mathbf{W'i}$	New resource output vector, by resource product.
$\mathbf{R'} = \mathbf{O}(\widehat{\mathbf{i}^{\mathrm{T}}\mathbf{R'}})$	New resource matrix to fulfil $\mathbf{Y'}$.
$\mathbf{r'} = \mathbf{R'i}$	New total resource output vector, by resource stocks.

Table 2.6: Symmetric Physical Input-Output structure, matrices definition, and coefficients meaning.

Matrix definition	Matrix coefficients meaning
$\underset{\text{p×i}}{\mathbf{Z}^*} = \mathbf{V}^{\mathrm{T}}\widehat{\mathbf{f}}^{-1}$	Coefficient (k, l) represents the output of product k when industry l receives one unit of input, independently of the energy product (perfect substitution assumption).
$\underset{\text{p×i}}{\mathbf{C}^*} = \mathbf{U}\widehat{\mathbf{f}}^{-1}$	Coefficient (k, l) represents the fraction of product k in industry l inputs.
$\underset{\text{i×p}}{\mathbf{D}^*} = \mathbf{U}^{\mathrm{T}}\widehat{\mathbf{q}_c}^{-1}$	Coefficient (k, l) represents the fraction of product l used by industry k.
$\underset{\text{p×s}}{\mathbf{O}^*} = \widehat{\mathbf{q}_c}^{-1}\mathbf{Y}$	Coefficient (k, l) represents the fraction of product k used by final demand sector s.
$\underset{\text{p×p}}{\mathbf{A}^*} = \mathbf{Z}^*\mathbf{D}^*$	Coefficient (k, l) represents the amount of product k that is made available by direct transformation when supplying one unit of product l. Direct transformation refers to transformation through a single industry.
$\underset{\text{p×p}}{\mathbf{L}^*} = (\mathbf{I} - \mathbf{A}^*)^{-1}$	Coefficient (k, l) represents the total amount of product k that is made available when supplying one unit of product l to the Energy Conversion Chain.
$\underset{\text{i×p}}{\mathbf{L}^*} = \mathbf{D}^*(\mathbf{I} - \mathbf{A}^*)^{-1}$	Coefficient (k, l) represents the total output of industry k that is induced when one unit of product l is made available to the Energy Conversion Chain.

2.2.2 Building the Multi-Regional Physical Supply Use Table framework

In this section, we describe how to construct the MR-PSUT framework from IEA data [45] using as an example the period 2000–2017. Furthermore, the `R` code used to construct the tables is available in the associated online repository (see

Table 2.7: Estimating the effects of a change in the resource matrix. The new resource matrix is noted $\mathbf{R}''$, and matrices induced by the new extracted resources are noted with a prime.

New matrix	Note
$\mathbf{h}'' = \mathbf{R}''^{\mathrm{T}}\mathbf{i}$	New total resources output vector, by resource products.
$\mathbf{q}'' = \underset{\mathrm{p\times p}}{\mathbf{L}^*}\mathbf{h}''$	New total output by product induced by $\mathbf{R}''$.
$\mathbf{Y}'' = \widehat{\mathbf{q}''}\mathbf{O}^*$	New final demand matrix that can be fulfilled by $\mathbf{R}''$.
$\mathbf{y}'' = \mathbf{Y}''\mathbf{i}$	New final demand by product that can be fulfilled by $\mathbf{R}''$.
$\mathbf{U}'' = \widehat{\mathbf{q}''}(\mathbf{D}^*)^{\mathrm{T}}$	New "use" matrix induced by the resource matrix $\mathbf{R}''$.
$\mathbf{V}'' = \underset{\mathrm{i\times p}}{\mathbf{L}^*}\mathbf{h}''(\mathbf{Z}^*)^{\mathrm{T}}$	New "make" matrix induced by the resource matrix $\mathbf{R}''$.
$\mathbf{W}'' = \mathbf{V}''^{\mathrm{T}} - \mathbf{U}''$	New value added matrix.

Data statement). As shown in Figure 2.2, the process to build the multi-regional tables from the national PSUTs can be divided into four steps: (i) region selection and aggregation, (ii) constructing the regional PSUTs, (iii) specifying the multi-regional **R**, **V**, **U**, and **Y** matrices, and (iv) defining the multi-regional matrix. The specification process gathers all regional tables into a single multi-regional table, with each product and industry specified respectively by region of origin and region of location of the industry. The whole process is conducted using the **IEATools** [41] and **ECCTools** [42] open source R packages.

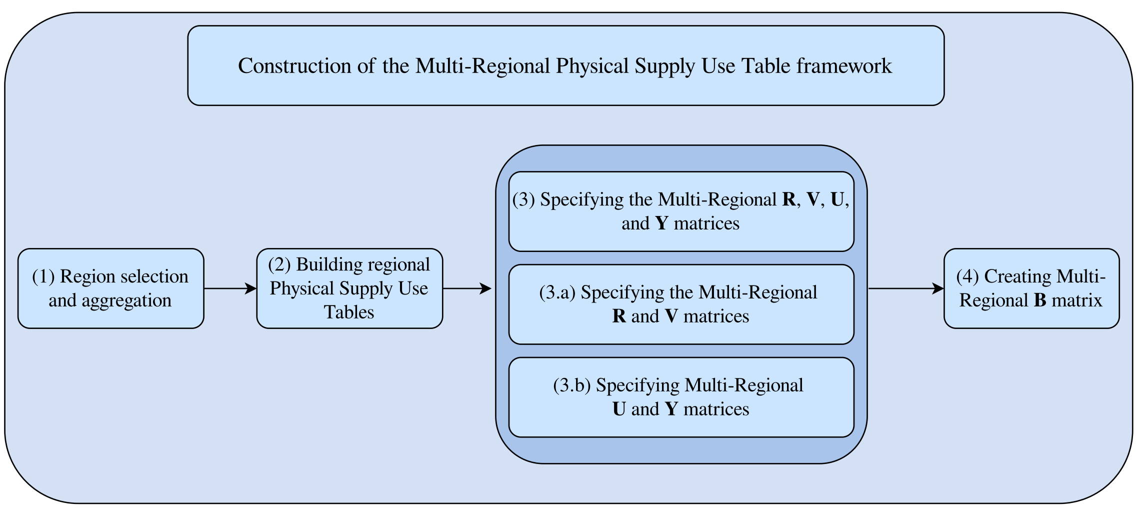

Figure 2.2: Graphical representation of the process followed to construct the Multi-Regional Physical Supply Use Table framework.

Regions selection and aggregation

To limit the size of the matrices and to simplify calculations in the examples presented in Sections 2.3 and 2.4, we aggregate regions in our example following a concordance matrix of IEA regions to the 49 regions of the Multi-Regional Input-Output Model EXIOBASE [46, 47]. Further, and still to limit matrix sizes, we aggregate the EU27 countries (EU28 minus the United Kingdom), which are different regions in EXIOBASE, to a single region, leaving only 23 regions remaining. The concordance matrix for the aggregation is available in the associated online repository. Note, however, that the MR-PSUT framework is independent of and works with any aggregation. Once all energy flows are aggregated by region, we adapt trade flows so that only net trade is registered for each new region.[6]

Building regional PSUTs

The next step is to produce regional PSUTs for each region. The construction of national PSUTs from IEA data was thoroughly described by Heun et al. [28], and the same methodology is adopted here. The **IEATools** open source `R` package is used to construct national tables, and a thorough description of the process involved can be found in the documentation associated with the package [41].

Specifying the multi-regional matrices

Specifying the multi-regional R and V matrices Specifying the multi-regional $\mathbf{R}$ and $\mathbf{V}$ matrices is straightforward, as flows constituting both matrices correspond respectively to domestic extraction and production. As such, we ascribe each of the product output, industry, and resource stock to the region of occurrence. In practice, for each regional $\mathbf{R}$ and $\mathbf{V}$ matrices, we prefix each column (product) and row (industry, or resource stock) by the region name. Then, we drop all rows of the $\mathbf{V}$ matrix that correspond to imports of energy products. Finally, we gather respectively all $\mathbf{R}$ and $\mathbf{V}$ matrices in a multi-regional $\mathbf{R}$ and $\mathbf{V}$ matrix, filling coefficients that do not belong to any regional matrix with zeros.

[6]Indeed, as a result of the aggregation, a newly aggregated region may be found to both import and export a given energy product, which would be an issue in the following steps. Hence, we determine and retain the corresponding imports or exports for relevant products.

Specifying the multi-regional U and Y matrices Each industry of the matrix **U** and final sector of the matrix **Y** are respectively domestic industries and domestic final demand sectors of the region. Hence, we prefix each region name to each column name of regional **U** and **Y** matrices. The next step is to specify each consumed product by region of provenance. Here, we combine two assumptions. First, we define the global market assumption, according to which imports of a given energy product come from an assumed global market for that energy product. Second, we apply the imports proportionality assumption, according to which "imported commodities are proportionally distributed over the target sectors (individual industries and final demand categories) of an importing region" [48, p.1]. The steps needed to specify **U** and **Y** are described in Appendix A.4.

Creating the multi-regional balancing matrix

Next, we remove "stock changes" and "statistical differences" flows from the supply mix and we locate them in the **B** matrix, as described in Table 2.2. This adjustment is necessary, because otherwise, "stock changes" supplying a product (for instance gasoline) would not be translated into primary resources extraction (in this case crude oil), thereby introducing flaws in the calculations.[7] By removing such flows from the supply mix, we assume that products coming from stock changes come instead from the rest of the supply mix. Considering that a product drawn from stocks is a product that was produced in one of the previous years, and then consumed in the present year, the assumption is reasonable, if the goal is to determine the primary energy extracted to fulfil a given final demand, independent of the year of extraction. We also relocate "stock changes" and "statistical flows" that belong to final demand in the "balancing" matrix (**B**). In addition, the minor imbalances that appear when building the MR-PSUT framework due to inconsistencies in IEA data can be corrected by adding a balancing column to the **B** matrix.[8]

[7] We note that the decision to remove stock changes and statistical differences from the supply mix is a decision that the analyst must take depending on the research question, it may be more suitable to keep these flows in some situations.

[8] Such imbalances are to be expected because (i) IEA data does not cover the whole world, (ii) some countries may report a given energy product with a different name, and (iii) the regional balances may be inaccurate — which can be due to poor reporting, or to illegal energy flows and energy smuggling. The balancing column in **B** is therefore a good measure of inconsistencies appearing in IEA data when constructing the MR-PSUT framework.

In the next sections, we present two examples of applications of the MR-PSUT framework. All calculations are conducted using the `R` open source **Recca** package [49].

2.3 Application to energy security

Energy security is a crucial aspect of energy policy, particularly for those countries and regions that do not have significant energy resources (for instance, the EU27 [50]). We show in this section how the MR-PSUT framework can be used to determine the origin of energy products (at the extraction stage) consumed in a given region, which helps to inform energy security issues.

2.3.1 Calculations methodology

Determination of Total Primary Energy Supply, and breakdown by region of origin

Our first step is to use the MR-PSUT framework to determine the TPES for each country. This is because the TPES reported by the IEA for each country in the World Energy Extended Balances data set [45] are incorrect for two reasons. First is the treatment of energy imports and exports. Energy imports are accounted as primary energy supply, although these may refer to final energy products such as electricity or gasoline, while energy exports are subtracted from the primary energy supply, which fails to capture, and subtract, all the primary energy that was needed to produce the energy products exported. Second, energy products supplied by stock changes are also included as primary energy supply, even though they may also be final energy products that have been produced in another year. Hence, and following the new IEA terminology (see World Energy Extended Balances, 2020 edition [51]), we refer to the number reported by the IEA as the "Total Energy Supply" (TES). To determine the actual TPES by region, we define for each region τ the national demand $\mathbf{Y}_\tau$ where only final demand sectors of region τ are included. Then, we compute the new $\mathbf{R}_\tau$ matrix following Table 2.5. The TPES of region τ, noted E_τ can then be calculated by summing up all coefficients of $\mathbf{R}_\tau$, namely:

$$E_\tau = \mathbf{i}^{\mathrm{T}}\mathbf{R}_\tau\mathbf{i}. \tag{2.3}$$

Then, we disaggregate the TPES by supplying region s. The TPES supplied by region s, noted $E_{\tau,s}$, can be calculated by summing all coefficients corresponding to a resource stock (rows) located in region s, and is written as:

$$E_{\tau,s} = \mathbf{i}^{\mathrm{T}}\widehat{\mathbf{k}}_s\mathbf{R}_\tau\mathbf{i}, \tag{2.4}$$

where $\mathbf{k}_s$ is the vector that selects resource stocks located in region s (with ones for resource stocks located in region s, and zeros elsewhere). Similarly, the TPES of region τ supplied by a given energy source type t (for instance, bioenergy), and noted $E_{\tau,t}$, can be calculated by adapting Equation 2.4:

$$E_{\tau,t} = \mathbf{i}^{\mathrm{T}}\widehat{\mathbf{k}}_t\mathbf{R}_\tau\mathbf{i}, \tag{2.5}$$

where $\mathbf{k}_t$ is the vector that selects resource stocks belonging to energy sources of type t (with ones for resource stocks of type t, and zeros elsewhere).

Exposure to overseas supply by energy source

Adapting Equations 2.4 and 2.5, the primary energy supply of region τ supplied by region s from a given energy source type t, can be calculated as:

$$E_{\tau,s,t} = \mathbf{i}^{\mathrm{T}}\widehat{\mathbf{k}}_t\widehat{\mathbf{k}}_s\mathbf{R}_\tau\mathbf{i}. \tag{2.6}$$

Using Equation 2.6, it is possible to determine the contribution of each region s to the primary energy supply by energy source t in country τ, and hence to analyse the exposure of each energy source t to overseas supply.

Exposure to overseas supply by final demand sector

We define, for each region τ and for each final demand sector u, the final demand matrix $\mathbf{Y}_{\tau,u}$. Then, following Table 2.5, we determine the corresponding resource matrix $\mathbf{R}_{\tau,u}$. The primary energy supply of region τ for final demand sector u provided by region s can then be determined as:

$$E_{\tau,s,u} = \mathbf{i}^{\mathrm{T}}\widehat{\mathbf{k}}_s\mathbf{R}_{\tau,u}\mathbf{i}. \tag{2.7}$$

Using Equation 2.7, it is possible to determine the contribution of each region s to the primary energy supply of sector u in country τ, and hence to analyse the exposure of each final demand sector u to overseas supply.

2.3.2 Energy security: results

Determination of the Total Primary Energy Supply, and breakdown by region of origin

Figure 2.3 shows the TPES for a set of eight selected regions, by supplying region (Equation 2.4). The TPES has increased over time for almost all these regions, particularly steeply in the case of China, India, and Brazil, due to their recent rapid economic growth. Some regions, such as the United States (US), China, or Brazil, predominantly consume domestically extracted energy, and have therefore a limited exposure to overseas energy suppliers. The share of domestic TPES in the US has increased since 2010 alongside the surge in US tight oil production [52], while it has decreased in Mexico as domestic oil production decreased by 37% between 2000 and 2017 [1, p. 144]. Remarkably, in the case of Russia, the country is a net exporter for almost all energy carriers, meaning that virtually all its primary energy supply is domestic.[9] Conversely, regions such as the EU27 or Turkey have a very high exposure to overseas suppliers.

Before breaking down the supply of each energy source by region of origin, we separate in Figure 2.4 each region's TPES by energy source (Equation 2.5). Figure 2.4 shows that all regions remain highly dependent on fossil fuel energy, and that the overall increase in renewable energy during recent years has been very modest.[10] In the case of India and Brazil, a significant share of national TPES is based on bioenergy sources, although that share has declined in the Indian case, due to a surge in the reliance on fossil fuels, particularly coal products. The EU, Russia and the US are the only regions shown here to base a significant share of their regional TPES on nuclear fuels (i.e. on uranium), which may increase artificially their domestic TPES (further discussed in Section 2.3.3). We note that a graph similar to Figure 2.4 could be obtained directly from the IEA World Energy Extended Balances, but for the inconsistencies described in Section 2.3.1 (e.g. energy imports and stock changes accounted as primary energy supply). (Appendix A.5 shows and discusses the TES

[9] Virtually, for two reasons. First, there are minor imports of primary energy in our calculations in Russia, but these are so small that they do not appear in the figure. Second, the methodology described in Section 2.2.2 is based on net energy trade flows, which hides gross energy flows. We discuss this issue further in Section 2.3.3.

[10] We note, however, that the quantification of the primary energy of renewable electricity is subject to methodological issues, and that the convention used is of crucial importance. See Sousa et al. [53] or Miller et al. [54] for a comprehensive discussion.

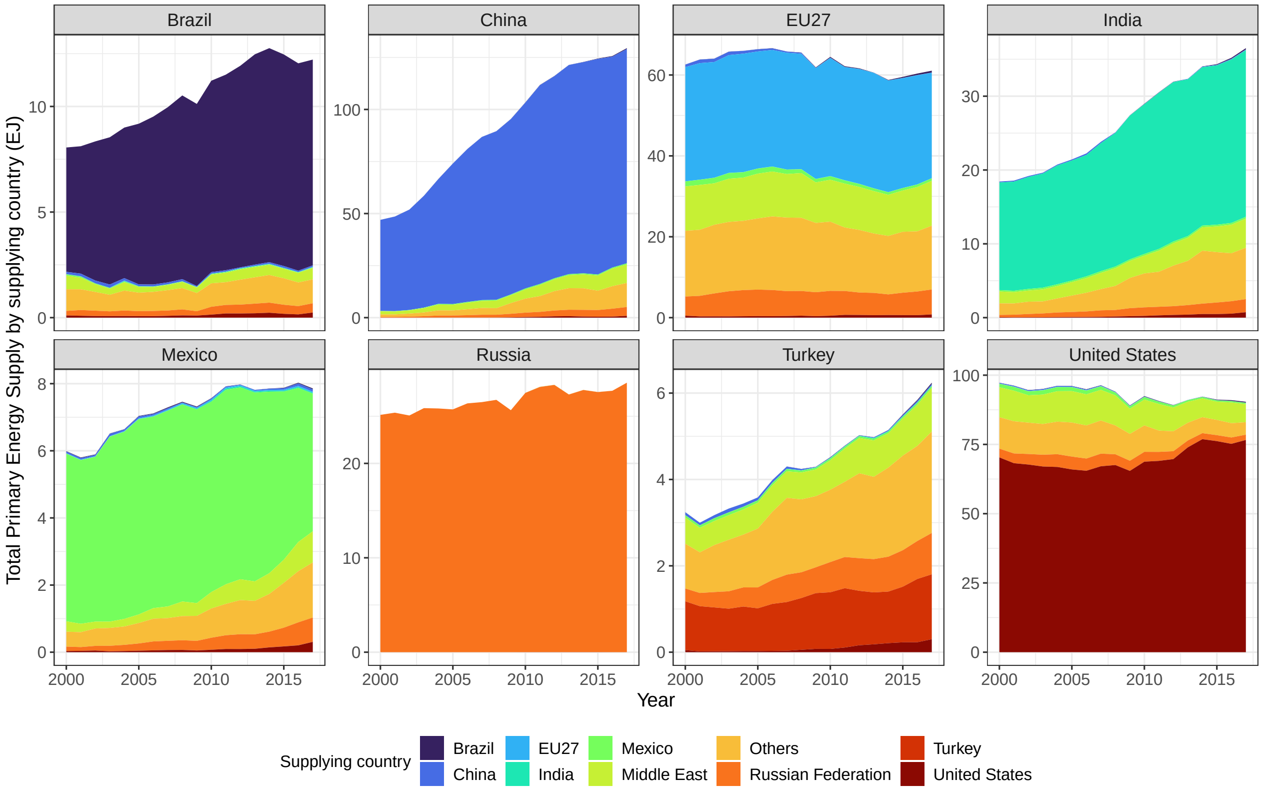

Figure 2.3: Total Primary Energy Supply for different regions, broken down by supplying region.

graphs obtained when directly using IEA data.)

Exposure to overseas supply by energy source

Figure 2.5 shows the exposure to overseas suppliers by energy source in the case of China, the EU27, India, and the United States, both in 2000 and 2017 (Equation 2.6). The exposure to overseas suppliers is in general particularly high for fossil fuels. Oil products come in all cases with the highest exposure, followed by natural gas, and then by coal products. Hence, the reduction of fossil fuel consumption would tend to reduce each region's dependence on imported energy — assuming that substitutes are not overseas supplied — particularly in the case of the EU27 and India. Then, bioenergy, renewable energy, and nuclear energy present low exposures to overseas supply — although this result is, in the case of renewable energy and nuclear energy, crucially dependent on the boundaries of the Energy Conversion Chain

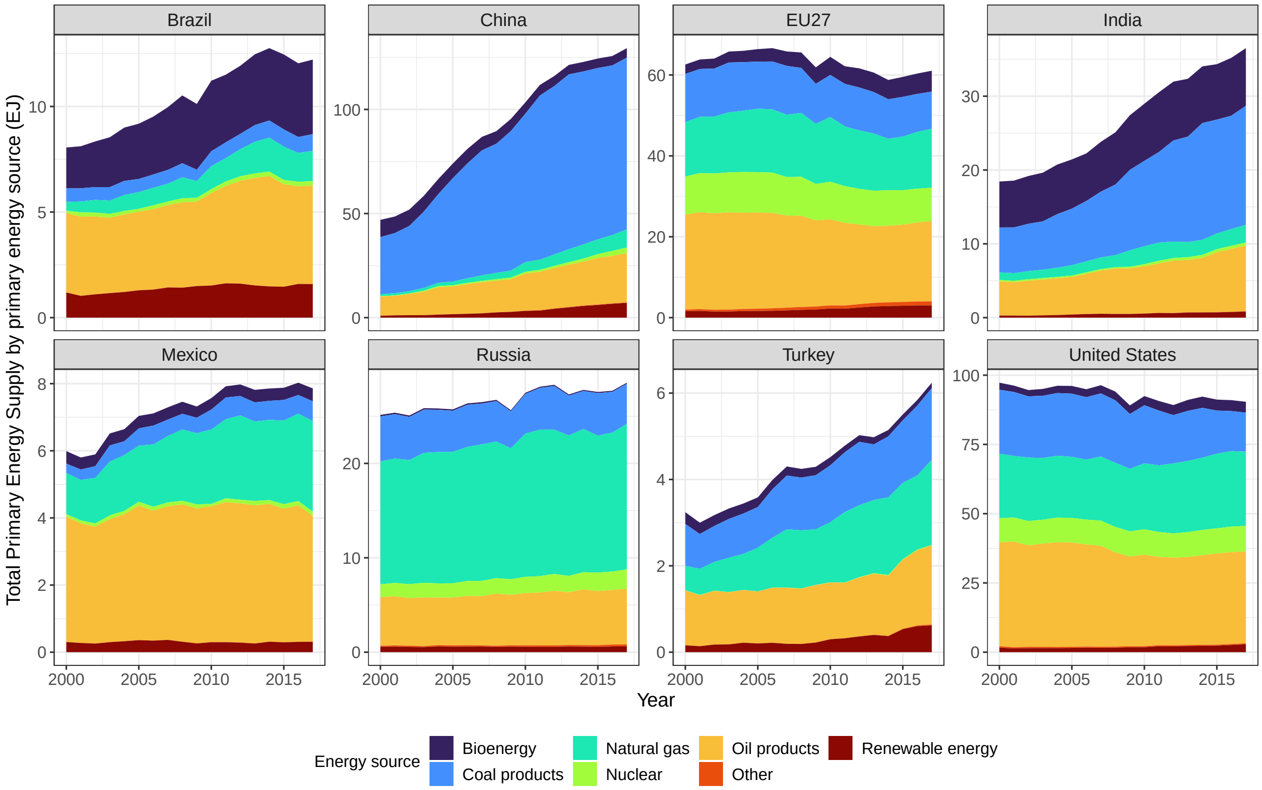

Figure 2.4: Total Primary Energy Supply for different regions, broken down by primary energy source.

adopted (see Section 2.3.3). The exposure of China and India to overseas suppliers, for oil products and natural gas, has increased in recent years, as demand and imports have surged as consequence of rapid economic growth. Conversely, the US has reduced its import dependence as oil products and natural gas come increasingly from domestic sources, as a consequence of the tight oil boom in the US. Lastly, the EU27's exposure to overseas supply, when looking at fossil fuels, increases over time, as fossil fuel extraction activities are being phased out in the EU27.

Exposure to overseas supply by final demand sector

Figure 2.6 shows the exposure to overseas supply by final demand sector in the case of China, the EU27, India, and the United States, in 2000 and 2017 (Equation 2.7). Road transportation has in almost all cases the highest exposure to overseas supply — due to the fact that road transportation consumes mostly oil products — and

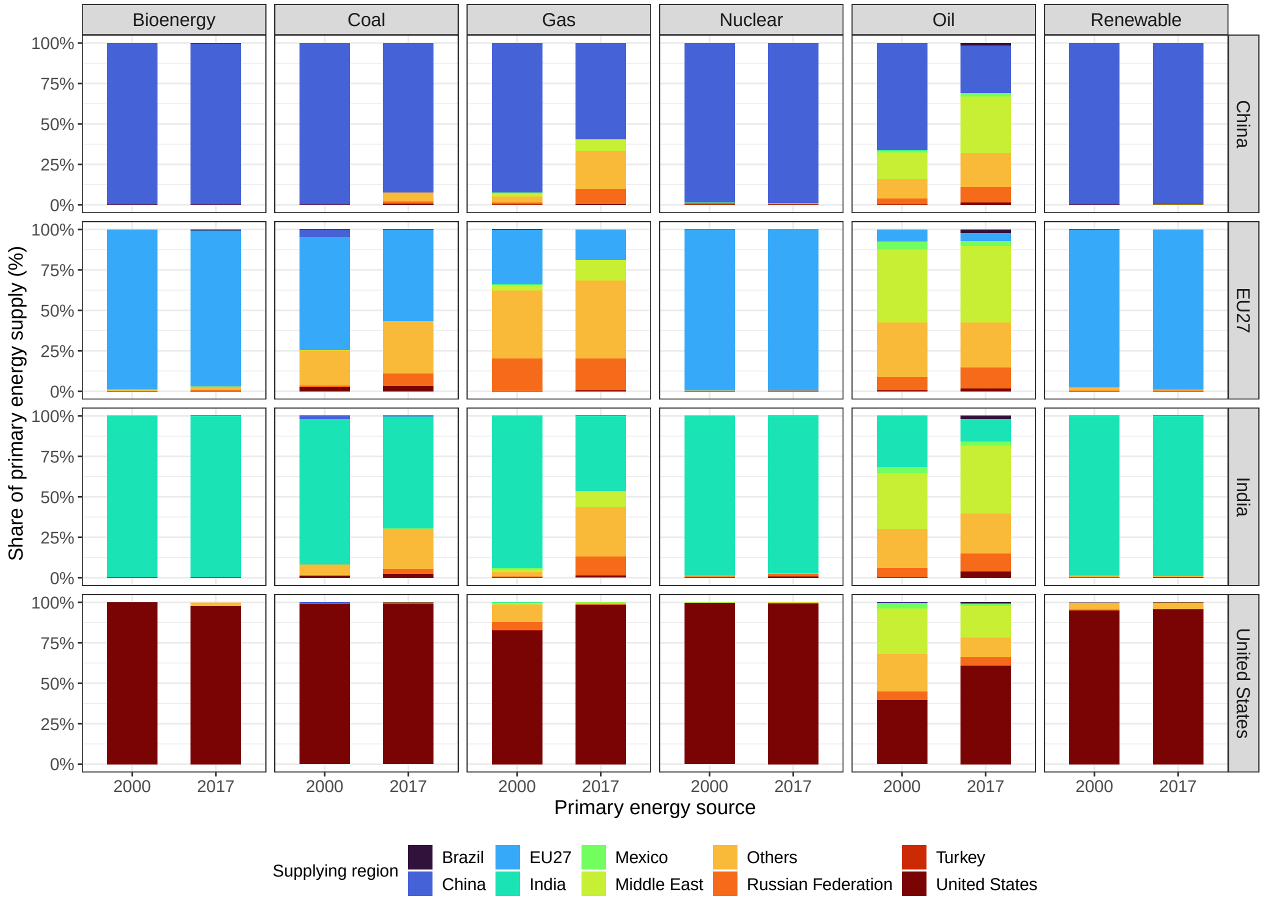

Figure 2.5: Primary Energy Supply for different energy sources, broken down by supplying region.

reaches the highest levels in the case of the EU27 and India. The exposure to overseas supply of Chinese sectors has increased in the period 2000–2017, as the country relies increasingly on imported oil products and natural gas. In most cases, the exposure of the rail sector is significant, which is partly due to the fact that rail transportation still relies on diesel as a fuel, but also due to the fact that electric trains may be consuming fossil fuel based electricity. Last, the US exposure has dramatically decreased, again due to the tight oil boom in the US.

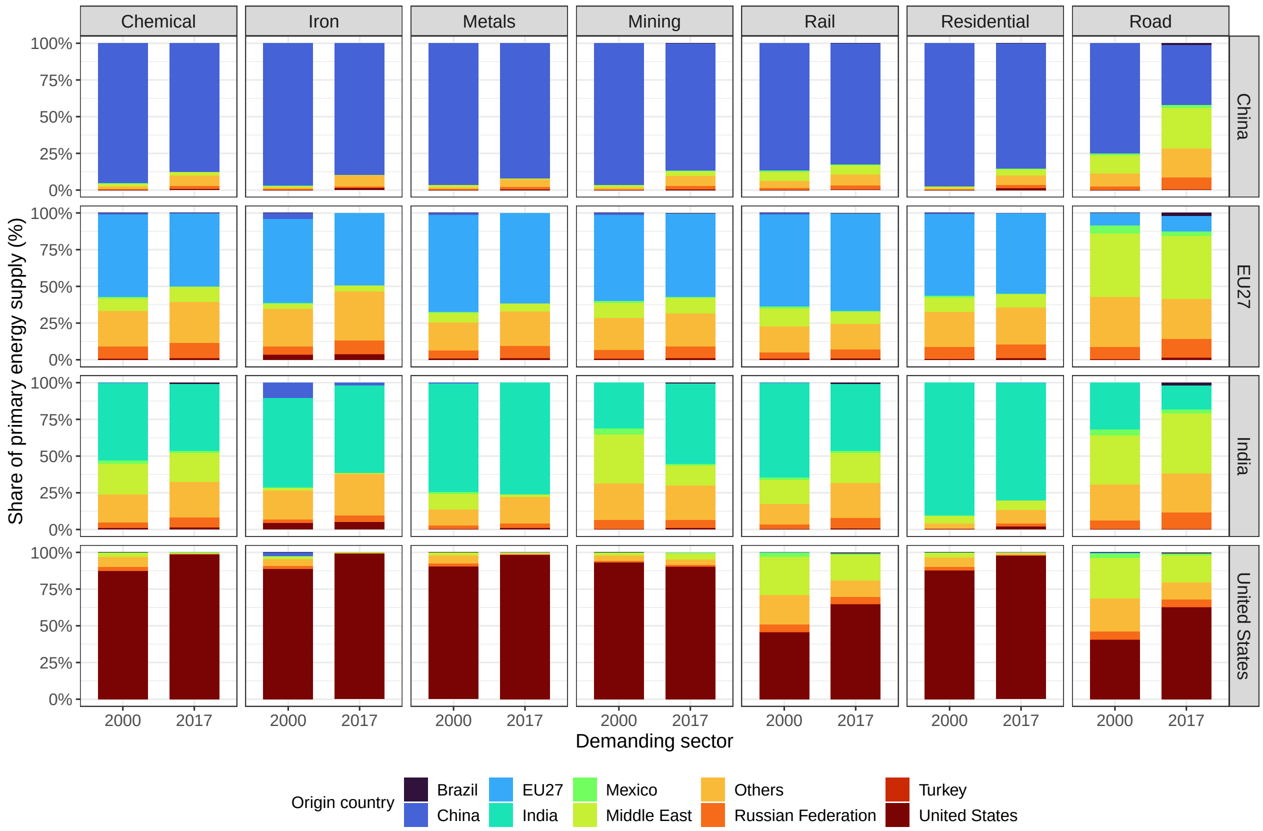

Figure 2.6: Primary Energy Supply for different final demand sectors, broken down by supplying region. Metals: Metallic ores processing and metal refining.

2.3.3 Implications, limitations, and recommendations

This first example shows that the MR-PSUT framework, as it tracks energy flows across regions, can be used to determine the region of origin of a given final energy product, and hence can be used in the broad field of energy security [55, 56] — particularly, to assess the reliance of a given region on overseas primary energy supply, either for a given product or for a given final demand sector. There are however three limitations that any analyst needs to consider. First, the global market assumption is a simplifying assumption. Indeed, the global trade of energy products occurs in such a way that some regions are chief suppliers of other regions (for instance, the EU imports considerable amounts of natural gas specifically from Norway Algeria, and Russia). The trade of energy products is heavily reliant on installed infrastructure: in the case of natural gas, pipelines are built only when long-term contracts ensure their viability, while gasification and liquefaction plants constrain exporting and importing capacities through gas tankers [57]. The MR-PSUT framework is however not dependent on such a global market assumption, and the trade linking process (Section 2.2.2) could well be performed with bilateral trade data. The **ECCTools** package enables users to use bilateral trade data to refine the trade-linking process. Considering that the main purpose of this paper is to introduce the MR-PSUT framework, its structure and potential applications, the global market assumption is sufficient here, but further studies applying the framework to energy security would benefit from use of bilateral trade data.

Second, the MR-PSUT framework has been constructed using net energy flows, i.e. considering that each region is either an importer or an exporter of a given energy product (or alternatively, does not trade the given energy product). Such an assumption is also simplifying to the extent that some energy products, such as electricity, are imported and exported depending on the supply and demand of electricity, and indeed, such a situation is likely to increase as electricity generation moves increasingly towards renewable energy, which is highly dependent on climatic conditions [8]. Hence, results yielded by the MR-PSUT framework should be seen as the energy balance over a year, expressed in net energy terms, and it should be kept in mind that such results may hide some energy trade between regions.

Third, an important limitation is related to the upstream boundary of the energy industry. Results in Section 2.3.2 show that the exposure to overseas supply is zero in the case of nuclear energy. However, nuclear fuels are extracted in a handful of countries [58, p. 87], which invalidates the conclusion of nuclear energy being mostly domestically produced. This limitation is however not related to the MR-PSUT framework, but rather to the input data — the IEA's World Energy Extended Balances data [45] do not include flows corresponding to nuclear fuels extraction. Improving the input data to explicitly represent nuclear fuels extraction would overcome such a limitation. The boundary of the energy industry is also worth keeping in mind when looking at renewable energy, which may be domestically produced, but which (i) relies on numerous rare minerals and metals [59, 60], many of which are extracted in a handful of countries [61], and (ii) relies on systems (e.g. solar panels, wind turbines...) which may not be produced domestically. The concept of energy security is indeed complex and multidimensional [62, 63], and should not be analysed with the MR-PSUT framework only — in a similar vein, the fact that primary energy is domestically produced may contribute to a region's energy security, but does not guarantee altogether that energy supply is secure (one can think about possible strikes, dependence on private companies and technology, etc).

2.4 Application to the accounting of greenhouse gas emissions

The energy industry, and particularly, fossil fuel consumption, is responsible for most greenhouse gas emissions worldwide. We show in this example how energy-related greenhouse gas emissions can be accounted for and disaggregated in terms of energy use by the energy industry, downstream energy use (i.e. energy use by final demand sectors), and methane leakages and flaring, and then ascribed to the final demand region.

2.4.1 Calculations methodology

Determination of energy-related greenhouse gas emissions by energy product

For this analysis, we differentiate greenhouse gas emissions in terms of (i) emissions due to energy use in the energy industry (i.e. energy use for extracting primary energy products, and refining and transforming them into final energy products), (ii) emissions due to downstream energy use (i.e. energy use by final demand sectors), and (iii) emissions due to methane flaring and leakages in the extraction process (fugitive emissions). We exclude transportation emissions because transportation sectors are included as final demand sectors in the MR-PSUT framework.

To calculate these emissions, we start by defining the CO_2 equivalent extension vector $\mathbf{e}_{\mathrm{c}}$ as the greenhouse gas emissions due to the combustion of one unit of each resource product. In addition, we define the CO_2 equivalent extension vector $\mathbf{e}_{\mathrm{f}}$ as the fugitive emissions (methane flaring and leakages) due to the extraction of one unit of each resource product — in the rest of the paper, we use CO_2 emissions to mean CO_2 equivalent emissions — and greenhouse gas emissions.[11] The

[11] Accounting for CO_2 emissions at the extraction of resource products avoids the double accounting of CO_2 emissions. Indeed, an energy product may undergo numerous transformations

CO_2 extension vectors are constructed using IEA data and are further described in Appendix A.6.

To determine energy-related CO_2 emissions for each energy product, we take advantage of Input Output multipliers, which are defined as the effect of a change in final demand on total aggregate output [15]. Hence, output multipliers capture both the direct and indirect effects, i.e. the total effects, of an increase in the final demand vector $\mathbf{y}$. The vector of energy-related CO_2 emissions by product due to combustion, i.e. the vector of combustion-related CO_2 multipliers [39, 64], is defined as:

$$\mathbf{m}_{\mathrm{c}}^{\mathrm{T}} = \mathbf{e}_{\mathrm{c}}^{\mathrm{T}} \widehat{\mathbf{k}}_p \underset{\mathrm{p} \times \mathrm{p}}{\mathbf{L}} \mathbf{i}. \tag{2.8}$$

where $\mathbf{k}_p$ is the vector that selects resource products; i.e. for which the value is one for resource products, and zero otherwise. Then, we determine the vector of emissions due to energy use by the energy industry, by energy product, as:[12]

$$\mathbf{m}_{\mathrm{eiou}}^{\mathrm{T}} = \mathbf{m}_{\mathrm{c}}^{\mathrm{T}} \mathbf{Z}_{\mathrm{eiou}} \underset{\mathrm{i} \times \mathrm{p}}{\mathbf{L}} \mathbf{i}. \tag{2.9}$$

The vector of emissions due to downstream energy use by energy product is then calculated as:

$$\mathbf{m}_{\mathrm{d}} = \mathbf{m}_{\mathrm{c}} - \mathbf{m}_{\mathrm{eiou}}. \tag{2.10}$$

Then, the vector of fugitive emissions by product due to methane flaring and leakages is defined as:

$$\mathbf{m}_{\mathrm{f}}^{\mathrm{T}} = \mathbf{e}_{\mathrm{f}}^{\mathrm{T}} \widehat{\mathbf{k}}_p \underset{\mathrm{p} \times \mathrm{p}}{\mathbf{L}} \mathbf{i}. \tag{2.11}$$

and the vector of total energy-related CO_2 emissions, i.e. the vector of CO_2 multipliers, is defined as:

$$\mathbf{m}_{\mathrm{CO_2}} = \mathbf{m}_{\mathrm{eiou}} + \mathbf{m}_{\mathrm{d}} + \mathbf{m}_{\mathrm{f}}. \tag{2.12}$$

To understand better the energy-related CO_2 emissions by energy product, we quantify the primary energy embodied in each energy product and we break it down by

before being consumed, but eventually, the CO_2 content of the resource product being extracted from the ground, is released in the atmosphere.

[12]Note that $\mathbf{Z}_{\mathrm{eiou}}$ is defined as $\mathbf{U}_{\mathrm{eiou}} \widehat{\mathbf{g}}^{-1}$, according to Table 2.4.

primary energy type. We follow Guevara et al. [39] to define a vector of primary energy multipliers as:

$$\mathbf{m}_{\mathrm{e}}^{\mathrm{T}} = \mathbf{k}_{p}^{\mathrm{T}} \underset{\mathrm{p}\times\mathrm{p}}{\mathbf{L}} . \tag{2.13}$$

Then, we decompose the embodied primary energy by resource product following Equation 2.14:

$$\mathbf{M}_{e} = \widehat{\mathbf{k}}_{p} \underset{\mathrm{p}\times\mathrm{p}}{\mathbf{L}} . \tag{2.14}$$

We can then simply aggregate by primary energy type (e.g. oil products).

Determination of energy-related greenhouse gas emissions by final demand sector

For each region τ, we determine the vector of energy-related CO_2 emissions due to combustion $\mathbf{f}_{\mathrm{c}}$ by sector (so, the vector containing in coefficient k the energy-related CO_2 emissions by final demand of sector k) as:

$$\mathbf{f}_{\mathrm{c}}^{\mathrm{T}} = \mathbf{e}_{\mathrm{c}}^{\mathrm{T}} \widehat{\mathbf{k}}_{p} \underset{\mathrm{p}\times\mathrm{p}}{\mathbf{L}} \mathbf{Y}_{\tau}, \tag{2.15}$$

and the vector of fugitive emissions due to methane flaring and leakages $\mathbf{f}_{\mathrm{f}}$ as:

$$\mathbf{f}_{\mathrm{f}}^{\mathrm{T}} = \mathbf{e}_{\mathrm{f}}^{\mathrm{T}} \widehat{\mathbf{k}}_{p} \underset{\mathrm{p}\times\mathrm{p}}{\mathbf{L}} \mathbf{Y}_{\tau}. \tag{2.16}$$

Then, the vector of total energy-related CO_2 emissions is defined as:

$$\mathbf{f}_{\mathrm{CO_2}} = \mathbf{f}_{\mathrm{c}} + \mathbf{f}_{\mathrm{f}}. \tag{2.17}$$

2.4.2 Accounting for greenhouse gas emissions: results

Determination of energy-related greenhouse gas emissions by energy product

Figure 2.7 shows the energy-related CO_2 emissions intensity by energy product (Equations 2.9–2.12), in 2010 and 2017, for China, the EU27, Russia, and the United States. Emissions due to the downstream use of energy products are considerably higher than emissions due to both energy use by the energy industry and emissions due to methane flaring and leakages. Differences across regions increase with the degree of transformation of energy products: for crude oil, natural gas, and coking coal, differences are hardly noticeable, while they are striking in the case of heat and electricity. Indeed, such differences in the case of electricity and heat are mostly due to the differences in the composition of the primary energy of heat and electricity, which are shown in Figure 2.8 (Equation 2.14), for the same four regions.

The differences in the composition of embodied primary energy explains the differences in the energy-related CO_2 emissions intensities observed in Figure 2.7. A large share of the EU electricity comes from nuclear fuels and renewable energy, leading to a relatively low energy-related CO_2 emissions intensity observed in Figure 2.7. In the Russian case, the energy-related CO_2 emissions intensity of electricity is lower than in the US and China due mostly to a higher use of natural gas and lower use of coal products for electricity generation. Important changes can be observed in the period 2000–2017 for particular products, for instance the coal products embodied in electricity has significantly decreased in China and in the US, leading to an improvement in CO_2 emissions intensity of electricity (Figure 2.7). The embodied primary energy in heat has also been significantly reduced in the US, mainly because of reduced consumption of embodied coal products, which has led to a reduced CO_2 intensity. Evolutions over time are particularly noticeable for electricity and heat, which may come from decarbonised energy sources, while fossil fuels are inherently carbonised.

Determination of energy-related greenhouse gas emissions by final demand sector

Figure 2.9 shows the greenhouse gas emissions by sector (Equations 2.15, 2.16, 2.17) for the EU27, the US, India and China, using the chemical and petrochemical, iron and steel, and road transportation final demand sectors as examples. The road transportation sector is responsible for considerably more emissions than the chemical and petrochemical and iron and steel sectors in the EU27 and the US, which shows the large scale of the road transportation sector in such industrialised regions. Emissions of the road transportation sector are unsurprisingly mostly due to oil products, while most emissions of the iron and steel sector come from coal products, due to the large use of coke to reduce iron ore in the sector. Emissions from the chemical and petrochemical and iron and steel sectors have decreased over years

Figure 2.7: Energy-related CO_2 emissions for a unit of energy product delivered, disaggregated in terms of (i) emissions due to energy use by the energy industry, (ii) emissions due to downstream energy use by final demand sectors, and (iii) fugitive emissions due to methane flaring and leakages. Unit: kgCO_2 equivalent per GJ.

in the EU27 and in the US as a combination of increasing efficiencies and moving industrial activities to developing countries — a deeper study would be needed to untangle these effects (see [20] for an example) — while emissions of these sectors have increased in China and India (particularly for the iron and steel sector) as the regions are increasing industrial output.

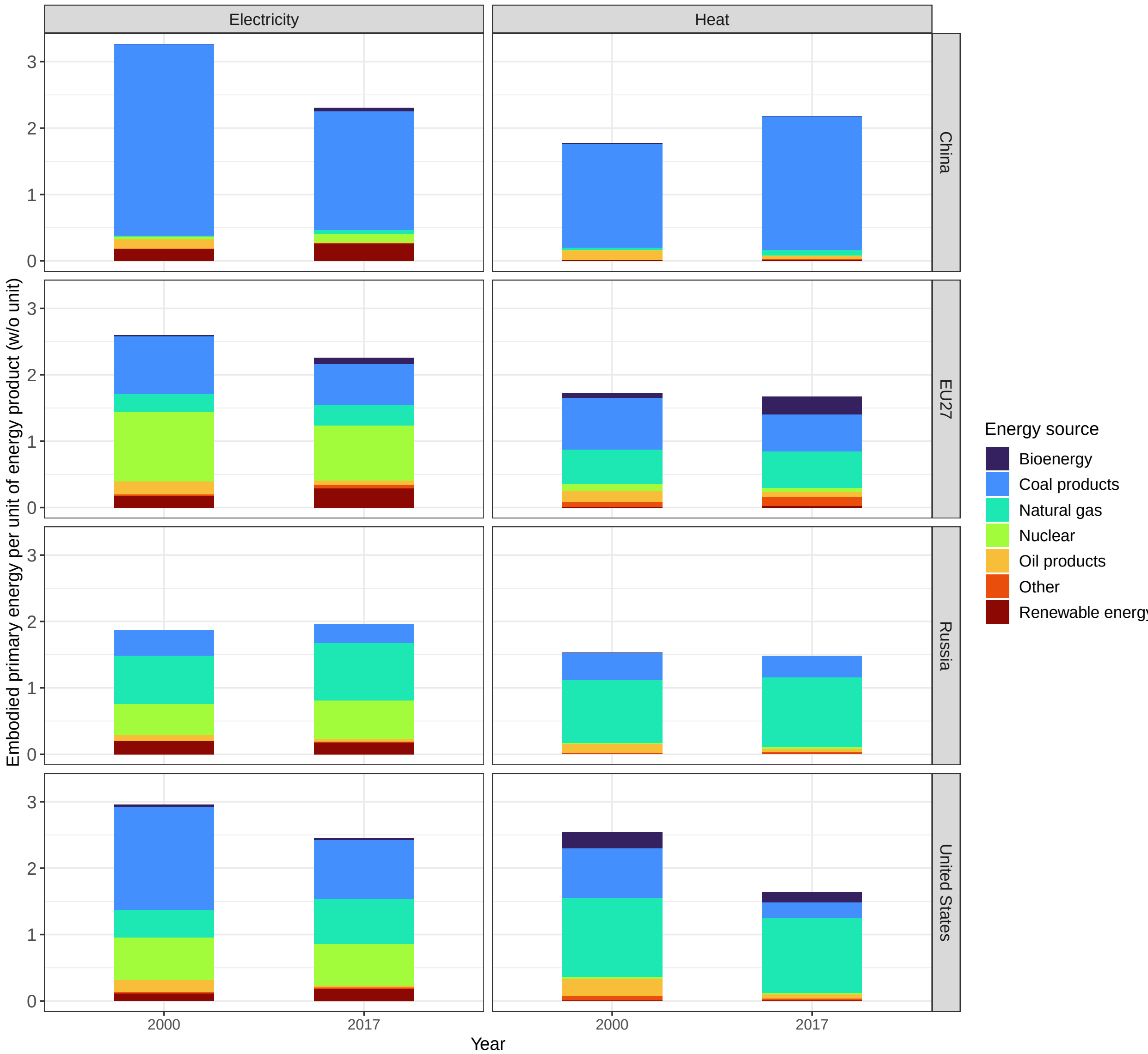

Figure 2.8: Embodied primary energy by primary energy source, for one unit of provided final energy, in the case of electricity and heat. Without unit (energy per energy).

2.4.3 Implications, limitations, and recommendations

Quantification of greenhouse gas emissions We have shown (in Figures 2.7 and 2.9) how energy-related greenhouse gas emissions can be quantified and disaggregated by type of emissions (due to energy use by the energy industry, downstream energy use by final demand sectors, and fugitive emissions due to methane flaring

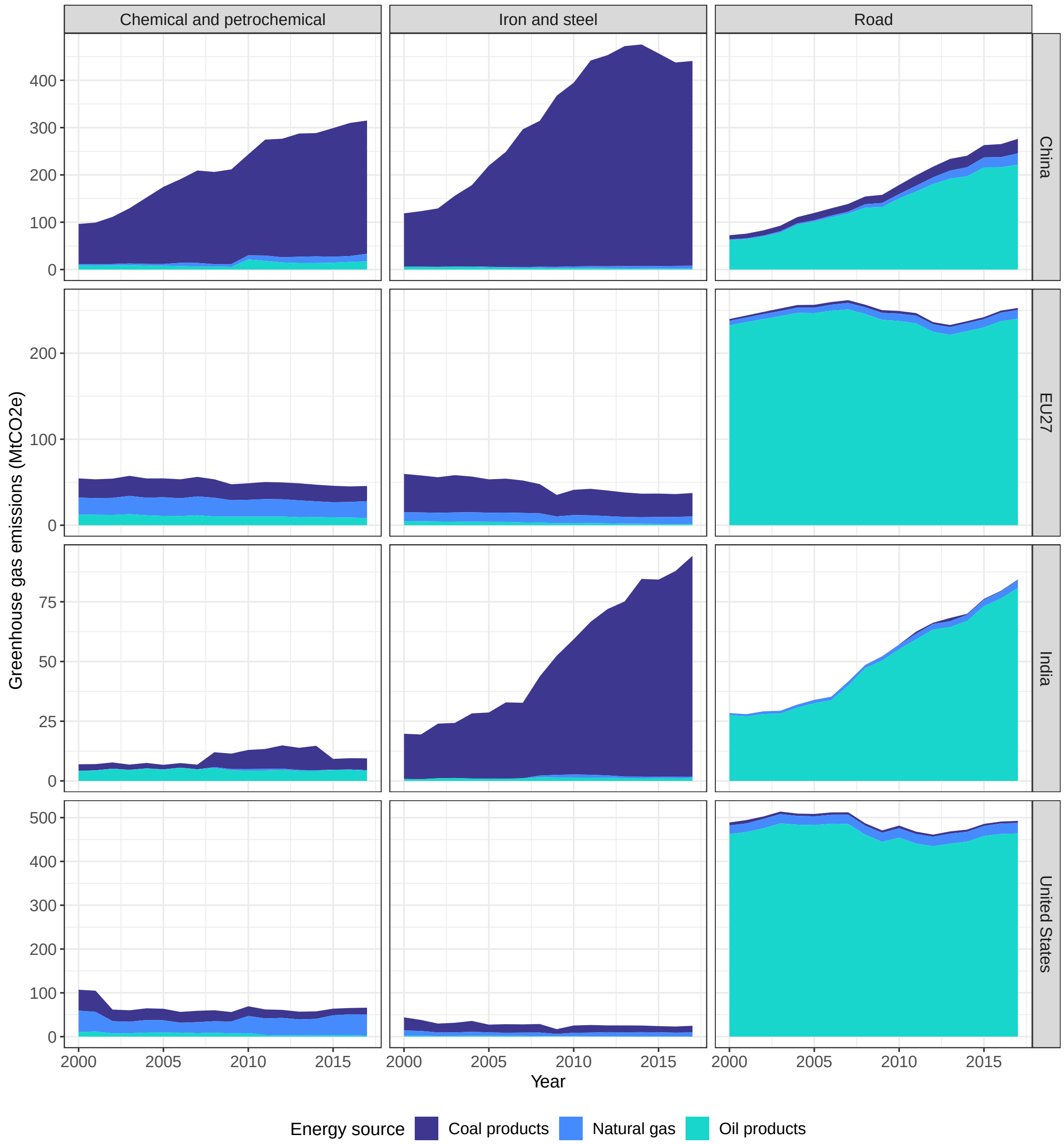

Figure 2.9: Greenhouse gas emissions by sector and energy source. Values in $MtCO_2e$ (1e6 tons of CO_2 equivalent).

and leakages) using the MR-PSUT framework. Emissions may be accounted for by energy product, or by final demand sector, and the framework also allows analysts to monitor evolutions over time and their causes, for instance looking into the composition of the embodied primary energy, be it by energy product or final demand sector. While we have demonstrated the framework focusing on fossil fuel emissions only, the framework can also be used to quantify the greenhouse gas emissions of bioenergy, which may become crucial in the near future. Indeed, while recent EU and US legislation favours the development and the consumption of bioenergy and biofuels (see pieces of legislation [65–67]), recent studies have questioned the environmental benefits of principally biofuels, most notably because of the possible induced indirect land use change [68, 69]. By tracking energy flows across borders, the framework allows analysts to identify the region of primary production of such fuels, and to ascribe greenhouse gas emissions due to deforestation to the final consumer region.

In addition to the limitations already raised in Section 2.3.3, an important limitation is that the MR-PSUT framework only allows analysts to account for greenhouse gas emissions related to the energy industry, either because of energy production or because of downstream energy combustion. But other greenhouse gas emissions, coming for instance from cement production, or from the reduction of metallic ores, cannot be captured with the framework. Likewise, greenhouse gas emissions due to the manufacture of the energy industry infrastructure (oil fields, refineries, solar panels, wind turbines...) cannot be estimated with the MR-PSUT framework. Other techniques such as Life Cycle Analysis need to be adopted to assess such emissions [70].

Further application: accounting for resources extraction We have also shown that the framework allows analysts to quantify the primary energy embodied in energy products, and hence in each final demand sector, by final energy product. More generally, a key feature of the MR-PSUT framework is that it explicitly describes primary energy resources extraction through the resource matrix, and hence consistently binds energy products supplied to society to the level of primary energy resources extraction. Such an explicit representation makes the framework useful for energy-economy modelling, as energy products required for the functioning of the economy may be linked to the primary energy resources extraction, thereby facilitating the dynamic representation of primary energy resources stocks in broader models.

2.5 Conclusion

In this paper, we have introduced a Multi-Regional Physical Supply Use Table framework that builds on recent work. The new framework enables analysts to track energy flows across countries and to analyse the global trade of energy products using Input Output techniques. In doing so, it overcomes limitations of single region Physical Supply Use Table frameworks, which represent imports as a supplying industry and exports as a final demand sector. The adoption of a physical description of energy flows rigorously binds energy products supplied to the economy to a given Energy Conversion Chain, thereby overcoming some of the key limitations of traditional Energy Extended Input Output analysis. In addition, the expansion of the existing Physical Supply Use Table framework with a new resource matrix provides the framework with symmetry, binding energy products supplied to the economy to extracted primary energy resources and to the location of extraction. The symmetry of the framework enables analysts to reverse Input Output calculations, and to determine the downstream consequences of the extraction of primary energy in a given location. The practical process to construct the Multi-Regional Physical Supply Use Table framework using data from the International Energy Agency has been described, and we have introduced open source `R` packages (**IEATools**, **ECCTools**, and **Recca**) that allow for a straightforward adaptation of the present work.

The framework is of particular value for linking the origin of primary energy extraction to the final demand region and sector for final energy products that are traded multiple times throughout their processing; for instance oil products that are extracted, refined, and finally consumed, in different regions. The framework is flexible, so that it may be used as a screening tool using an approximative assumption such as the global market assumption in the trade linking process. It may also be used as a tool to study in-depth the supply chain of a given energy product and region, in which case the relevant trade links can be built more precisely, while keeping as background a simplifying assumption for those flows less relevant to the question investigated.

The MR-PSUT framework is versatile, and may be useful for a wide range of energy analysis subfields. In addition to the applications demonstrated in this article (i.e. the analysis of a region's energy security and the accounting of greenhouse gas emissions) historical and energy transition studies may benefit from coupling the framework with the long time series of the International Energy Agency's World Energy Extended Balances. The framework can be of particular relevance to the Societal Exergy Analysis community, for it enables analysis both in energy and exergy terms, as well as at the useful stage of the Energy Conversion Chain. A wide range of environmental impacts related to the energy industry may be estimated and ascribed to the final demand region using the framework. For instance, biodiversity impacts and land use change induced by biofuel production could be estimated depending on the type of primary energy extracted and the location of extraction. The explicit representation of primary energy resources extraction allows the framework to be coupled with a stock-flow consistent structure, and thereby to account dynamically for energy resource stocks, which is crucial for energy-economy modelling in a resource-constrained future.

Data statement

The IEA data used to construct the MR-PSUT framework (World Energy Extended Balances 2019) is not publicly available; the user needs to access IEA data through a valid license. However, the `R` code that we used to construct the MR-PSUT framework from the raw IEA data and the concordance matrix for the regional aggregation are available under a CC-BY-4.0 license at the University of Leeds Data Repository: https://doi.org/10.5518/1091.

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Chapter 3

Global energy consumption of the mineral mining industry: exploring the historical perspective and future pathways to 2060

Emmanuel Aramendia, Paul E. Brockway, Peter G. Taylor, Jonathan Norman

The mining industry globally is responsible for significant energy consumption, and is an important source of greenhouse gas emissions. Considering that future mineral demand is likely to increase and that the final energy consumption per unit mass of mineral extracted (energy intensities of mining) is also forecast to increase as a result of a decrease in mineral resource deposit qualities, the mining industry's final energy consumption will increase in the future. But the scale of that future increase remains unexplored. In this study, we (i) provide the first bottom-up assessment of the mining industry's final energy consumption globally (1971–2015), (ii) use 1.5°C consistent socio-economic scenarios to conduct an exploratory study of future possible pathways for the mining industry's final energy consumption, and (iii) review the extent to which such energy consumption is considered in energy-economy models.

We find that the mining industry is currently responsible for approximately 1.7% of global final energy consumption. However, the mining industry's final energy consumption is likely to increase significantly, by a factor in the range 2–8 by 2060, depending on the future economic trajectory, on the evolution of energy intensities, and on future recycling rates. We also find that mineral material flows and their associated energy requirements (including the mining industry's energy consumption) are insufficiently covered in many energy-economy models. Our work suggests that the limited representation of material flows and associated energy requirements is currently an important blind spot in energy-economy modelling and may hinder the efforts of the community to build consistent energy transition pathways.

3.1 Introduction

3.1.1 Mining, energy consumption, and environmental impacts

The mining industry is responsible for a wide range of environmental and societal impacts, including biodiversity loss [1, 2], soil and water pollution [3, 4, Chapter 6], water consumption [5, 6], and health impacts in workers and neighbouring communities [7, 8]. In particular, the mining industry consumes considerable amounts of energy, which results in significant greenhouse gas emissions [9–11]. The magnitude of all these impacts has considerably increased over time as the quantities of extracted minerals has surged since the industrial revolution [12, 13], driven by industrialisation and rapid economic growth [14, 15]. The large environmental impacts caused by mining activities are of particular concern in the present context of major environmental degradation and transgression of some planetary boundaries that underpin the state of the Earth System [16, 17], and in particular, climate change. The Paris Agreement was reached with the aim of limiting global warming to well below 2°C (compared to pre-industrial levels), and at pursuing efforts to limit the Earth's warming to 1.5°C [18, 19]. Achieving such ambitious climate targets requires a steep reduction in greenhouse gases until net-zero emissions are reached [20], which, in turn, requires a rapid curtailment in fossil fuel consumption [21]. Limiting the level of global energy consumption is needed to help abate fossil fuel consumption, and hence, achieve net-zero targets.[1] Understanding the future possible energy pathways of energy-intensive industries, including the mining industry, is therefore key to supporting climate change mitigation efforts.

Despite the need for climate change mitigation, current trends suggest a future increase in the scale of mining activities (measured by extracted volumes — note that fossil fuel extraction activities are outside the scope of this study) and associated energy consumption, due to three main drivers. First is future economic growth, which has been shown historically to be highly correlated to energy and resources use [28, 29] — and thus resources extraction and mining activities. As the evidence

[1] Of the four marker scenarios used in the Intergovernmental Panel on Climate Change's Special Report on 1.5°C, the two that do not rely on speculative carbon dioxide removal technologies assume a decrease in final energy consumption [22, Chapter 2]. (See [23–27] for a critical discussion on carbone dioxide removal technologies.)

of absolute decoupling between natural resources use and economic growth remains, at a global level, very thin [30–32], future economic growth is likely to increase the scale of global mineral extraction. In addition, the growth in the information and communications technology sector, which has high demand for many minerals and metals [33], is likely to hamper such decoupling. Second is the renewable energy transition. Renewable energy systems are highly dependent on critical raw minerals [34–36], and their deployment will induce a surge in the demand and extraction of particular materials [37–40], potentially leading to bottlenecks in the supply chain and availability issues for specific materials [41–44]. Third comes the increase in the final energy required per unit mass of mineral recovered — i.e. the energy intensities of mining activities — associated with the decrease in natural resources deposits qualities. As high quality deposits tend to be exploited first, sustaining mineral extraction requires a move towards lower quality deposits (lower ore grades, lower grinding size, deeper and increasingly remote mines...), which in turn augments the energy consumption (as well as other environmental and social impacts) of mineral extraction [4, 45, 46]. Such a situation, characteristic of the ongoing process of natural resources depletion [47, 48], is likely to happen to numerous minerals as the quality of tapped deposits decreases [5, 49–52], and is already limiting the productivity growth of the mining industry [53].

The three drivers of increasing mining activities and associated final energy use can conceptually be summarised by Equation 3.1:

$$
\begin{aligned}
\mathrm{E} &= \mathrm{E}_{\text{growth}} + \mathrm{E}_{\text{transition}} \\
&= \sum_{m} \mathrm{GDP} i_m (1 - r_m) e_m + \sum_{t,m} c_t j_{t,m} (1 - r_m) e_m,
\end{aligned}
\tag{3.1}
$$

where E stands for the mining industry's final energy consumption, i_m for the material intensity of the economy for mineral m, r_m for the recycled content (or recycling input rate) of mineral m, e_m for the final energy intensity of mining mineral m, c_t for the newly installed technology t, and j_t for the material intensity in mineral m of technology t. Only recycling rates appear as a potential offsetting lever. Taken together, these three drivers suggest that the energy consumption of the mining industry is likely to increase. In this context, it is crucial to explore the future pathways that the mining industry's energy consumption may follow.

3.1.2 Aim, approach, and content

The aims of the paper are threefold. First, to estimate the historical global (1971–2015) final energy consumption of the mining industry. Second, to explore the range of future possible pathways for the mining industry's final energy consumption to 2060. These pathways are based on a range of socio-economic scenarios taken from the Integrated Assessment Models (IAMs) literature, combined with different assumptions regarding the recycling rates of minerals and the increase in the final energy intensities of mining activities (denoted as energy intensities in the rest of the article). Third, to explore the extent to which the mining industry's global energy consumption and the energy requirements of material flows are incorporated in a number of influential energy-economy models, and discuss their treatment in the light of the future pathways previously constructed. The paper is structured as follows. Section 3.2 reviews the literature related to energy consumption of mining activities. Section 3.3 presents the methodology used for the historical and prospective analysis of the mining industry's final energy consumption, and Section 3.4 presents the results (first and second aims). Section 3.5 reviews the consideration of the mining industry's energy requirements in energy-economy models, as well as the consideration of broader material flows and associated energy requirements (third aim). Then, Section 3.6 discusses our findings and Section 3.7 presents the conclusions the study. Appendix B, Section B.2 presents a short definition of the energy-related terminology used throughout the paper.

3.2 Mining and associated energy use: a review

Although the process of mineral extraction differs between minerals and extraction techniques, it may be decomposed in the following steps: (i) ore extraction, (ii) ore beneficiation, or concentration, and (iii) concentrate refining, which are represented in Figure 3.1, and further described in Appendix B.1. The first two stages generally occur at the mine location and are considered part of the mining process, while the last stage usually occurs in a downstream metallurgical plants. In this article, we define the mining industry as the ore extraction and ore beneficiation stages for all minerals, excluding fossil fuels.[2]

[2]Categories 07, 08 excluding 0892, and 099 of the United Nations International Standard Industrial Classification [54].

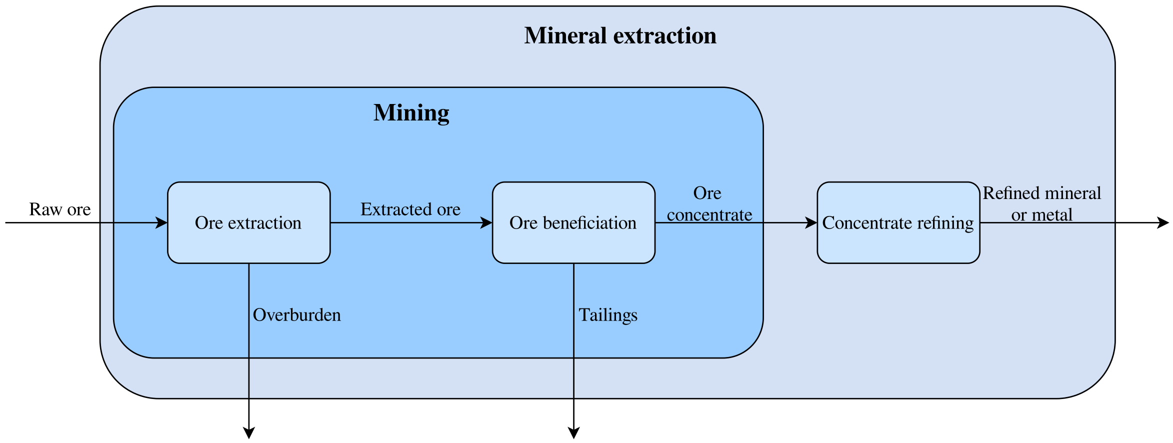

Figure 3.1: Graphical representation of the mineral extraction process. The mining activities cover the ore extraction and ore beneficiation steps, while the refining process, mostly relevant for metals, belongs to the metallurgical industry. *Energy intensities* only refer to the ore extraction and ore beneficiation stages in this paper.

3.2.1 The energy consumption of the mining industry

Global estimates

Global estimates of the energy consumption of the mining industry are scarce. The International Energy Agency (IEA), in its yearly World Energy Extended Balances (WEEB) [IEA, 2019] reports such energy consumption to be slightly below 1% of total final energy consumption. Such an estimate is likely to be somewhat underestimated, as mining activities are occasionally informal [55], meaning that their energy consumption may not be reported by national statistical agencies to the IEA.[3] Another important note on the IEA dataset is that the accounting method only includes the direct energy used (energy used in-situ by an industry or activity — see Appendix B.2 for a definition of the energy-related terminology used throughout the paper), and excludes the indirect energy used (energy used by an industry or activity's supply chain), which avoids double accounting of energy flows in different end-use sectors. Next, some studies have assessed the global energy consumption of primary metal production using a whole supply chain perspective (accounting for both direct and indirect energy requirements). For instance, Bardi [47] estimates the energy consumption of metal production around 5–10% of Total

[3]Note that the methodology we describe in Section 3.3 does not fully address this issue, which is due to the availability of data. We further discuss this in Appendix B.4.

Primary Energy Supply (TPES), and Bihouix and De Guillebon [56] around 8–10%. Similar values are obtained by Nuss and Eckelman [57] for the whole metal production process. We note, however, that these studies fail to differentiate such energy consumption in terms of mining activities, and downstream metallurgical processes, which explains the very large difference to the much lower values reported by the IEA (the scope adopted by these studies, which include indirect energy, as well as the quantification in terms of primary energy, also contribute to the difference, but to a lesser extent). Holmberg et al. [58] attempted to fill this gap with a top-down approach, and estimated the energy consumption of global mining activities to be around 12 EJ, i.e. 3–4% of total final energy consumption, although we note that the adopted approach relies on the IEA's WEEB.

Determinants of energy consumption of mining processes

Different factors determine the energy consumption of the mining industry. First, ore grades (i.e. the share, in mass, of valuable mineral contained in the mined ore) are inversely correlated to energy consumption [59] — see [60] and [45] for early studies. Such a relationship has been shown empirically in the case of copper [52, 61–64], gold [52, 65, 66], nickel [10, 62, 67], zinc [10, 52, 68], lead [10, 68], rare earth elements [69], platinum group metals [70], and uranium [71, 72]. Indeed, as ore grades decrease, more ore needs to be extracted, moved, hauled and crushed, to obtain the same amount of valuable mineral. Second, the grind size of the extracted ores, which determines the size to which mineral particles must be ground to separate valuable minerals from the gangue (rest of the mined ore), is a key parameter [10, 62, 73]. Indeed, the smaller the particles need to be ground to liberate the element of interest, the higher the required energy consumption in the comminution (reduction in particles sizes) process [74]. Third, the mine depth is also an important determinant; the deeper the ore needs to be extracted from, the higher the energy consumption of the mining process. Koppelaar and Koppelaar [64] quantify the "interactive effect between mine depth and ore grades," and finds significant influence of mine depth. Fourth, the energy consumption of mining activities depends on the extraction technique employed. Norgate and Jahanshahi [62] state that "the most appropriate route [...] in terms of embodied energy and greenhouse gas emissions depends on the mineralogy of the ore deposit concerned." Hence, the technique that minimises energy consumption depends on the type of ore, ore grade, grind size, recoverable by-products, and other characteristics of the ore deposit [64, 67] Lastly, the effects of technological improvements and innovation are also important, as new extraction techniques and improvements in the machinery used may result in increases in energy efficiency and hence, in lower energy intensities [59, 75, 76].

3.2.2 Increase in energy intensities of mining activities

Historical evolution of energy intensities

Although there is evidence that average ore grades have decreased over time in the case of numerous minerals, there are only rare studies exploring the historical evolution of average energy intensities with a national or global scope. First, Calvo et al. [52] finds an increase of 12% in the Chilean copper energy intensities in the period 2003–2013 using company and mine level data (average yearly increase of 1.1%). Second, the Chilean Copper Commission [77] reports national copper production and energy use over time, from which one can build the energy intensity time series of copper extraction in Chile (Figure 3.2), which shows that energy intensities have increased by 66% in the period 2001–2019 (average yearly increase of 3.0%). Third, Rötzer and Schmidt [76] adopt a process-based approach to quantify the energy intensities in the copper mining industry in the 1930s, 1970s, and 2010s. The authors show how the relationship between ore grade and energy intensity changes over time with the effect of technological improvements, and find that technological improvements have considerably reduced energy intensities of copper mining despite decreasing ore grades between the 1930s and 1970s. Conversely, the scale of the technological improvements effects has been much more limited between the 1970s and 2010s, leading to an increase of approximatively 30% in average copper energy intensities. Hence, studies point to an increase of energy intensities in recent years, meaning that the influence of geological factors and depletion has outstripped technological improvements. Such a situation may well carry on, as there are thermodynamic and practical limits to the energy efficiency of processes [59, 75, 78].

Forecasting future evolutions of energy intensities

The few studies that have attempted to model future increases in energy intensities of mining activities proceed in two steps: (i) extrapolation of the future ore grade

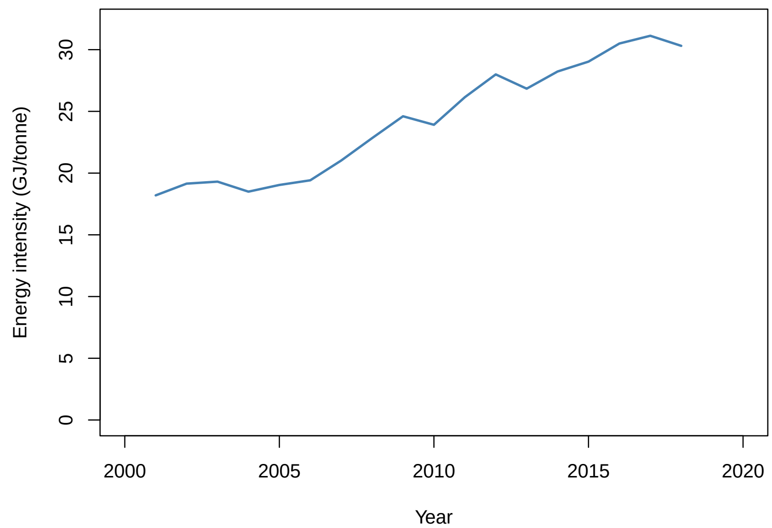

Figure 3.2: Energy intensity of copper mining over time in Chile. Time series deduced from the data provided by the Chilean Copper Commission. (See e.g. [77].)

of a given mineral, and (ii) determination of the energy requirements based on the ore grade-energy relationship for that given mineral.[4] The evolution of future ore grades may be determined in two ways. First are studies that use a time-dependent function fitted to historical data, but independent of future cumulative extraction. Van der Voet et al. [80] modelled first ore grades as a decaying exponential with respect of time to assess environmental impacts of major metal production. A similar method was used later by Kuipers et al. [81] and Dong et al. [82], who assessed the environmental impacts of future copper production globally and in China respectively. Second are studies that adopt a mechanistic approach, linking cumulative extraction of a given mineral to the ore grade, hence assuming an ore grade-tonnage distribution for the mineral under study. Harmsen et al. [83] explicitly constructs a global ore grade-tonnage distribution for copper, and assess how future extraction will increase copper energy intensities. Elshkaki et al. [84] and Ciacci et al. [85] both link the average copper ore grade to cumulative copper production in order to estimate environmental impacts of copper production globally and in the EU28 respectively.

[4]We also note the work of Fizaine and Court [79], who use a different approach, as they assess the sensitivity of renewable energy systems energy returns as function of the average decline in ore grades, independently of time.

There are however large uncertainties associated with the estimation of the future evolution of energy intensities. First, because there are only few studies and data available regarding the historical evolution of energy intensities, and because the increases in energy intensities affect differently each mineral, mine and country, which complicates the extrapolation of particular case studies to the broader mining industry. Second, modelling the future ore grade for each mineral remains a complex task. To proceed to such a forecast, one needs to either model the ore grade as a function of time, or to link the cumulative extraction to the ore grade through an ore grade-tonnage distribution. While the second approach is endogenous and more accurate than the time dependency function, it comes with significant uncertainties associated with the construction of ore grade-tonnage distributions. Whether ore grade-tonnage distributions follow a unimodal [86] or bimodal [87] distribution remains a matter of scientific debate [88], and may well have dramatic implications for the future evolution of energy intensities — see Appendix B.3. Hence, there is large uncertainty associated with the future evolution of ore grades, which depend on unknown geological factors.

3.3 Methodology

This section introduces the methodology followed in this study. The data used and data sources are described in Appendix B.4. We cover 59 minerals, the full list can be found in Appendix B.5 (Table B.2).

3.3.1 Historical final energy consumption of the mining industry

The historical final energy consumption of the mining industry for a mineral m is simply determined as:

$$E_{m,t} = P_{m,t} f_m, \tag{3.2}$$

where $P_{m,t}$ is the primary extraction of mineral m in the year t, and f_m is the historical (and constant over time) final energy intensity (in the rest of the paper, energy intensity refers to *final* energy intensity, unless stated otherwise) of mineral m. We use energy intensities independent of time for the historical analysis because

(i) uncertainties in the estimates were too significant to produce robust time series for energy intensities, and (ii) uncertainties related to the historical values of energy intensities are covered by the sensitivity analyses (using a Monte Carlo simulation) introduced subsequently.

Historical energy intensities by extracted mineral. The energy requirements of mining activities may be distinguished in terms of direct and indirect energy requirements [11, Chapter 9], and are usually quantified in terms of primary energy requirements using Life Cycle Analysis methods. Direct energy requirements refer to the energy used in-situ to operate the mine. Conversely, indirect energy requirements refer to the energy used in the mine supply chain, but ex-situ, to provide inputs needed to operate the mine (e.g. chemicals, machinery...). When adding direct and indirect energy requirements (quantified as primary energy requirements), the Gross Energy Requirement (GER) is obtained.[5] As both the direct and indirect (due to increasing requirements of non-energy inputs as well) energy requirements of mining are likely to increase as a result of mineral depletion, we adopt the GER as a measure of primary energy intensity of each mineral.[6] We review the literature to estimate the GER of each mineral using the studies of Norgate and Jahanshahi [10], Rankin [11], Nuss and Eckelman [57], Hammond and Jones [89], Mudd [90], Norgate and Haque [66], and Calvo et al. [91]. Then, we determine the average final-to-primary energy ratio for the global mining and quarrying sector for the period 2000–2015 (the ratio is very stable in that time period, with an average value of 0.58) using a recently developed Physical Supply Use Table framework [92, 93] (an explanation of the method and calculations is available in Appendix B.8), and we multiply the GER by this average ratio to determine the historical final energy intensity for each mineral. The values used as GERs, as well as details on the estimation of each GER are available in the dataset associated with the chapter (see Data Statement).

[5]Note that the GER indicator may be called the Cumulative Energy Demand (CED) in the Life Cycle Analysis terminology.

[6]The estimation often involved separating the primary energy requirements of the mining and metallurgical steps (for metal production) using a figure showing the breakdown in one of the cited studies.

Sensitivity analysis regarding historical energy intensities. We analyse the sensitivity of results to the historical energy intensity f_m chosen for each mineral m. We do so by conducting a Monte Carlo simulation (1000 runs) where each mineral's historical energy intensity f_m follows a normal probability distribution function — see Appendix B.8 for more information on the standard deviations used.

3.3.2 Estimating the future final energy consumption of mining activities

Figure 3.3 summarises the four step approach for generating future pathways for the mining industry's final energy consumption. First, we determine future mineral demand for the rest of the economy using six different socio-economic scenarios, which provide global GDP and final energy projections. Second, we determine future mineral demand for Energy Transition Technologies (ETTs)[7] using a high and low bound of mineral demand for the development of ETTs, to capture the uncertainty related to the mineral requirements of the energy transition (see for instance [95] for a quantification of such uncertainty). Third, we determine the required primary mineral extraction using three recycling rates scenarios (constant, moderate increase, and high increase). Fourth, we determine the mining industry's energy requirements, using three energy intensities scenario (constant, low increase, and high increase). Hence, we obtain 54 possible combinations of socio-economic, recycling rates, and energy intensities scenarios, each combination having a high and low bound of mineral demand for ETTs.

Socio-economic scenario selection. To explore future pathways, we select the Beyond 2 Degrees Scenario (B2DS) developed by the IEA [96], as well as the four 1.5°C consistent marker scenarios chosen by the IPCC in the Special Report on 1.5°C [22, Chapter 2], three of which are based on the Shared Socioeconomic Pathways (SSPs) [97]; SSP1 [98], SSP2 [99], SSP5 [100], and the last being the Low Energy Demand scenario [101]. In addition, we recognise the validity of the recent argument

[7]Material requirements are considered for the following technologies according to the review of Watari et al. [94]: solar photovoltaic, concentrated solar power, wind onshore and offshore turbines, electric vehicles, fuel cells, nuclear, geothermal, biomass, Carbon Capture and Storage (CCS), as well as additional grids and storage batteries needed for the deployment of renewable energy. Note that the scope adopted does not cover all mineral demand required for a low-carbon economy, for instance mineral demand for the insulation of houses or for heat pumps is not covered.

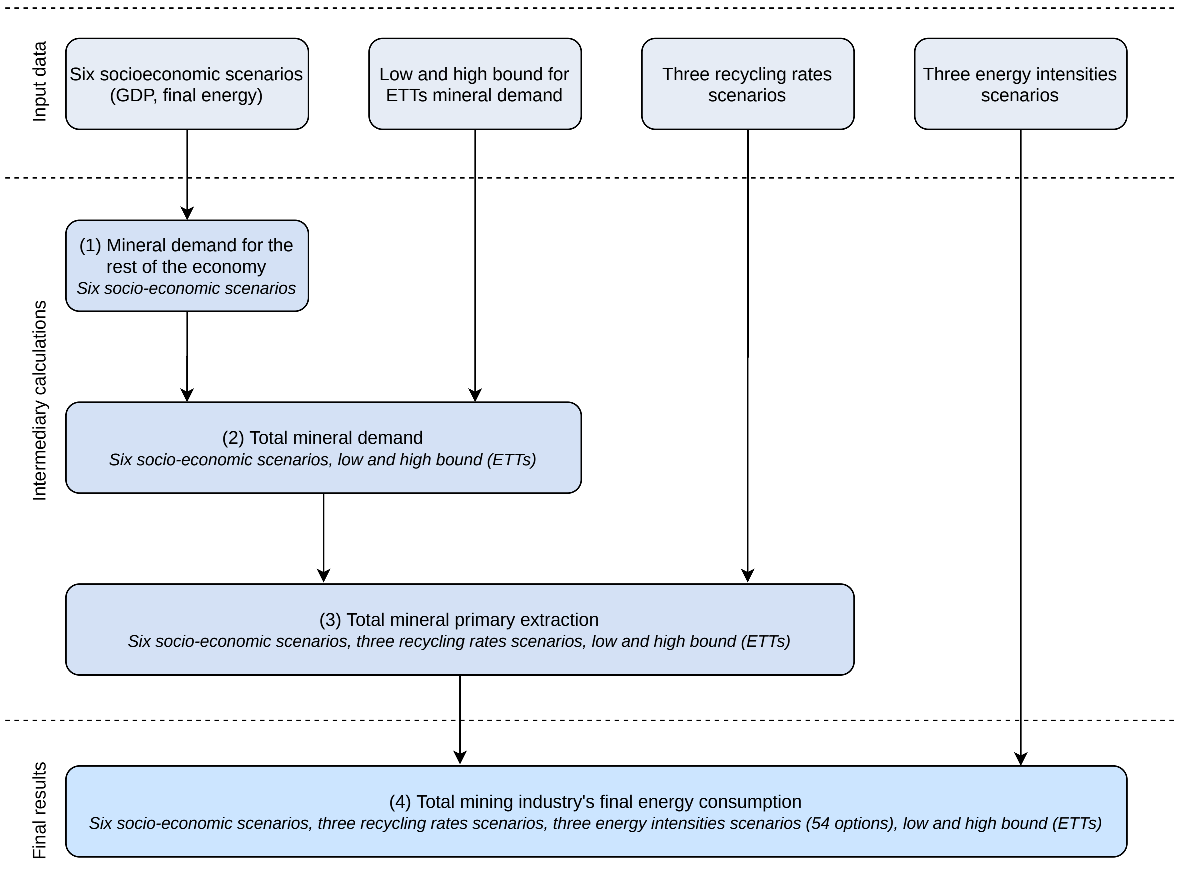

Figure 3.3: Workflow for constructing future pathways of the mining industry's global final energy consumption, and possible combinations of socioeconomic scenario, recycling rates scenario, mining energy intensities scenario, and mineral requirementsfor ETTs. ETTs: Energy Transition Technologies.

in favour of exploring a broader set of socio-economic scenarios and of exploring post-growth scenarios [102, 103]. Hence, we also define and include a post-growth socioeconomic scenario, in which global GDP declines by 0.2% yearly.

Estimation of future mineral demand for the rest of the economy

Considering the strong historical link between economic activity and material consumption [13], we follow the approach developed by Capellán-Pérez et al. [43] to estimate mineral demand for the rest of the economy by constructing for each mineral a linear model of mineral demand as function of economic activity, accounted for by the GDP metric. Hence, the demand for mineral m for the rest of the economy over time is determined as:

$$D_{m,RoE} = a_m y + b_m, \tag{3.3}$$

where y stands for GDP, and a_m and b_m are determined for each mineral m fitting historical data.[8] For the few minerals that do not correlate well to GDP — in general the linear regression works remarkably well — we use a constant demand equal to the average demand in the period 2005–2015. The values of the linear regression coefficients, the r^2 coefficient, the historical period for fitting data, and the demand value used for minerals for which demand is kept constant, are reported in Appendix B.5.

Estimation of future mineral demand for ETTs

To estimate the future mineral demand for the energy transition, we use first the literature review of the critical metal requirements for the energy transition conducted by Watari et al. [94], which summarises the metal requirements for the energy transition to 2050 determined by numerous studies, for a range of metals. Second, for those minerals that are not covered in the review, we use the study conducted in Capellán-Pérez et al. [43], which estimates the mineral requirements of the energy transition for three scenarios (respectively 50%, 75%, and 100% renewables in 2060). Then, we define both a high and a low future mineral demand for the ETTs following Table 3.1 — see Appendix B.8 for more information.

Estimation of future primary mineral extraction

The future primary mineral extraction of mineral m (determined in tonnes) is then determined as:

$$P_{m,t} = D_{m,t}(1 - r_{m,t}), \tag{3.4}$$

where $D_{m,t}$ represents the total demand for mineral m at t, and $r_{m,t}$ represents the recycled content of mineral m at t, i.e. the share of recycled material m relative to total new consumption of material m. Next, we define the three recycling

[8] We note that rigorously, one would need to subtract the GDP due to the development of the ETTs, the material requirements of which are accounted for according to Section 3.3.2.

Table 3.1: Sources for mineral demand by the deployment of Energy Transition Technologies, for the high and low bound of mineral demand. The future demand of minerals that are covered in the review conducted by Watari et al. [94] follow the pattern described in column (a), and the future demand of minerals that are not covered in the review but that are covered in the work conducted by Capellán-Pérez et al. [43] follow the pattern described in column (b).

Mineral demand	(a) Review by Watari et al.	(b) Study by Capellán-Pérez et al.
Low	Lowest value of the studies reviewed	Demand in the scenario with transition to a 50% renewables energy mix in 2060.
High	Highest value of the studies reviewed	Demand in the scenario with transition to a 100% renewables energy mix in 2060.

Table 3.2: Description of the evolution of recycling rates (recycled content) over the period 2015–2060 for the three recycling rates scenarios. The limit on recycled content does not apply to initial recycled contents because all are below 80%.

Recycling rate	Recycled content evolution	Limits on recycled content	Comment
Constant	Recycled content remains equal to its initial value.	No limit.	Pessimistic scenario
Moderate increase	Initial recycled content increases by 50%.	If recycled content reaches 80%, it is then held constant.	Realistic scenario
High increase	Initial recycled content doubles. If the doubling of the initial recycled content does not reach 30%, the recycled content is set to increase linearly until reaching 30% in 2060.	If recycled content reaches 80%, it is then held constant.	Optimistic scenario

rates scenarios presented in Table 3.2: the constant recycling rate scenario, where no improvements are made, the moderate increase scenario, where recycling rates increase by 50% in the period 2015–2060, and the high increase scenario, where recycling rates double in the period 2015–2060 — initial recycling rates are taken from [104] and [105], and can be found in the dataset associated with the chapter (see Data Statement).[9] We set a maximum limit of 80% recycled content for all minerals to account for the fact that some applications require very high purity materials, which can only be supplied by primary production.

[9]The dynamic recycling rates are thus mineral specific, and evolve by a given yearly percentage based on the initial recycling rate.

Estimation of the future mining industry's final energy consumption

We apply Equation 3.5 to determine the future final energy consumption of mining activities:

$$E_{m,t} = P_{m,t} e_{m,t}, \tag{3.5}$$

where $e_{m,t}$ stands for the future *final* energy intensity of mining mineral m, at a given time t, defined thereafter.

Future energy intensities The energy intensity $e_{m,t}$ associated with mineral m at a given time t is modelled to vary over time as:

$$e_{m,t} = f_m \alpha_{m,t}, \tag{3.6}$$

where f_m is the historical energy intensity of extraction of mineral m, i.e. the likely future energy intensity of mineral m if depletion effects were not at play, and $\alpha_{m,t}$ a coefficient modelling the increase in the energy intensity of mineral m in year t.[10] To model the increase in energy intensities, we begin by classifying minerals in terms of minerals that are likely to be affected by decreasing ore deposit qualities (e.g. copper, silver, zinc, etc.), and those that are not likely to be affected by decreasing ore deposits (e.g. sand, gravel, limestone, etc.). The classification is done using various information found in the literature and expert judgment, and is fully described in in the dataset associated with the chapter (see Data Statement). To deal with the uncertainty associated with increasing future energy intensities (see Section 3.2.2), we define three different scenarios. In the "constant intensities" scenario, which should be interpreted as a baseline scenario assuming the absence of mineral depletion effects (or their full compensation by technological improvements), energy intensities are held constant over time. In the "low increase" scenario, energy intensities start increasing around 2000 and follow a linear trend fitted to the 12% increase reported by Calvo et al. [52] for the period 2003–2013. In the "high increase" scenario, energy intensities start increasing around 2000 and follow a linear trend fitted to the 66% increase determined from the Chilean Copper Commission in the period 2001–2019

[10] We note that the adopted approach supposes that all energy inputs to the mining processes, be they direct energy in the form of fuel or electricity, or indirect energy embodied in other inputs or equipment, increase equally as a result of mineral depletion.

[77]. Figure 3.4 shows the evolution of $\alpha_{m,t}$, for those minerals affected by depletion, in each of the three scenarios. We also note that the $\alpha_{m,t}$ coefficient, as it is constructed from empirical historical data represents the effect of mineral depletion *minus* the effect of technological improvements, which are also accounted for. Appendix B.6 shows that our increasing energy intensity scenarios are in line (in terms of magnitude) with other studies.

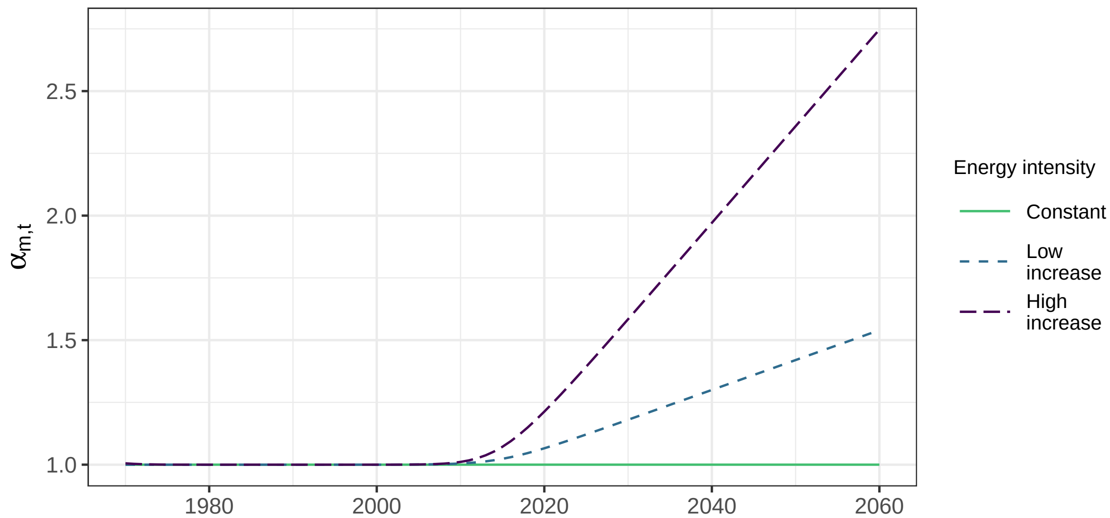

Figure 3.4: Values of $\alpha_{m,t}$ for minerals affected by the decrease in mineral deposit qualities for the three increasing energy intensities scenarios. Constant scenario: energy intensities are kept constant for all minerals. Low increase: energy intensities start increasing around the year 2000 and are extrapolated following the trend reported by Calvo et al. [52]. High increase: energy intensities start increasing around 2000 and are extrapolated following the trend calculated from the Comisión Chilena del Cobre data [77].

3.3.3 Methodology limitations

Exogenous inputs

Our methodology uses several exogenous parameters (recycling rates, future energy intensities, mineral demand for ETTs), while these parameters are in reality dependent on the socio-economic scenario and endogenous parameters. As this article aims at exploring the range of possible future pathways for the mining industry's final energy consumption, and not at accurately modelling the future, we believe that the following assumptions are appropriate. However the following points should be noted:

- *Exogenous future future recycling rates.* Recycled minerals are in reality a function of both end-of-life recycling rates and minerals reaching their end-of-life from in-use stocks, which represents a limiting factor to the maximum amount of minerals that can effectively be recycled. Hence, some of the recycling rates scenarios (especially, the high recycling rate scenario) may not be realistic, particularly when combined with high mineral demand (i.e. high economic growth) socio-economic scenarios, because there may not be enough minerals reaching their end-of-life from in-use stocks to reach such recycled contents.

- *Exogenous future energy intensities.* Future energy intensities account for the fact that extracting minerals from deposits becomes harder as a result of the depletion of higher quality deposits. Hence, the higher cumulative extraction is, the faster will energy intensities increase. Consequently, energy intensities are in reality function of future mineral demand, of the amount of minerals that can be supplied through recycling processes, and of geological factors. In addition, the constant energy intensities that we use for fairly abundant minerals assume that technological improvements will be sufficient to offset the effects of mineral depletion, but such energy intensities may even decrease if technological improvements outstrip depletion effects.

- *Exogenous future mineral demand for ETTs.* In a similar vein, the mineral demand for developing ETTs is a function of the socio-economic scenario, particularly in terms of final energy demand and of the ETTs that are deployed to fulfil such final energy demand.

Mineral demand modelling

The approach we follow to determine mineral demand for the rest of the economy (Equation 3.3) does not explicitly represent future trends, such as digitalisation, increasing demand for specific metals like Rare Earth Elements — such trends are only partly captured by our modelling of mineral demand. Likewise, our approach does not take into consideration structural changes that may allow economic growth to be at least partly decoupled from mineral demand in the future, such as in-use stocks saturation [106, 107], material demand saturation [108], structural economic changes towards less material intensive sectors [109], or increases in the material efficiency with which services are delivered [110, 111]. Particularly, this implies that our approach for mineral demand modelling may not be appropriate for those socioeconomic scenarios that inherently assume a high material-GDP decoupling, such as the LED or B2DS scenarios. However, while such decoupling may indeed occur to some extent, we argue that unless the underlying dynamics are made explicit in energy-economy models, one can legitimately think that historical trends will continue. Extrapolating historical trends is thus appropriate to determine the importance of explicitly modelling the mining industry's final energy consumption.

Some caveats should be noted on the linear regressions conducted to determine mineral demand. Indeed, the linear regressions do not respect the requirement of independence of residuals. It can be noted in Appendix B (Section B.5) that residuals are serially correlated, which is a typical issues when working with time series that both present an increasing (or decreasing) trend. Conducting a linear regression on such time series may yield spurious results, and the the R-square and p-values given in Appendix B (Section B.5) should be handled with caution. A more robust statistical approach would have been to conduct a cointegration analysis. Such an analysis would have yielded both statistical evidence that global GDP and global mineral extraction are correlated, and the coefficients describing the strength of the relationship.

Energy requirements of recycling

This study has not considered the energy requirements of recycling materials. Consequently, the study does not represent the fact that some of the decrease in the energy requirements of mining in high recycling scenarios may be offset by increasing energy requirements in the recycling sector. However, to be fully able to account for these effects, the boundary of analysis should be expanded to the metallurgical (or mineral refining) sector. Indeed, recycling processes would substitute both mining activities and the downstream metallurgical processes. In general, recycling presents significant energy and environmental benefits over the production of virgin materials, although these benefits depend on the type of product and application from which materials are recycled (see Section 3.6 for further discussion).

Table 3.3: Historical final energy consumption of the mining industry alongside values reported by the International Energy Agency. Both default and Monte Carlo analysis results are shown. Note that calculated values account for both direct and indirect energy, while the IEA's accounting method only includes direct energy. Values in EJ (J.1e18).

Value	1971	1980	1990	2000	2010	2015
Default estimation	1.93	2.39	3.01	3.86	5.59	6.64
Low bound, 90% confidence	1.58	1.97	2.47	3.12	4.54	5.42
High bound, 90% confidence	2.27	2.82	3.52	4.55	6.60	7.81
Low bound, 95% confidence	1.51	1.88	2.39	3.01	4.35	5.16
High bound, 95% confidence	2.34	2.90	3.62	4.68	6.78	8.05
IEA	6.25e-1	1.08	1.64	1.64	2.55	3.03

3.4 Results

3.4.1 Historical final energy consumption of the mining industry

Figure 3.5.a shows the historical final energy consumption of the mining industry obtained with constant energy intensities alongside the 90% and 95% confidence intervals obtained with the Monte Carlo simulation. The final energy consumption of the mining industry has increased considerably in the period 1970–2015, and has reached about 6.6 EJ in 2015. The uncertainty associated with such an estimate is however substantial, and the Monte Carlo simulation yields as 95% confidence interval a range of 5.2–8.0 EJ. Then, Figure 3.5.b shows the share of global final energy consumed by the mining industry. Such share has increased from around 1.1% in 1970 to around 1.7% in 2015. Likewise, we quantify as the 95% confidence interval a range of 1.3–2.0% of global final energy consumption in 2015. The final energy consumption of the mining industry is therefore a small share of the global final energy consumption, although higher than the value (0.75%) reported by the IEA (see Section 3.2.1 for the limitations of IEA data), as shown in Table 3.3. As explained in Section 3.2.1, a key reason is the fact that the IEA's methodology only accounts for direct energy use (to avoid double accounting across end-use sectors), while our calculations include indirect energy, i.e. final energy used by other industries that are part of the mining industry's supply chain.

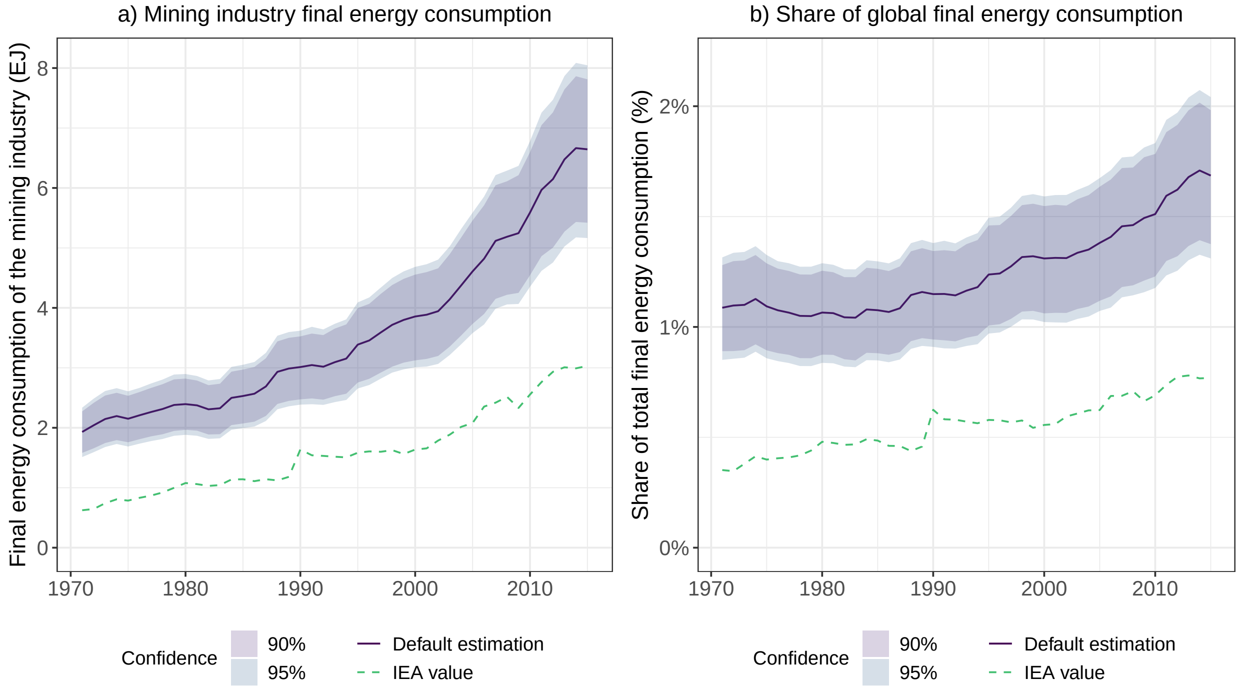

Figure 3.5: Final energy consumption of the mining industry (left), and share of global final energy consumption consumed by the mining industry (right). Note that calculated values account for both direct and indirect energy, while the IEA's accounting method only includes direct energy.

Figure 3.6 shows the breakdown of final energy consumption by mineral[11] — note that the breakdown by mineral should be interpreted with caution due to the uncertainty of the historical energy intensities fm estimated for each mineral. The extraction of just a few minerals (aluminium, clays, copper, gold, iron ore, limestone, Platinum Group Metals (PGMs), sand and gravel, and silver) appears to be responsible for around 90% of the mining industry's final energy consumption. Construction minerals (clays, limestone, sand and gravel) are responsible for a large share of final energy consumption despite low energy intensities, because of the large tonnages extracted yearly. Precious metals (gold, silver, and PGMs) are also responsible for a large share of final energy consumption, but for the opposite reasons: although they are extracted in small amounts, they require large amounts of energy to be extracted. Then, ferro-alloy metals and non-ferrous metals

[11]See Appendix B.9 for the evolution of the breakdown over time and for the breakdown by mineral group.

each contribute to a considerable share of final energy consumption, which is mostly due to the extraction of iron ore, chromium, molybdenum and nickel in the case of ferro-alloy metals, and of aluminium, copper, and zinc in the case of non-ferrous metals.

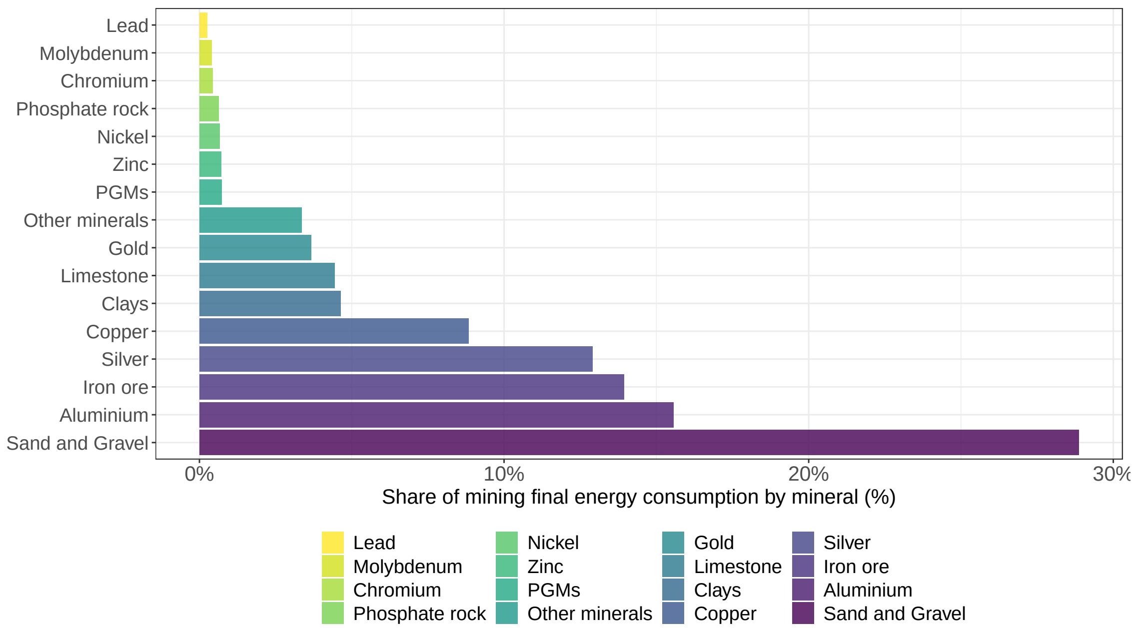

Figure 3.6: Breakdown of historical final energy consumption of the mining industry by mineral for the year 2015. PGMs: Platinum Group Metals.

3.4.2 Future pathways for the mining industry's final energy consumption

Figure 3.7 summarises the increase of the mining industry's final energy consumption in 2040 and 2060 relative to 2015, for all constructed pathways (54 scenario combinations, each with a high and low bound of mineral demand for ETTs). The mining industry's final energy consumption increases significantly in almost all cases: by a factor in the range 2–6 for high growth scenarios (i.e. SSP2, LED, B2DS, SSP1), and by a factor in the range 3–8 in the case of the extremely high growth SSP5 scenario. Only in the case of the post-growth scenario are there moderate changes in the mining industry's final energy consumption, reaching at most a 50% increase, and remaining constant or decreasing in some cases.

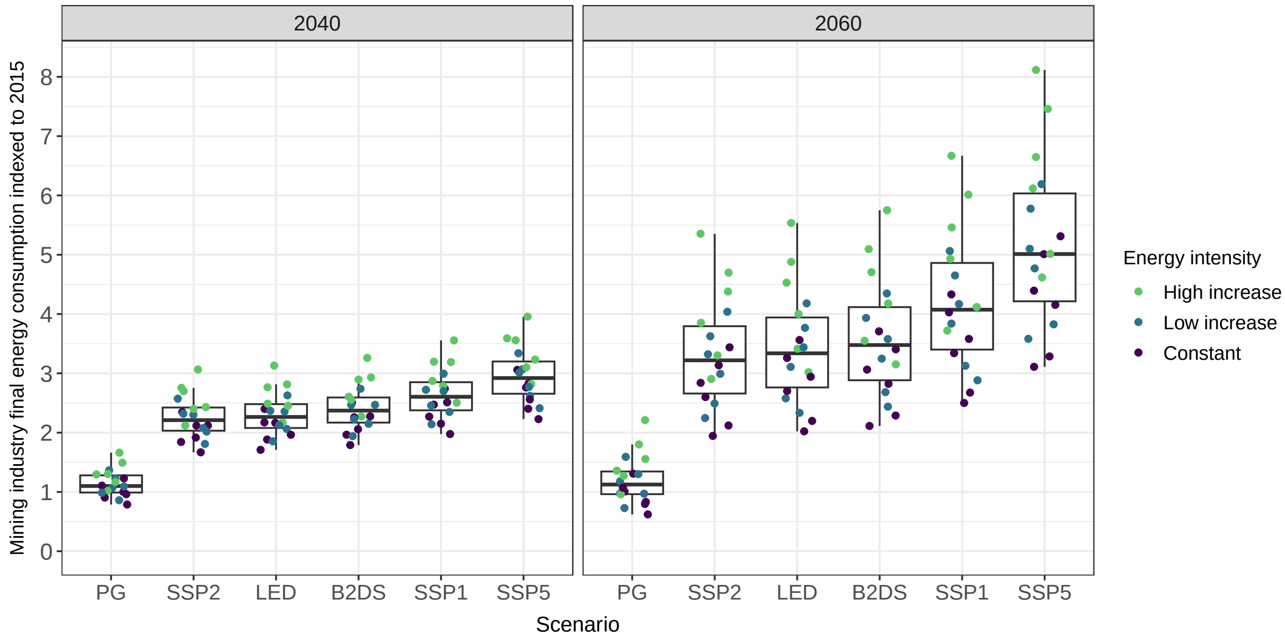

Figure 3.7: Final energy consumption of the mining industry in 2060 relative to 2015, for each different socio-economic, recycling rate, energy intensity, and renewable energy scenario. (2015 = 1.) Points with the same colour and shape correspond to the high and low range of mineral demand for the Energy Transition Technologies, with the same recycling rate and energy intensity scenarios.

Figure 3.8 shows the influence of each parameter by displaying (a) the cumulative final energy consumption and (b) the final energy consumption in 2060 in the case of the B2DS socio-economic scenario (results for other socio-economic scenarios are available in Appendix B.9), as function of the recycling rates and energy intensities scenarios (graph for the high bound value of mineral demand for ETTs). Results show that even when using the high bound of mineral demand due to the energy transition, the rest of the economy remains responsible for the very large majority of the mining industry's final energy consumption — the main driver for such energy consumption is global economic output. The influence of the future evolution of recycling rates and energy intensities is considerable, particularly when looking at the final energy consumption in 2060. The magnitude of increasing energy intensities affects the results considerably. The high increase in energy intensities scenario yields a final energy consumption in 2060 higher than the low increase and the constant energy intensity scenarios by respectively 35% and 60%. Increases in recycling rates can help to reduce the primary extraction and hence the mining industry's final energy consumption. Indeed, the moderate increase in recycling rates scenario reduces final energy consumption by approximatively 20% compared to the constant recycling rates scenario in 2060, and the high increase in recycling rates scenario, by 40%.

Figure 3.9 shows the future energy pathways for each combination of socio-economic, energy intensity, and recycling rates scenarios, when considering the high bound for mineral demand for the ETTs. (See Appendix B.9 for low bound and for energy use breakdown by mineral.) Results show that the socioeconomic scenario is of critical importance — only the post-growth scenario limits the increase in the mining industry's final energy consumption. Hence, the future economic trajectory, in terms of GDP, appears to be critical for the future pathways of the mining industry's final energy consumption with higher economic activity leading to higher mining industry final energy consumption. The figure shows how the influence of the future evolution of recycling rates and energy intensities considerably increases over time to very significant levels. The mining industry's final energy consumption increases more slowly from 2055 onwards (and even decreases in the post-growth scenario) due to the underlying ETTs development data (see Table 3.1), according to which most of the energy transition is accomplished by 2055 in the high range of mineral demand for the ETTs.[12] Table 3.4 then provides the maximum fraction of global final energy consumption devoted to the mining industry reached over the 2015–2060 time period, for each of the socio-economic scenarios (see Appendix B.9 for the evolution of the fraction over time in each scenario). Results reveal that in the high growth socio-economic scenarios, if we consider that the low increase in energy intensities is at minima likely, the future mining industry's final energy consumption is likely to reach values in the range of 4–12% of forecasted global final energy consumption — depending on the trajectory of future recycling rates — and even higher in the most pessimistic scenarios (steep increase in energy intensities). Such values would be extremely high, and call into question whether the final energy projections reported by each socio-economic scenarios would then be followed — and hence whether climate targets would be reached — or whether global final energy

[12] We note that such a trend is highly dependent on the pace of the energy transition, and there is no evidence that the final energy consumption due to the ETTs development will start to decline after 2055. However, the trend shows that once the energy transition is accomplished, the final energy consumption of the mining industry entailed by the ETTs will decrease.

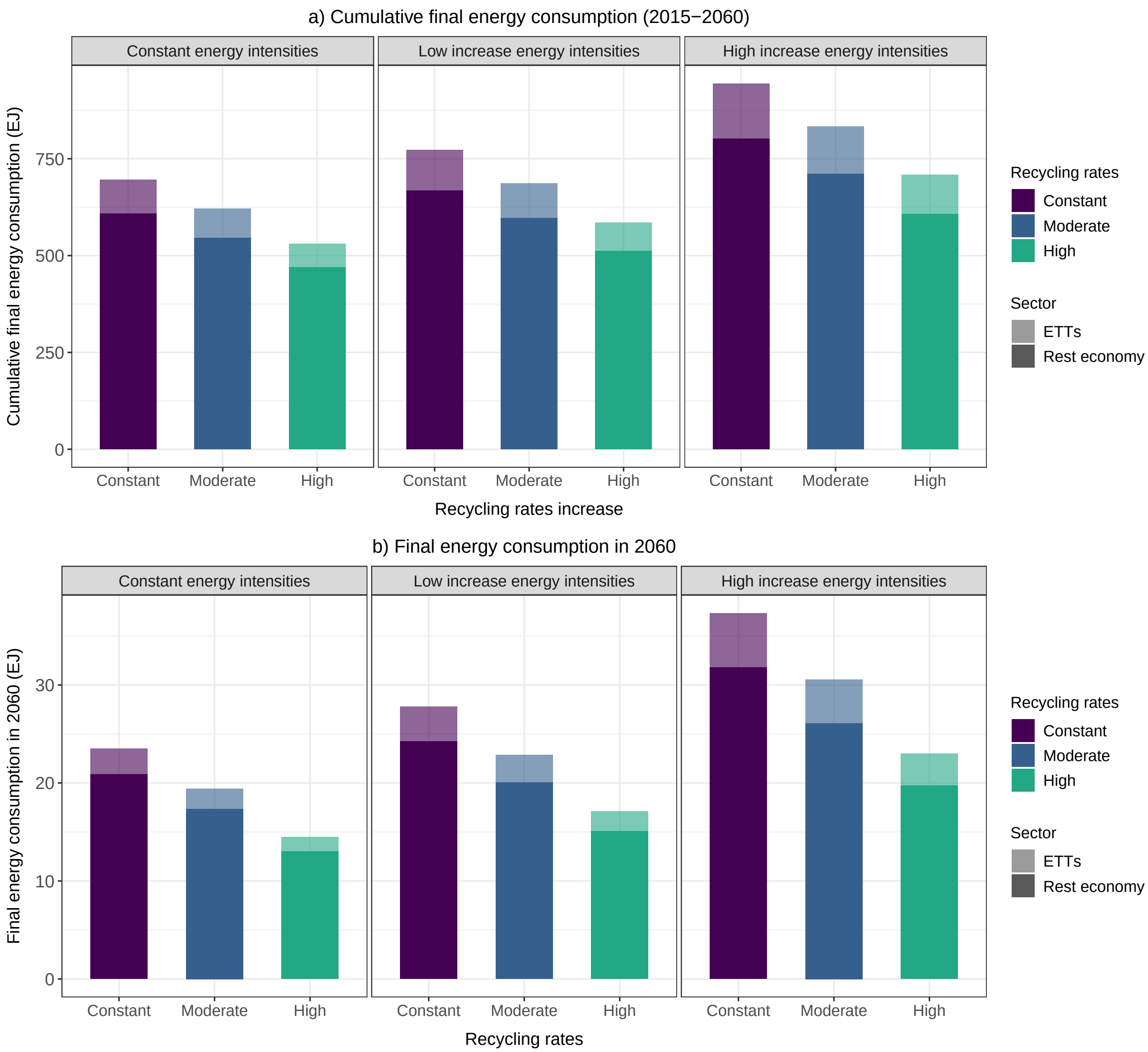

Figure 3.8: (a) Cumulative final energy consumption (2015–2060) and (b) Final energy consumption in 2060 for the Beyond 2 Degrees Scenario, as function of the recycling rates scenario, of the energy intensities scenario. Results for the high bound value of mineral demand for Energy Transition Technologies (ETTs).

consumption would be higher than forecasted. Conversely, in the case of a post-growth socio-economic development, the mining industry's final energy consumption is likely to remain below 4% of global final energy consumption, which is much closer to historical values.

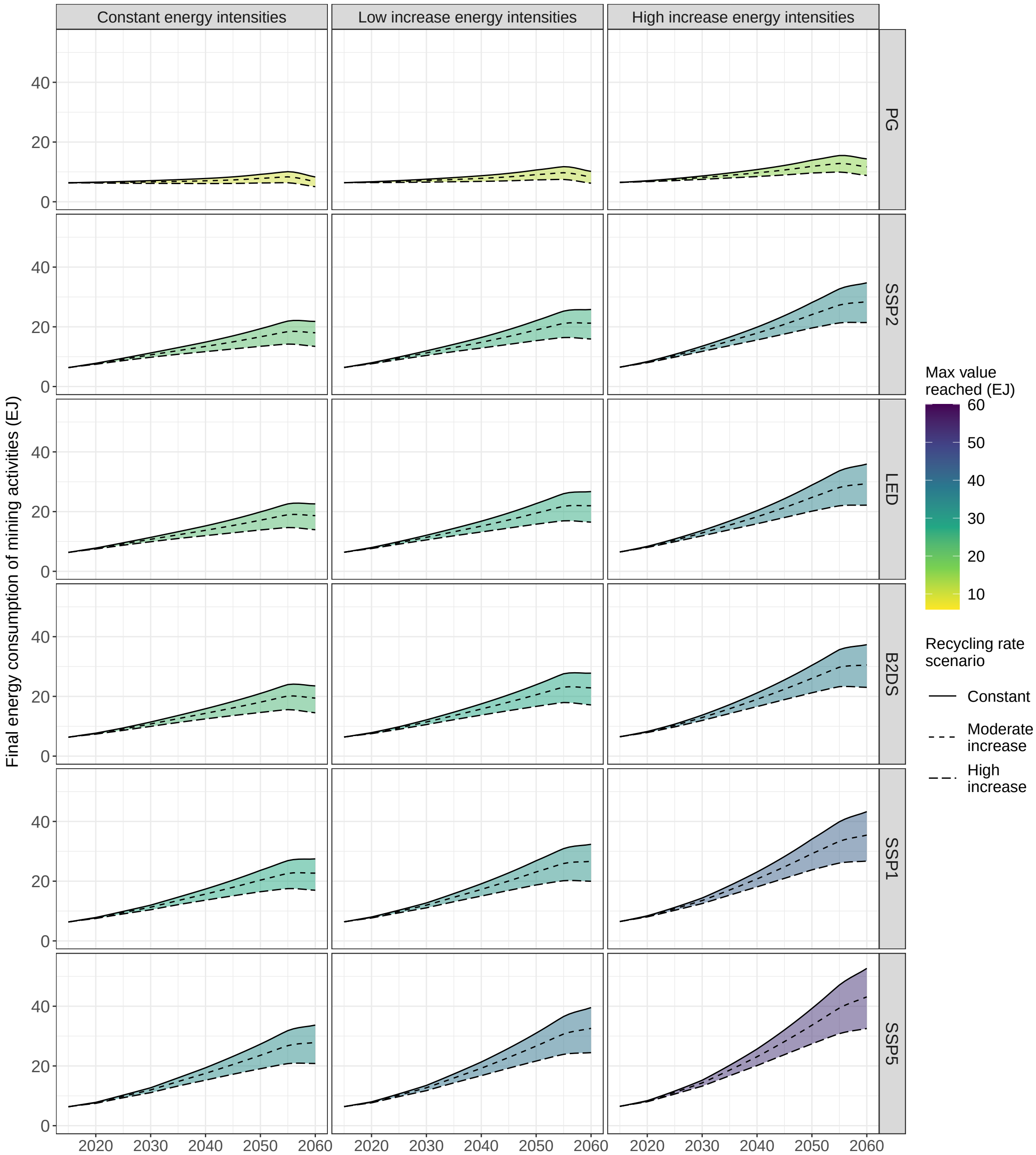

Figure 3.9: Future mining industry's final energy consumption pathways by socio-economic scenario, energy intensity scenario, and recycling rate scenario, when considering the high range for mineral demand for Energy Transition Technologies.

Table 3.4: Maximum fraction of global final energy consumption reached by the mining industry's final energy consumption over the 2015–2060 time period. Values in percentages.

Energy intensity scenario	Recycling rate scenario	PG	SSP2-1.9	LED	B2DS	SSP1-1.9	SSP5-1.9
Constant	Constant	2.95	5.51	10.78	7.26	9.11	7.12
	Moderate	2.44	4.62	8.98	6.07	7.55	5.89
	High	1.86	3.57	6.89	4.70	5.79	4.52
Low increase	Constant	3.43	6.37	12.66	8.38	10.73	8.36
	Moderate	2.84	5.31	10.42	6.99	8.83	6.88
	High	2.18	4.12	7.98	5.42	6.69	5.21
High increase	Constant	4.53	8.39	17.03	11.11	14.35	11.13
	Moderate	3.75	6.90	13.93	9.09	11.75	9.11
	High	2.90	5.35	10.51	7.02	8.86	6.87

3.5 Mineral materials in energy-economy models: a review

3.5.1 General approach

In many models, the mining industry is represented as an economic sector, through its monetary output, which may be linked to the monetary output of other sectors (e.g. the construction sector). In this review, we focus on the extent to which the production of mineral materials (which includes their mining) is considered explicitly through physical quantities (i.e. in tonnes), because such an approach provides a more accurate representation of mineral material flows and associated energy requirements than using monetary values. The mining industry is hence considered in this review through the lens of the primary production of mineral materials, which is closely related to the consideration of broader material cycles in models, as the amount of extracted materials is a function of the mineral demand as well as of the amount of end-of-life materials that can be effectively recycled. Hence, we review the broader consideration of material cycles and associated energy requirements in models through the following four criterion: (i) the mineral materials covered, (ii) the description of material demand, (iii) the differentiation of primary mineral extraction and secondary production (recycling), and (iv) the feedback of material flows on energy consumption — Appendix B.7 summarises the approach of each reviewed model in respect of each criterion.

3.5.2 Review findings

We summarise here the findings of the review — implications for the modelling community are further discussed in Section 3.6.2.

Mineral materials coverage Most models only consider cement and (or) steel. The Shell WEM, the E3ME model, and the GEM-E3/PRIMES model have a high mineral material coverage, although it comes at the expense of aggregating heterogeneous materials in broad categories (e.g. non-ferrous metals, industrial minerals, etc), which limits the precision with which material flows can be represented. The IEA's WEM performs best in terms of mineral materials coverage and disaggregation, with steel, aluminium, copper, nickel, lithium, cobalt and rare earth elements covered for both the ETTs and the rest of the economy, and zinc, PGMs, manganese, graphite, and molybdenum are covered for the ETTs. The MEDEAS model also performs well in terms of mineral materials coverage and disaggregation, although it only translates material flows into energy requirements indirectly and partially, through the dynamic Energy Return On Investment of the energy system [43].

Consideration of mineral materials stocks and flows Only the IEA's WEM, and the IMAGE model explicitly consider the whole material cycles through stocks and flows, leading to a primary mineral material demand (and hence, feedback on energy consumption) consistent with mineral material stocks and flows, although only for a limited number of materials. In addition, work is under way in the GEM-E3/PRIMES model to describe material stocks and scrap availability, and in the IMAGE model to incorporate the stocks, flows and energy requirements of a larger set of mineral materials (see [112–114]). Conversely, most models do not differentiate between primary and secondary production, or do it using exogenous recycled content data or following historical trends.

Feedback of mineral material demand on energy consumption. There are three types of mechanisms through which mineral material demand is connected to energy consumption in the reviewed models. First come models (AIM/CGE and

E3ME) for which mineral material demand increases the monetary sectoral output of relevant industries, and consequently, the energy requirements of such industries. Second come General Equilibrium Models (REMIND-MAgPIE and IMACLIM), for which an equilibrium between output and inputs (including energy requirements by energy carrier) is directly determined through an optimisation procedure, and hence for which the determination of the exact feedback of mineral material demand on energy requirements is complex. Third come the remaining models (excluding MEDEAS) which link mineral material demand to energy requirements through the use of energy intensities of production for each material (e.g. GJ per tons of primary or secondary steel produced) — such energy intensities may be broken down by energy carrier, may depend on the modelled technology mix or on exogenous assumptions, depending on the model. We note that no model considers the increasing energy intensities of mining activities.

3.6 Discussion

3.6.1 Levers to limit the mining industry's final energy consumption

This study has shown that the mining industry's final energy consumption may increase considerably in the future, although there are large uncertainties associated with such a prospective analysis. However several levers can help limit such increases, which we critically discuss hereafter.

Innovation, technological improvements, and efficiency gains. Favouring innovation and energy efficiency in the mining sector may help to limit future increases in energy intensities, as there are still significant energy efficiency opportunities in the mining industry [75]. Increasing the share of electricity as final energy carrier in mining activities may also contribute to limiting future increases in energy intensities, as electricity tends to be used with significantly higher efficiencies than fuels. However, current trends (see Section 3.2.2), at least for relatively scarce metals, indicate the predominance of geological factors over technical developments, thereby questioning the extent to which innovation and efficiency can limit future increases in energy intensities. For minerals affected by mineral depletion, energy intensities are likely to carry on increasing, (particularly as any technological improvements may be used precisely to mine lower quality deposits). Technological improvements may however be able to lower the energy intensities of fairly abundant minerals, although there are thermodynamic and practical minimum limits to energy intensities [59, 75, 78].

Fostering recycling rates. Fostering high recycling rates appears to be a key lever to reduce the mining industry's final energy consumption. Significantly increasing recycling rates obviously implies reaching high end-of-life collection rates, developing appropriate technologies and industrial sectors, but it also implies rethinking the current use of minerals, particularly in the case of metals used for high-tech applications. Indeed, some metals are consumed in multiple dispersive uses [59], for which recycling is either altogether impossible, or is currently not achievable, and are hence "lost by design" [115].[13] Some other metals are used in extremely low concentrations, for instance in superalloys and high-tech applications, making their recycling very difficult. For some minerals the final use concentration may sometimes be lower than currently mined deposits concentrations, so that the recycling process may even lose its energy saving and climate mitigation potential [116]. Recycling may sometimes only be possible as nonfunctional recycling, whereby the mineral becomes an impurity and loses its functionality (for instance, minor metals alloyed to steel and recycled as secondary steel, mixed with different steel types). Reconsidering the extent to which these dispersive and hardly recyclable uses are employed appears crucial to reach high end-of-life recycling rates.

Future economic activity. In our analysis, global economic activity remains a chief determinant of mineral demand, and consequently, of the mining industry's final energy consumption. Only the post-growth socio-economic scenario limits the final energy consumption of the mining industry to a level comparable to its current value. In addition, it is worth noting that conversely to what is assumed in this study, energy intensity and recycling rates scenarios are not independent from the

[13] Examples include galvanisation and sacrificial anodes (e.g. zinc, magnesium, aluminium), pigments (titanium, cobalt, bismuth), fertilizers and pesticides (e.g. phosphorous, copper, selenium), additives in (petro)chemicals (e.g. platinum to improve the combustion of gasoline), use in catalysis (e.g. platinum group metals, germanium), pyrotechnics and fireworks (e.g. aluminium, copper, chromium). For a broader review of dispersive uses of metals, see [115].

socio-economic pathway. Indeed, the higher mineral extraction is (e.g. because of a high economic growth), the quicker will ore quality deposits decrease, and hence the faster will energy intensities increase. Similarly, the higher mineral demand is, the lower the fraction of the demand covered by recycled minerals can be, and the lower the recycled content of consumed mineral materials can be. Hence, our results support the argument that exploring post-growth socio-economic scenarios as an approach to limiting environmental damage is an essential research direction for the energy-economy modelling community [102, 103].

3.6.2 The need for a consistent modelling of mineral material flows and associated energy requirements in energy-economy models

We have shown in Section 3.4 that the mining industry's energy requirements are likely to increase considerably in the future, and may reach very high levels if historical demand trends carry on. Then, Section 3.5 has shown that mineral material flows and their associated energy requirements, including the mining industry's energy requirements, are only described to a limited extent in the energy-economy models we reviewed. Hence, this paper has shown the need to move towards a more explicit and comprehensive consideration of material flows and of their associated energy requirements. Here, we suggest and discuss four principles for an improved modelling of material flows and associated energy requirements.

Material demand as a function of economic activity or bottom-up human activities. A key principle for energy-economy models is to explicitly describe material demand (in physical quantities) as function of economic activity. In this work, we have done so by a simplistic (although consistent with historical trends) approach, linking global GDP to mineral demand. Other approaches may include the use of econometric techniques linking particular socio-economic drivers (e.g. population, sectoral output) to material demand, or the use of material intensities for each economic sector. Material demand may also be estimated by directly quantifying the material requirements of human activities, i.e. translating an explicit representation of services such as transportation, housing, infrastructure into material requirements, which is the approach increasingly taken by the IMAGE model.

Particular attention should be given to the continuity with historical trends, and in the case of an important decoupling of economic activity and material demand occurring, the underlying socio-economic drivers should be made explicit in the modelling.

Explicitly modelling in-use stocks and flows. We have shown that the extent of recycling is critical when determining the energy consumption of mining activities. However, the extent of recycling is determined not only by end-of-life recycling rates, but also by the mineral material flows available for recycling at a given time, which are function of the share of in-use stocks reaching their end-of-life, and hence, of the lifetimes of each material in society [117]. Recent work by Elshkaki et al. [118] and Deetman et al. [114] explicitly models in-use stocks and shows that the availability of materials acts as an important limiting factor to the potential of recycling. Such explicit representation of in-use stocks and end-of-life flows is crucial as it prevents from modelling an extent of recycled materials inconsistent with physical stocks.

Explicitly modelling the energy requirements associated with mineral material flows. It seems crucial that the energy requirements associated with mineral material flows (mining and refining, and secondary recycling) are explicitly represented in models. Such energy requirements may be quantified through an increase in the material producing sectors output (and consequently an increase in their energy consumption), or through the use of energy intensities of production for each material. The former technique may require translating a demand for heterogeneous materials into a demand for sectors aggregating numerous materials, and to use monetary units, which may distort physical flows and their energy requirements. Conversely, the latter approach is likely to remain closer to underlying physical flows, but care should be given to the evolution of energy intensities of production over time, so that they account both for thermodynamic limits (i.e. limit to efficiency gains that can be achieved), and for the increasing energy intensities of mining activities — an explicit modelling of the mining extraction stage may hence be helpful.

Mineral materials to consider. The number of mineral materials that can be realistically modelled is necessarily limited by time and resources available. This study has allowed us to explore the magnitude of mining industry's historical final energy consumption related to different minerals, as well as potential evolutions in the future. Hence, we suggest that in addition to steel and cement, which are traditionally considered in energy-economy models, other relevant mineral materials responsible for a high final energy consumption include aluminium, copper, gold, limestone, sand and gravel (partly considered as cement), and silver. In addition, other mineral materials may be worth modelling for instance due to significant energy requirements in the mineral refining stages, or for different reasons such as criticality for the energy transition and supply risks [41].

3.7 Conclusion

This paper has provided an estimate of the historical final energy consumption of the mining industry globally, as well as an exploratory analysis of future possible pathways for the mining industry's final energy consumption (excluding fossil fuel extraction activities). We find that the mining industry is currently responsible for a small, and yet significant, share of global final energy consumption — approximatively 1.7%. However, such a share is likely to increase considerably in the future as a result of a substantial increase in the mining industry's final energy consumption if current trends continue (i.e. high economic growth alongside a high material-GDP coupling), until reaching a value in the range 4–12% of forecasted global final energy consumption for the socioeconomic scenarios adopted in this study. We also find that the mining industry's future final energy consumption is first and foremost determined by future economic activity: final energy consumption due to mineral demand for energy transition technologies is dwarfed by the final energy consumption due to mineral demand for the rest of the economy. In addition, future recycling rates and energy intensities of mining are key factors determining the mining industry's future final energy consumption — while the latter is partly exogenous (due to geological constraints), the former is dependent on political, industrial, and technological choices.

This study has found that mineral material flows and associated energy consumption are only covered to a limited extent in the energy-economy models reviewed. We argue that mineral material flows need to be explicitly represented for a set of critical materials, from the mineral mining stage to the mineral refining and recycling stages, and that the energy implications of such flows need to be explicitly modelled, so that models produce internally consistent scenarios. Particularly, it is crucial that models explicitly represent (i) material demand as function of economic activity or underlying human activities and services, (ii) primary mineral extraction and material recycling as function of material demand, end-of-life materials, and end-of-life recycling rates, and (iii) the energy requirements of these material flows and processing activities, taking into consideration the increasing energy intensities of mining activities due to mineral depletion.

Lastly, our results, combined with the limited coverage of material flows in energy-economy models, raises concerns regarding the consistency of mainstream socio-economic scenarios in terms of relationship between economic activity and final energy consumption forecasts. Indeed, when tightly coupling material demand to economic activity, consistently with historical trends, we find that the mining industry's final energy consumption may increase considerably and account for a significant fraction of global final energy consumption, hence raising the concern that global final energy consumption may be underestimated in mainstream socio-economic scenarios. The limited consideration of mineral material flows and associated energy requirements seems to be an important blind spot in energy-economy models and may hinder the efforts of the community to build consistent energy transition pathways.

Data statement

The dataset associated with this chapter can be found in the online repository associated with this thesis, hosted at the University of Leeds Data Repostory: https://doi.org/10.5518/1322.

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Chapter 4

Estimation of fossil fuels useful stage Energy Return On Investment and implications for renewable energy systems

Emmanuel Aramendia, Paul E. Brockway, Peter G. Taylor, Jonathan Norman, Matthew K. Heun, Zeke Marshall

The net energy implications of the renewable energy transition have so far only been analysed at the primary or final energy stage. Here, we argue that the energy valuable to society is useful energy, i.e. energy after conversion in an end-use conversion device, and that considering the large differences in final-to-useful efficiencies for different energy carriers, expanding the analysis to the useful stage is crucial in the context of the energy transition. In response, we determine the useful stage energy returns of fossil fuels, both globally and nationally, and for different end-uses, and use such values to determine the final stage Energy Return On Investment (EROI) for which renewable energy systems would deliver the same amount of net useful energy as fossil fuels.

We find that fossil fuels useful stage EROIs (~3.3) are considerably lower than at the final stage (~8.3), due to low average final-to-useful efficiencies, with values highly dependent on the type of fossil fuel and on the end-use considered. Our results suggest that an average EROI value of 4.5 for renewable energy systems would be sufficient to transition to renewable energy without long-term decline in the net useful energy available to society (final stage EROI equivalent). However, the EROI equivalent value varies considerably depending on the fossil fuel substituted and the end-use of substitution. The value we find is on the low range of EROI estimates for renewable energy technologies, which suggests that the energy transition may happen without decline in the net useful energy available to society.

4.1 Introduction: the need for expanding net energy analysis to the useful stage

While energy is fundamental to human societies, only a fraction of the produced energy (net energy) is available for productive and socially beneficial purposes. Indeed, some energy needs to be used in the energy system itself, to tap and convert a primary energy source into a final energy carrier. The energy returns of an energy yielding system may be quantified through different metrics, the most popular being the Energy Return On Investment (EROI), defined as the ratio of the energy delivered divided by the energy that had to be invested, for a given energy yielding system.

Tackling the climate change emergency requires a considerable change in the structure of our energy systems and to replace fossil fuels by renewable energy sources. Concerns have been raised recently regarding the net energy impacts [1–3] and the macroeconomic impacts of such an energy transition [4–8], because renewable energy systems have been traditionally thought to have substantially lower EROIs than fossil fuel-based energy systems [9]. Recent works have shown that such an understanding may be misguided, and based on inconsistent comparisons whereby the primary stage fossil fuel EROIs (fuel at the mine mouth) are compared to the final stage renewable energy EROIs (electricity output) [10, 11].

In this work, we follow researchers who argue that the energy valuable for productive and socially beneficial purposes is energy at the *useful* stage [12, 13], i.e. energy after conversion in an end-use conversion device (lamp, engine, heater, etc.) [14, 15]. We therefore argue that the energy valuable to society is the *net useful* energy, and hence, that the net energy implications of the energy transition should be analysed at the useful stage. Indeed, final energy stage analysis overlooks the fact that final energy carriers (e.g. electricity, coal, and gasoline) are of different natures and are used with different final-to-useful efficiencies [12, 16], so that two energy systems with the same final stage EROI may deliver very different amounts of net useful energy. Thus, we expand previous work [11] to estimate the useful stage EROIs of fossil fuels for different end-uses, both globally and nationally. Such estimates allow us to assess, for different end-uses, the final stage EROI for which renewable energy systems would deliver the same amount of net useful energy as fossil fuels (i.e., the final stage EROI equivalent). We then compare these EROI equivalent values to the actual renewable energy system EROIs reported in the literature.

When expanding the analysis to the useful stage of energy use, we find that fossil fuel energy returns considerably drop (from an average of approximately 8.3 at the final stage to 3.3 at the useful stage in 2019), due to low final-to-useful efficiencies — although trends and values are highly dependent on the fossil fuel group and end-use considered. Additionally, results show that reaching an EROI value of 4.5 (final stage EROI equivalent) would be sufficient for electricity-yielding renewable energy systems to deliver the same amount of net useful energy as fossil fuels, although the EROI equivalent values vary considerably depending on the fossil fuel and end-use being substituted. Overall, such findings question the conventional narrative according to which the energy transition will imply a decrease in the net energy available, and suggest instead that in the long-term, the energy transition may bring about net useful energy gains.

4.2 Analytical approach

4.2.1 Determination of fossil fuel useful stage EROIs

The first step of this work builds on previous work by Brockway et al. [11], who calculated global final stage EROIs for fossil fuels using data from the International Energy Agency's (IEA) World Energy Extended Balances (WEEB) and from the Exiobase Multi-Regional Input Output (MRIO) model [17]. We expand this work in two main directions. First, by using a recently developed Multi-Regional Physical Supply Use Table (MR-PSUT) framework [18, 19] and applying it to the IEA's WEEB, we are able to determine fossil fuel final stage EROIs over the time period 1971–2019 for a wide range of energy products, at the global and national levels, while taking into consideration energy flows across borders. Second, using a recently developed primary-final-useful energy (and exergy) database [20] enables us to determine the average final-to-useful efficiencies for each energy product, both at the economy-wide and end-use (e.g., low temperature heating, mechanical drive, road propulsion, etc.) levels. Then, we are able to determine fossil fuel useful stage EROIs, for each end-use. We define the final stage EROI as:

$$\mathrm{EROI_f} = \frac{\text{Final energy output}}{\text{Final energy input}}, \tag{4.1}$$

and the useful stage EROI as:

$$\mathrm{EROI_u} = \frac{\text{Useful energy output}}{\text{Final energy input}}, \tag{4.2}$$

which can therefore be expressed as:

$$\mathrm{EROI_u} = \eta.\mathrm{EROI_f}. \tag{4.3}$$

where η is the average final-to-useful efficiency with which a given energy product is used, either economy-wide, or for a particular end-use. The energy output for all these EROIs is expressed in gross energy terms, i.e. it includes the energy output that would need to be reinvested in the energy sector for its self-sufficient functioning.

In this work, EROIs are calculated including both direct energy requirements (energy use *in-situ* by the fossil fuel industry) and indirect energy requirements (energy use in the fossil fuel industry supply chain). Direct energy requirements are calculated using the aforementioned MR-PSUT applied to the IEA's 2021 WEEB [21] (see Supporting Information (SI), Methods C.1.1) for the period 1971–2019, and indirect energy requirements are calculated using Exiobase [17, 22] for the period 1995–2015, following a methodology inspired by the one introduced by Brockway et al. [11] (see SI, Methods C.1.2).[1] Indirect energy requirements are extrapolated for the remaining years using the average ratio of indirect energy requirements to final energy output over the 1995–2015 period, which is found to be relatively stable, as shown in Extended Data Figure (EDF) C.1. Energy requirements due to capital investments are not quantified in this analysis as the gross capital formation final demand vector is not available by industry in Exiobase, so that the fossil fuel EROI values we find are an upper-bound excluding capital investments, making our results conservative.

[1] The EROIs we determine may be considered a Power Return On Investment, as we use yearly energy flows instead of energy flows over the lifetime of an installation to determine net energy returns [23]. However, as the energy requirements of investments are not included in the analysis, we believe that the EROI term is more suited to the analysis conducted here.

4.2.2 Implications for renewable energy systems

Considering that the fraction of energy actually valuable for socially beneficial purposes is the net useful energy available, in the second part of this work we determine the final stage EROI equivalent for which electricity-yielding renewable energy systems (wind power, solar photovoltaic, and concentrated solar power) would deliver the same amount of net useful energy as fossil fuels. In the following equations, capital E refer to energy flows over the lifetime of an energy system, and lower case e refers to an energy flow per unit of final energy invested. The variation in the net useful energy available Δe_{u} resulting from investing one unit of final energy in a renewable energy technology instead of in fossil fuel energy can be expressed as:

$$\begin{aligned} \Delta e_{\mathrm{u}} &= \frac{\mathrm{E_{u,ret}}}{\mathrm{E_{f,input}}} - \frac{\mathrm{E_{u,ff}}}{\mathrm{E_{f,input}}} \\ &= e_{\mathrm{u,ret}} - e_{\mathrm{u,ff}}, \end{aligned} \tag{4.4}$$

where $e_{\mathrm{u,ret}}$ and $e_{\mathrm{u,ff}}$ refer respectively to the net useful energy obtained when investing one unit of final energy in the renewable energy technology and fossil fuel considered. Using Equation 4.2, one can express the net useful energy output for one unit of final energy input, for any energy system, as:

$$\begin{aligned} e_{\mathrm{u}} &= \mathrm{EROI_u} - \frac{\mathrm{E_{u,input}}}{\mathrm{E_{f,input}}} \\ &= \mathrm{EROI_u} - \eta_{\mathrm{m}}, \end{aligned} \tag{4.5}$$

where η_{m} stands for the final-to-useful efficiency of the manufacturing process (see SI, Methods C.1.3 for more details). Then, if we consider that renewable energy technologies need to be ultimately manufactured using energy from renewable energy technologies, $e_{\mathrm{u,ret}}$ can be expressed as:

$$\begin{aligned} e_{\mathrm{u,ret}} &= \mathrm{EROI_{u,ret}} - \eta_{\mathrm{elec}} \\ &= \mathrm{EROI_{f,ret}}.\eta_{\mathrm{elec}} - \eta_{\mathrm{elec}}, \end{aligned} \tag{4.6}$$

and $e_{\mathrm{u,ff}}$ as:

$$e_{\mathrm{u,ff}} = \mathrm{EROI_{u,ff}} - \eta_{\mathrm{ff}}, \tag{4.7}$$

where η_{ff} refers to the average efficiency with which fossil fuel based carriers (including fossil fuel-based electricity and heat) are used in society, and η_{elec} with the average efficiency with which fossil fuels would be substituted by electricity. (SI, Methods C.1.3 presents the equivalent equations under the alternative assumption that renewable energy technologies are manufactured with fossil fuel energy.) The efficiencies of substitution are determined under the default scenario where currently deployed electrified technologies substitute fossil fuels. (SI, Methods C.1.3 explains how we obtain the efficiency of substitution η_{elec}.) Then, we determine the final stage EROI equivalent $\text{EROI}_{\text{f,eq}}$ for which renewable energy systems would deliver the same amount of net useful energy as fossil fuels (i.e. null Δe_{u}, or $e_{\text{u,ret}} = e_{\text{u,ff}}$):

$$\text{EROI}_{\text{f,eq}} = \frac{\text{EROI}_{\text{u,ff}} - \eta_{\text{ff}}}{\eta_{\text{elec}}} + 1, \tag{4.8}$$

where $\text{EROI}_{\text{u,ff}}$ is specific to a given fossil fuel group. Next, these equations can be adapted to each end-use category c as (more details in SI, Methods C.1.3):

$$\text{EROI}_{\text{f},c,\text{eq}} = \frac{\text{EROI}_{\text{u},c,\text{ff}} - \eta_{\text{ff}} + \eta_{\text{elec}}}{\eta_{c,\text{elec}}}. \tag{4.9}$$

Both Equations 4.8 and 4.9 are applied at the national and global levels. SI, Table C.3 shows the average efficiencies of substitution (η_{elec}) obtained at the global level, for each end-use category. SI, Table C.4 shows and discusses the average final-to-useful efficiencies obtained for fossil fuels (η_{ff}) from the global primary-final-useful database [20] at the global level, for each end-use category. We note that this framework also allows us to determine final demand sector (e.g. iron and steel, residential, etc) specific useful stage EROIs for fossil fuels, and associated EROI equivalent values for renewable energy technologies — the method is detailed in SI, Section C.3 alongside an example. Last, we compare the EROI equivalent values obtained with EROI values reported in the literature [24, 25] for wind power and solar photovoltaic, which are expected to be the prominent future renewable energy technologies [26, 27] — SI, Section C.1.4 explains the methodological details ensuring consistency of the comparison.

4.3 Results

4.3.1 Useful stage energy returns

Figure 4.1 shows the final useful stage EROIs obtained at the global level for fossil fuels over time, both (**a**) on average and (**b**) by end-use category at the useful stage, when including fossil fuels used as fuels, electricity, and heat in calculations. (EDF C.2 shows the equivalent graph when including only fossil fuels used as fuels in calculations.) A few significant findings can be drawn from this figure. First, Figure 4.1.**a** shows that there is a considerable drop in fossil fuel EROIs when moving from the final to the useful stage (in 2019, approximately from 8.3 to 3.3 when all fossil fuels are considered as a group, much less in the case of fossil gas — approximately from 10.6 to 9.1), which is due to the low average final-to-useful efficiencies with which fossil fuels are used in society.

Second, and as a consequence, the useful stage EROIs of fossil fuels are much lower than the final stage EROIs usually reported in the literature, with an average global value in 2019 of approximatively 3.3 when all fossil fuels are considered as a group, 9.1 for fossil gas, 6.6 for coal products, 2.9 for oil and gas products, and 2.0 for oil products. Figure 4.2 shows the average (1995–2015) breakdown in terms of direct and indirect energy requirements for fossil fuels useful stage EROIs, with indirect energy accounting for values ranging from 18% (oil products) to 30% (coal products) of energy requirements.

Third, expanding the analysis to the useful stage shows that while final stage EROIs have moderately decreased over time (note that in a much less pronounced way than in studies conducting the analysis at the primary energy stage, approximately from 9.6 in 1971 to 8.3 in 2019), useful stage EROIs seem to have increased on average when looking at the average fossil fuel mix (approximately from 2.9 to 3.3), coal products (from 5.2 to 6.6), and oil products (from 1.9 to 2.0). Only for fossil gas can one observe a clear decrease over time in useful stage EROIs (approximately from 14.2 to 9.1). These trends are due to the effect of increasing final-to-useful efficiencies offsetting the decrease in final stage EROIs. Such findings show how expanding the analysis to the useful stage contradicts the conventional narrative, according to which fossil fuels have high, although rapidly decreasing, net energy returns.

Last, Figure 4.1.**b** shows that the average fossil fuel useful stage EROI differs significantly depending on the end-use category. Energy returns are particularly high for heating end-uses (particularly, low and medium temperature heating; respectively 12.0 and 8.2 in 2019), and much lower for mechanical end-uses, such as road propulsion and mechanical work (respectively 1.5 and 2.6 in 2019). The difference in EROIs between end-uses is due to (i) higher average final-to-useful efficiencies

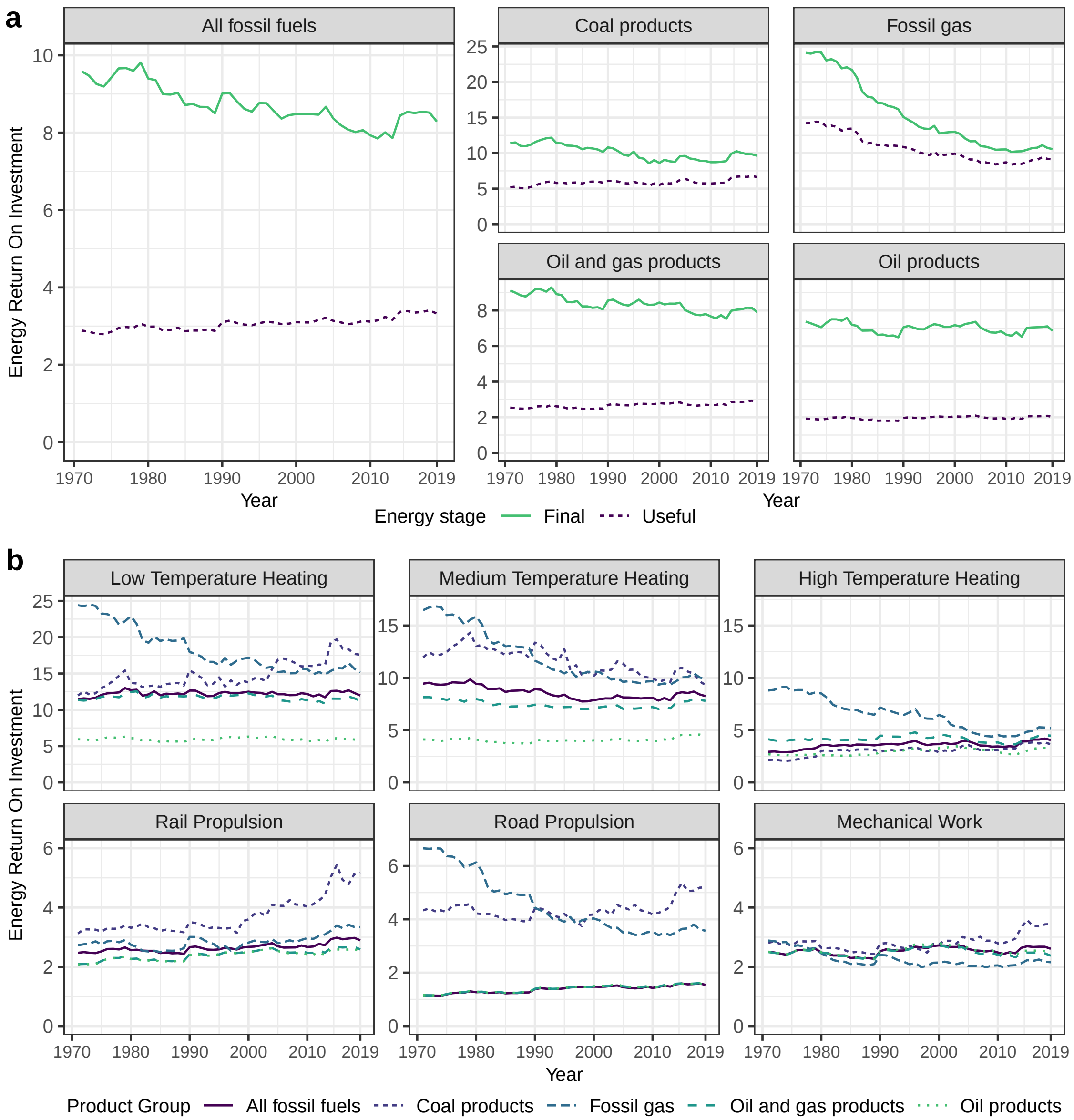

Figure 4.1: **a**, Final and useful stage average Energy Return On Investment (EROI) for the five fossil fuel groups, at the global level. **b**, Useful stage EROIs by end-use category for the five fossil fuel groups, at the global level. Calculations including fossil fuels used as fuels, electricity, and heat.

for heating end-uses than for mechanical end-uses, and (ii) a very different fossil fuel mix across end-uses (important when the focus is on the average EROI for all fossil fuels), with high EROI fossil gas accounting for much higher share of fossil fuel use in heating end-uses than in mechanical end-uses, and conversely, low EROI oil products accounting for a much higher share of fossil fuel use in mechanical uses

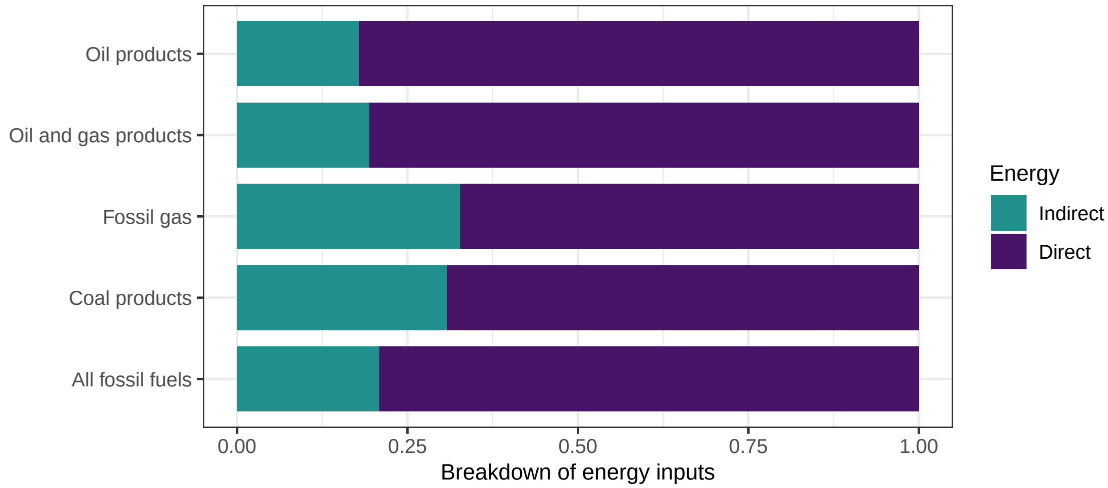

Figure 4.2: Average (1995–2015) breakdown of energy requirements in terms of direct and indirect energy requirements by fossil fuel group, at the global level.

(particularly, road transportation).

Further, Figure 4.3 shows useful stage EROIs for a selection of countries (EDF C.3 show their evolution over time), and shows that the range of values obtained at the national level are consistent with those obtained at the global level.

4.3.2 Energy Return On Investment equivalent of renewable energy systems

Figure 4.4 shows the final stage EROI equivalent values of renewable energy systems in 2019 alongside the EROI values of solar PV and wind turbines reported in the literature. (EDF C.4 shows the equivalent figure when only fossil fuels used as fuels are considered.) When including indirect final energy requirements, the EROI equivalent is as low as 4.5 when all fossil fuels are considered as a group, 8.5 for coal products, 10.4 for fossil gas, 4.0 for oil and gas products, and 3.2 for oil products. Figure 4.4.**b** shows that the EROI equivalent is very dependent on the end-use of substitution, with the substitution of fossil fuels used for heating end-uses requiring much higher EROIs than for mechanical end-uses. Indeed, the 2019 EROI equivalent values are as low as 4.6 for mechanical work and 2.3 for road transportation, but as high as 12.2 for low temperature heating and 10.2 for medium temperature heating. EDF C.5 shows that the variation obtained in the EROI equivalent values when changing the origin of manufacturing energy assumption (Section C.1.3) is minor.

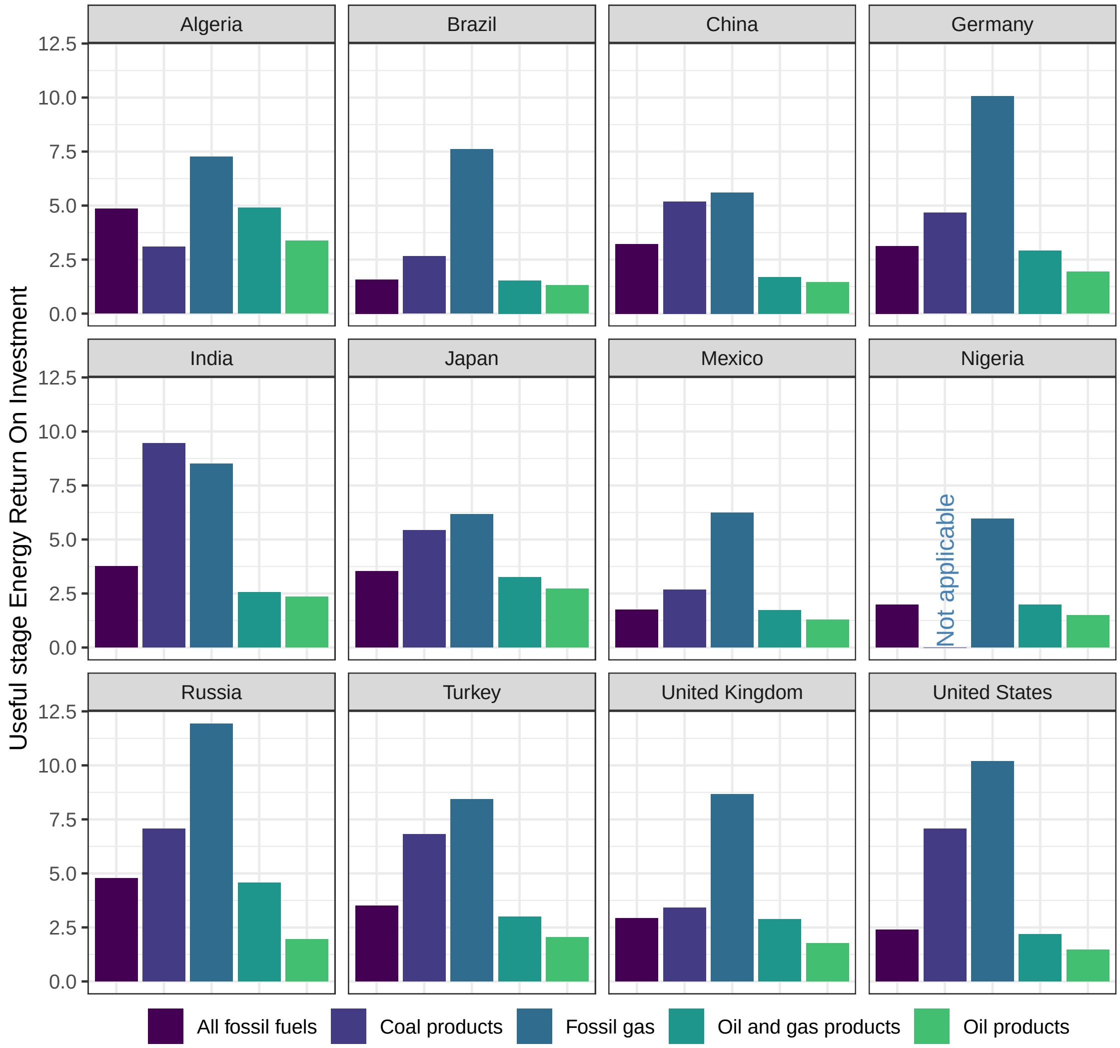

Figure 4.3: Useful stage average Energy Return On Investment (EROI) for a selection of countries (average 2000–2019), for the five fossil fuel groups. Calculations including fossil fuels used as fuels, electricity, and heat.

Figure 4.4.**a** also shows that the actual EROIs of renewable energy systems reported in the literature are, in most cases, higher than the economy-wide equivalent EROIs. When considering all fossil fuels together, oil and gas products together, or oil products, even the lowest EROI value reported for both wind and solar PV is higher than the equivalent EROIs. In the case of coal products and fossil gas the EROI equivalent is higher than the lower end of the reported EROIs in the literature, but remains lower than the median of these values. This result is how-

ever highly dependent on the end-use considered as showed by Figure 4.4.**b**, with the EROI equivalent reaching high values for heating end-uses, and particularly, for low temperature heating. These findings indicate that substantial net useful energy gains, or, alternatively, final energy savings, may be obtained as a result of the energy transition — see SI, Sections C.3.4 and C.3.5 for a quantification of the potential net useful energy gains and final energy savings, respectively.

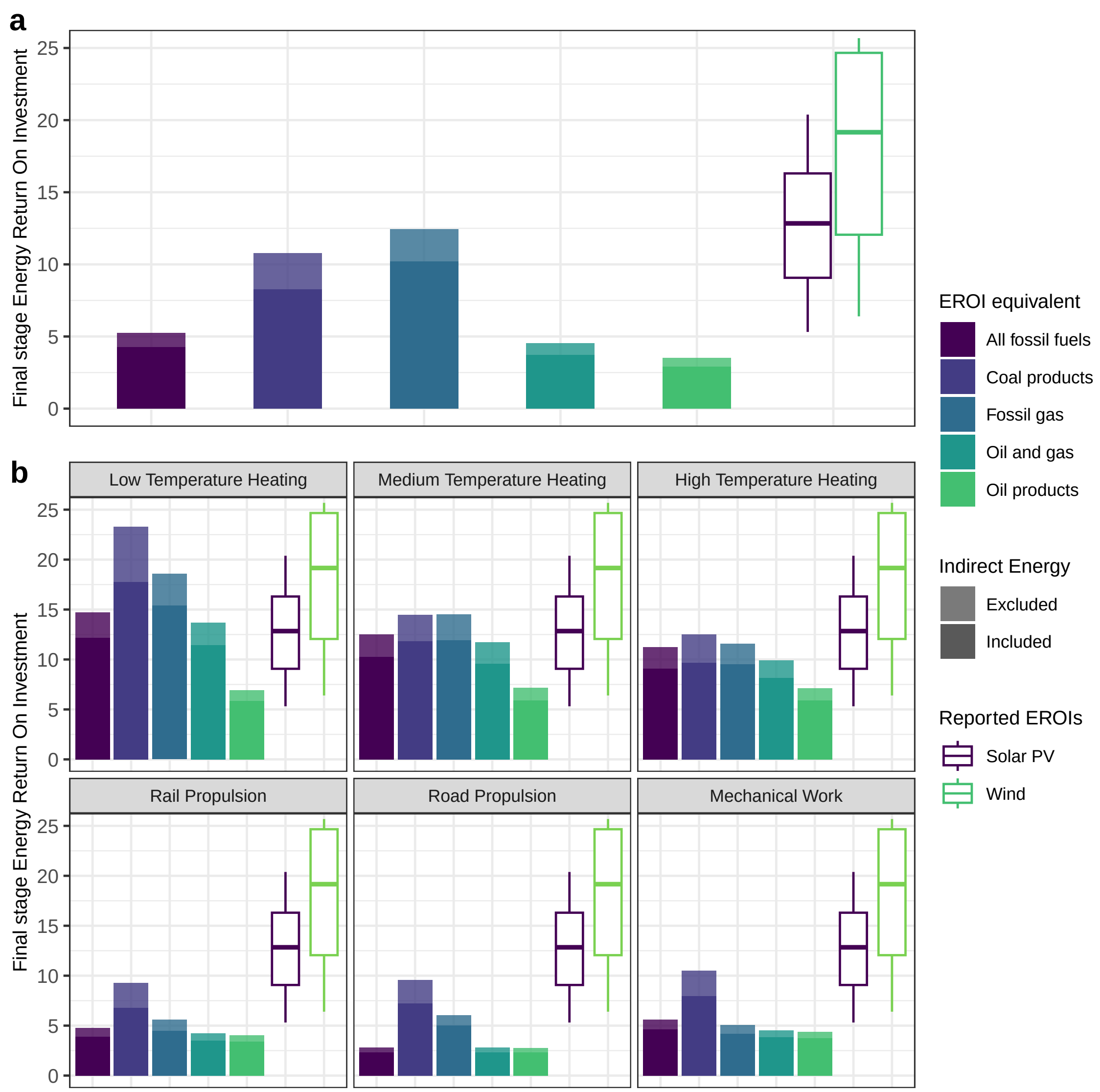

Figure 4.4: Final stage Energy Return On Investment (EROI) equivalent calculated for 2019 at the global level alongside actual EROIs of renewable energy systems reported in the literature, **a,** economy-wide, and **b,** by end-use category. Values calculated for fossil fuels used as fuels, electricity, and heat.

Next, Figure 4.5 shows the evolution of the EROI equivalent over time, whether economy-wide (**a**) or by end-use category (**b**). (EDF C.6 shows the equivalent figure when only fossil fuels used as fuels are considered.) The economy-wide EROI equivalent has slightly decreased over time, from approximately from 5.0 in 1971 to 4.5 in 2019, for all fossil fuels are considered as a group. Such a decreasing trend was mostly driven by the decline for natural gas (from approximatively 19.3 in 1971 to 10.4 in 2019), and is due partly to the declining final stage EROIs of fossil fuels and to the increasing final-to-useful efficiencies with which electricity (so, the renewable energy technologies considered here) is converted into useful energy. Whether or not the EROI equivalent will keep decreasing will be function of the future evolution of average final-to-useful efficiencies of electricity, of the future evolution of fossil fuel final stage EROIs, as well as of the future evolution of average final-to-useful efficiencies of fossil fuels.

Next, Figure 4.6 shows the EROI equivalent in each country, alongside the country's ratio of fossil fuel consumption (fossil group specific) to final energy consumption (the size of the dot represents the share of the country's global fossil fuel group consumption). The lowest and median value of renewable energy systems EROIs based on the literature are also shown for solar photovoltaic and wind power. The figure shows that in the case of oil products, oil and gas products, and when all fossil fuels are considered as a group, the EROI equivalent values are lower than the lowest renewable energy final stage EROIs reported in the literature for almost all countries. In the case of fossil gas, most countries EROI equivalents are below the median of the renewable energy final stage EROIs reported in the literature — only approximately half of the countries in the case of coal products. In general, it seems that the EROI equivalent values are rather on the lower end for countries consuming large amounts of fossil fuels (large dots), for which data can be expected to be of higher quality than for relatively small countries.

Last, Figure 4.7 shows the EROI equivalent for a selection of countries. (EDF C.7 shows the EROI equivalent for the same set of countries over time, and EDF C.8 shows the EROI equivalent for a set of EU countries.) Although there are significant differences across countries, the values remain relatively low when all fossil fuels are considered as a group (in the range 2.6–6.3), as well as for oil and gas products (in the range 2.5–6.3) and for oil products (in the range 2.1–4.8). The values are more variable and higher for coal products (in the range 3.4–13.4) and for fossil gas (in

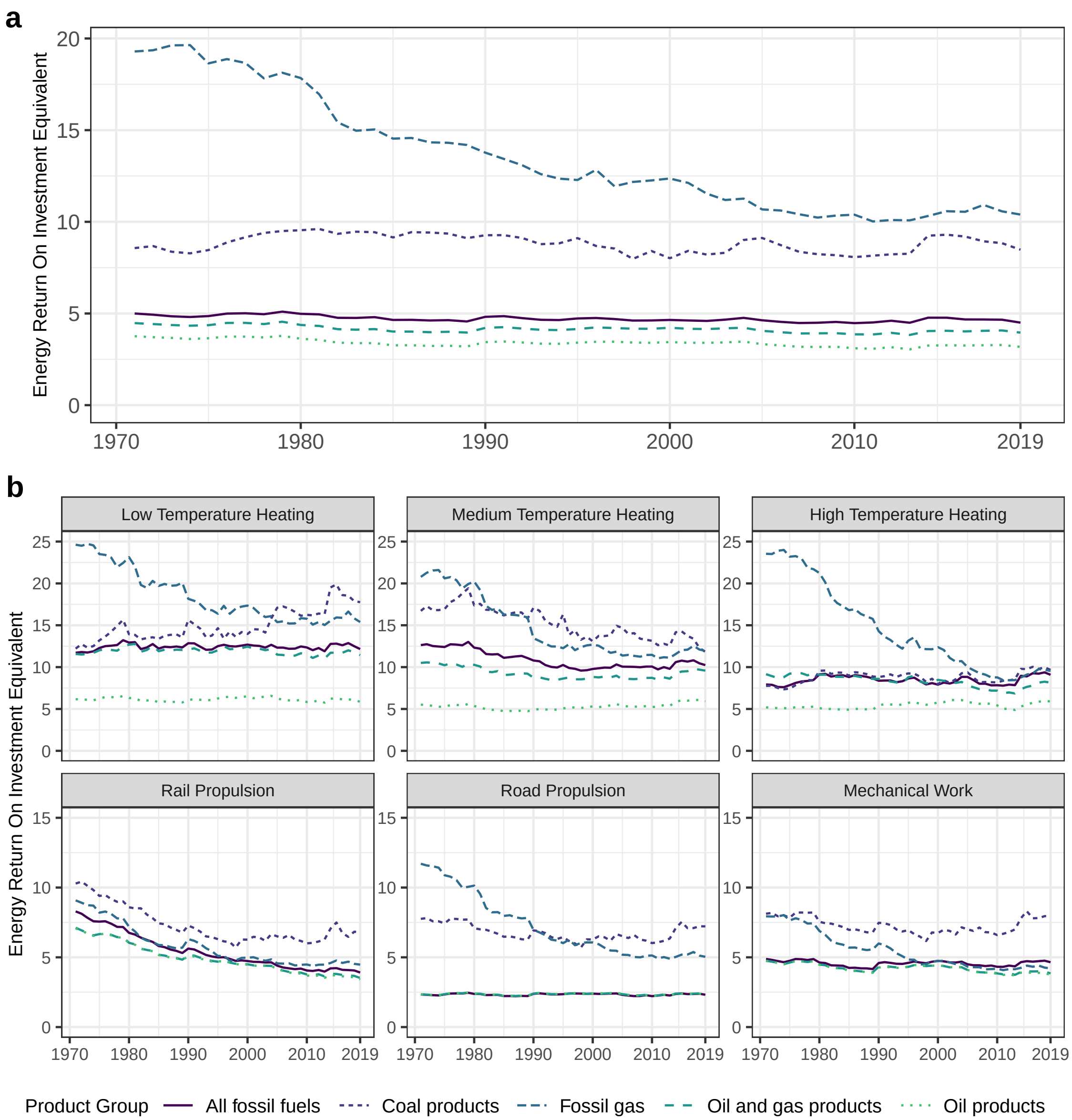

Figure 4.5: Final stage Energy Return On Investment equivalent for renewable energy systems over time at the global level, **a,** economy-wide, and **b,** by end-use. Values calculated for fossil fuels used as fuels, electricity, and heat.

the range 7.7–14.5). Such ranges seem to be clearly lower (all fossil fuels, oil and gas products, oil products) or on the lower end of the actual EROIs reported in the literature (fossil gas and coal products). The findings obtained strongly question the commonplace narrative that the energy transition will imply a decrease in the net energy available to society, and indicate instead that in the long-term, the energy

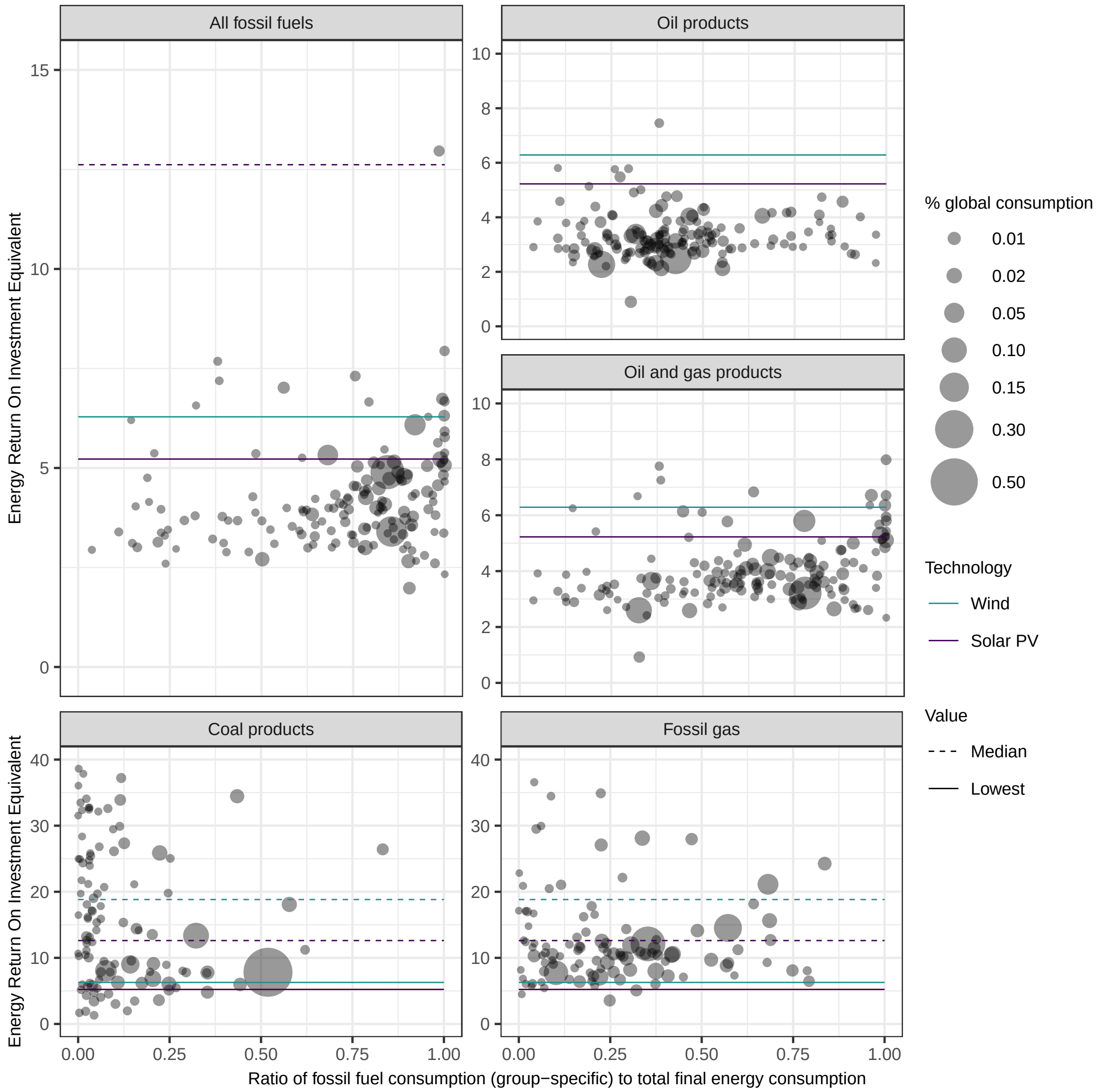

Figure 4.6: National-level economy-wide Energy Return On Investment equivalent (average 2000–2019) as function of the share of final energy consumption from fossil fuel origin (2019), and compared to reported EROIs for renewable energy systems in the literature. The size of the dots are function of the share of each country's global fossil fuel group consumption. Values calculated for fossil fuels used as fuels, electricity, and heat.

transition may entail net useful energy gains.

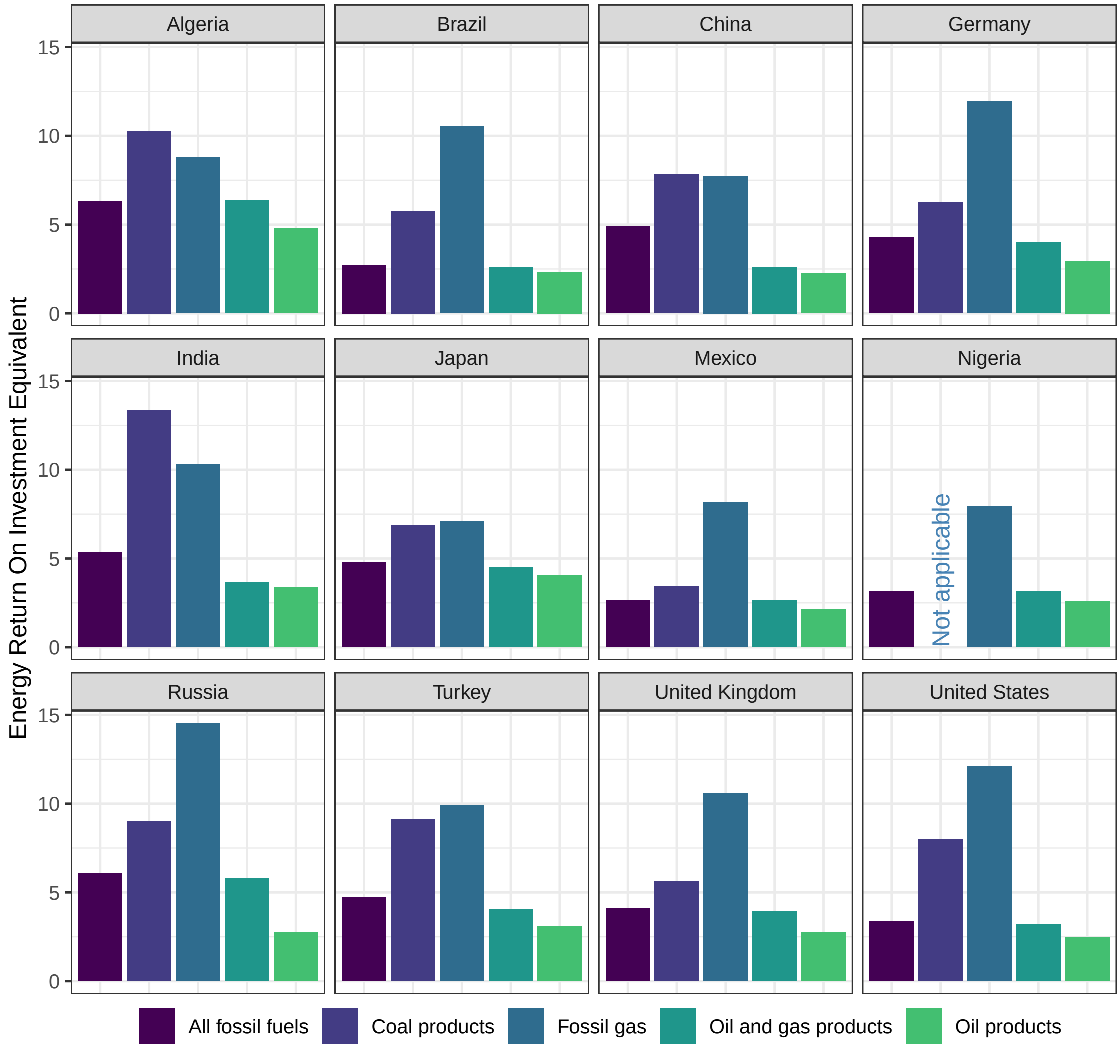

Figure 4.7: Final stage Energy Return On Investment equivalent for a selection of countries (average 2000–2019). Values calculated for fossil fuels used as fuels, electricity, and heat.

4.3.3 Limitations

A few caveats and limitations are worth mentioning. First, the energy transition will not only imply a change in the supply side of the energy conversion chain, but also a deep change in the final energy carriers — with greater use of electricity [28] — and end-use devices used (which will affect the average final-to-useful efficiencies of each energy carrier). For instance, a quick uptake of heat pumps can be expected, which would significantly increase the average final-to-useful efficiency of electricity for low temperature heating. The EROI equivalent of renewable energy technologies for low temperature heating purposes would consequently significantly decrease. Indeed, SI, Section C.3.2 shows that the EROI equivalent value drops to 2.3 under the alternative assumption that heat pumps will replace low and medium temperature (up to 100°C) heating processes, except cooking. By only using the current final-to-useful efficiencies of either electricity or fossil fuels within each end-use to estimate the EROI equivalent values, our study overlooks such synergies between changes in the supply side and end-use devices, which could reinforce the potential for net useful energy gains.

Second, the renewable energy transition implies a wide change in the energy system to deal with the intermittence of renewable energy technologies and with the electrification of end-uses, for instance through storage (e.g. with batteries), additional capacities, grids, charging points for electric vehicles, etc. Such additional needs will require significant amounts of energy, which will be diverted from the rest of society, and limit the potential net useful energy gains previously discussed. Whether the energy requirements of such factors should be included in EROI calculations or not has been heavily discussed [29–31], but they are of importance when quantifying the net useful energy implications of the energy transition. The EROI values that we have used in Figure 4.4 do not include such energy requirements, so that the net useful energy gains are likely to be somewhat overestimated. Moreover, the EROI values that we use for renewable energy technologies come from Life Cycle Analysis studies, which may yield underestimated energy requirements estimates due to truncations errors [32, 33].

Third, the present analysis is static and does not take into consideration the dynamic effects of the energy transition. Indeed, while we show here that renewable energy systems may have high enough net useful energy returns, such systems however require large upfront energy investments, and deliver energy back over their lifetime. Such effect is much more significant for renewable energy technologies (for which the energy requirements of operation and maintenance are very low compared to those of manufacturing) than for fossil fuel industries. Such dynamic effects may result in a situation in which the net useful energy available to society temporary drops as energy investments in the energy system take place, and then picks up once the bulk of investments is done [2, 3].

Fourth, the long-term net useful energy implications of the energy transition will also be function of the future evolution of the EROI of renewable energy systems. While some studies have argued that their energy returns are likely to decrease over time as the best locations are used first [34, 35], it seems that technological factors can also play an important role in offsetting such effects [36] — for instance, the capacity factors of wind turbines and efficiencies of solar modules have significantly increased over time in recent years [37], thereby increasing the energy output of renewable energy technologies.

4.4 Conclusion

This work has shown that the useful stage Energy Return On Investment of fossil fuels drops considerably when moving from a final stage (approximatively 8.3) to a useful stage analysis (approximatively 3.3). Such a low value however hides large differences between fossil fuels and end-uses, with average useful stage energy returns being much higher for heating end-uses compared to mechanical end-uses. In addition, we have shown that fossil fuel useful stage energy returns have slightly increased over time, or have remained fairly constant — only for fossil gas do energy returns present a clearly declining trend. Such findings question the conventional narrative according to which fossil fuels present very high, although quickly decreasing, energy returns.

Next, this study has shown that the final stage Energy Return On Investment equivalent of renewable energy systems is as low as 4.5 (a final stage analysis would suggest that a value of 8.3 is required to match the net energy returns of fossil fuels), which is due to the significantly higher final-to-useful efficiency of electricity compared to those of fossil fuel-based energy carriers. Such value is however highly variable across the end-use of substitution as well as fossil fuel being substituted. Then, we found that most energy returns of renewable energy technologies reported in the literature are (significantly) higher than the EROI equivalent we obtain (less so for fossil gas), which points to potential significant net useful energy gains as an outcome of the renewable energy transition — such gains would however be highly variable depending on the fossil fuel being substituted and end-use of substitution. In highly ambitious climate change mitigation pathways, such potential useful energy gains could be used to quickly reduce final energy consumption.

Our study has significant implications. First, we show that renewable energy systems have indeed high enough energy returns to allow the renewable energy transition to happen without a significant decrease in the net useful energy delivered to society, although the dynamic effects of the energy transition on the net useful energy have not been quantified, and may entail adverse effects in the short-term. The debate regarding whether renewable energy systems have high enough energy returns to sustain an industrial society seems therefore obsolete in the light of our results. Instead, we suggest that the net energy analysis community should direct efforts at identifying pathways ensuring a quick phase-out of fossil fuels while providing sufficient net useful energy to provide everyone with sufficient energy services for meeting decent living standards [38–42].

Second, most energy-economy models that adopt a net energy perspective may find overly pessimistic implications of the renewable energy transition. Indeed, we have already pointed out that many models inconsistently use Energy Return On Investment values, mixing primary stage values for fossil fuels while using final stage values for renewable energy (see e.g. [4, 6, 8]). Further, our study finds that even models using consistently final stage values across all energy carriers (for instance [43, 44]) may be overlooking the implications of the different final-to-useful efficiencies across energy carriers. Conducting the analysis at the useful stage of energy use appears crucial to fully understand the net energy, as well as economic and social implications of the energy transition.

Data statement

The dataset associated with this chapter can be found in the online repository associated with this thesis, hosted at the University of Leeds Data Repostory: https://doi.org/10.5518/1322.

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Chapter 5

Exploring the effects of mineral depletion on renewable energy technologies net energy returns

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As renewable energy technologies are heavily reliant on a range of minerals, some of them scarce, the transition to a renewable energy system poses a set of new challenges, including regarding the future net energy returns of the energy system. Indeed, the ongoing process of mineral depletion, i.e. the process whereby lower quality deposits need to be increasingly mined as high quality deposits get depleted, entails an increasing energy consumption per tonne of valuable mineral mined (i.e. energy intensity of mining). Such increases in the energy intensities of mining raise the question of how the future net energy returns of renewable energy technologies will be affected. In this article, we explore the effects of the increasing energy intensities of mining on the net energy returns of four renewable energy technologies: solar photovoltaic, concentrated solar power, onshore wind, and offshore wind.

Our findings indicate that the effects of mineral depletion on the net energy returns of renewable energy technologies will be marginal, because mining processes only represent a minor fraction of the energy inputs to the production, operation, and maintenance of renewable energy technologies. Indeed, the share of net energy returned decreases by less than 3 percentage points for the scenarios and technologies that we explore. In addition, we show that technological factors, such as improvements in metallurgical energy efficiencies, material intensities of manufacturing, and recycled input rates, have the potential to somewhat offset the effects of mineral depletion. Hence, our results indicate that the effects of mineral depletion are unlikely to affect significantly the net energy returns of renewable energy technologies.

5.1 Introduction

A large uptake in renewable energy technologies is expected in a short timespan as part of the ecological and energy transition [1]. Such a transition from traditional, fossil fuel based energy systems towards renewable energy systems poses a set of challenges, for instance due to electrification of end-uses [2], intermittency of electricity generation [3], the need for energy storage [4], or land requirements [5]. One of the potential challenges relates to the capacity of renewable energy systems to yield *net* energy. All energy systems need to consume some energy for their manufacturing and functioning, so that a given fraction of the produced energy needs to be reinvested in the energy system itself, and only the remaining fraction, i.e. the net energy, can be used for productive and beneficial purposes [6]. The net energy aspects of energy systems are often assessed through the Energy Return On Investment (EROI) metric, which is defined as the ratio of energy output delivered over the lifetime of an energy system to the energy input invested for the manufacturing, operation, maintenance and decommissioning of the studied energy system [7, 8]. While renewable energy technologies have been conventionally thought to have lower net energy returns than fossil fuel based systems, recent research has shown that when adopting equivalent boundaries and analysing the energy output at the final energy stage, renewable energy technologies have net energy returns comparable to fossil fuel energy [9, 10], although the comparison depends on the specific type of fossil fuel and renewable energy technology analysed, as well as on the geographical setting and conditions (wind potential, solar irradiation, etc).

However, most renewable energy technologies have a high reliance on non-renewable mineral resources [11, 12]. Recent studies have raised concerns regarding the future availability of some minerals in a context of growing mineral demand [13], and authors raised concerns regarding whether mineral reserves will be sufficient to meet mineral requirements for the energy transition and the broader economy [14–16]. Simultaneously, the mineral mining industry needs to extract mineral deposits of ever lower qualities (in terms of ore grades, grinding size, accessibility, etc), so that the energy intensities of mining (i.e. the energy required to extract one unit mass of valuable mineral) tend to increase over time. Such trends have been reported at the level of individual mines and companies [17], have been identified as a factor hindering the productivity of the mining sector by the Australian Government

Productivity Commission [18], and can be identified in the reports of the national Chilean Copper Commission (see [19]). This high reliance of renewable energy technologies on mineral resources (as compared to fossil fuels), combined with the increasing energy intensities of mining, has raised concerns as to whether the future net energy returns of renewable energy technologies may decrease — and by how much — as a consequence of increasing energy intensities of mining processes [16, 20, 21].

Recent works have attempted to model such increases in the energy intensities of mining to model the future energy consumption and greenhouse gases emissions of the metallurgical sector, globally [22, 23], for the EU28 [24], and for China [25]. However, few works have attempted to capture the impacts of these trends on the net energy returns of renewable energy technologies. First, Harmsen et al. [21] analyse the change in wind turbine EROIs that may be induced by the decrease in copper deposit qualities and finds a moderate impact (EROI decrease from 25.2 to 24.4), but the work does not quantify the impacts due to other minerals. Second, Fizaine and Court [20] estimated the decrease in renewable energy technologies EROIs as a function of the decrease of the ore grade deposits. The authors found that the effect of mineral depletion, when considered jointly for all minerals, may significantly affect the EROI of renewable energy technologies, particularly if ore grades decrease to very low concentrations. The work of Fizaine and Court [20] however fails to differentiate the energy consumption of mining processes from the downstream metallurgical processes, and therefore also applies increasing energy intensities to metallurgical processes, hence leading to an overestimation of the effects of mineral depletion.

In this paper, we build on the methodology developed by Fizaine and Court [20] to explore the potential effects of increasing energy intensities of mining (denoted as energy intensities in the rest of the article) on the net energy returns of renewable energy technologies when covering all relevant mineral materials. We use recent work by Aramendia et al. [26] to overcome previous limitations by clearly differentiating the ore mining stages of mineral extraction from downstream metallurgical processes. We also expand previous work by assessing and critically discussing the extent to which improvements in metallurgical energy efficiencies, recycled input rates, and material intensities of renewable energy technologies manufacturing may compensate for such increases in energy intensities. The paper is structured as follows: Section 5.2 describes the methodology, Section 5.3 presents the results, which are discussed in Section 5.4. Last, Section 5.5 presents the conclusions and implications.

5.2 Methodology

Our methodology is divided in two main parts. First, Section 5.2.1 presents the method for estimating the effects of mineral depletion on the net energy returns of renewable energy technologies, and second, Section 5.2.2 presents the method for estimating the potential of technological levers to offset mineral depletion effects.

5.2.1 Quantifying the effects of mineral depletion on the net energy returns of renewable energy technologies

Material intensities of renewable energy technologies

First, this study requires the material intensities (i.e. the material requirements for manufacturing and operating 1 MW of a given energy technology) for each of the four reviewed renewable energy technologies: solar photovoltaic (solar PV), concentrated solar power (solar CSP), wind onshore, and wind offshore. We base the material intensities on previous work by de Castro and Capellán-Pérez [27] and Beylot et al. [28]. The material intensities used for each technology as well as the source study can be found in the dataset associated with the chapter (see Data Statement).

Modelling future energy intensities

Following Aramendia et al. [26], we define the current final energy intensity f_m of mining a mineral m as the final energy that is currently required to extract one tonne of the mineral m — a nomenclature is provided in Supplemental Information (SI), Section D.1. The values we use for f_m are based on [26] are fully available in the dataset associated with the chapter (see Data Statement). Then, we define the future final energy intensity $e_{m,t}$ (in the rest of the paper, energy intensity refers to *final* energy intensity, unless stated otherwise) as the actual energy intensity of mining a mineral m at a given time t, once the effects of mineral depletion are taken into consideration, and we introduce the parameter $\alpha_{m,t}$ as the coefficient modelling the increase in energy intensities over time for a mineral m, so that:

$$e_{m,t} = \alpha_{m,t} f_m. \tag{5.1}$$

For the sake of simplicity, we consider here that each mineral is equally affected by mineral depletion, so that the parameter α is independent of the mineral m and should thus be interpreted as an average increase in the energy intensities over time. We reuse the scenarios developed for the α coefficients by Aramendia et al. [26]; such scenarios extrapolate trends in energy intensities based on historical data for copper derived from previous works and reports by Calvo et al. [17] and reports from the Chilean Copper Commission (see [19]). In addition, we add a scenario in which α values increase even faster, by a yearly rate of 2.9%, which is the average increase reported by the Chilean Copper Commission over the period 2001–2019. We note that using energy intensity scenarios based on copper for all minerals is a pessimistic assumption which tends to overestimate the effects of mineral depletion. Indeed, the mining of abundant minerals such as iron or aluminium is unlikely to be significantly affected by increasing energy intensities, as the energy consumption of crushing and grinding the ore only increases significantly at concentrations much lower than those at which these metals are currently mined [29, 30]. The different scenarios we use for α, alongside a baseline scenario of no increasing energy intensities, are displayed in Figure 5.1.

Hence, for a given renewable energy technology of capacity equal to 1 MW, we can express the variation of final energy requirements as function of time, for each energy intensity scenario, as:

$$\begin{aligned} \Delta e_{\text{mining},t} &= \sum_m (\alpha_{m,t} - 1) i_m f_m \\ &= (\alpha_t - 1) \sum_m i_m f_m, \end{aligned} \tag{5.2}$$

where i_m stands for the material intensity in mineral m of the given renewable energy technology.

Mineral depletion effects on the EROIs of renewable energy technologies

Then, we adapt the methodology introduced by Fizaine and Court [20] to estimate the effects on the EROIs of the change in energy input requirements Δe_{mining}. For

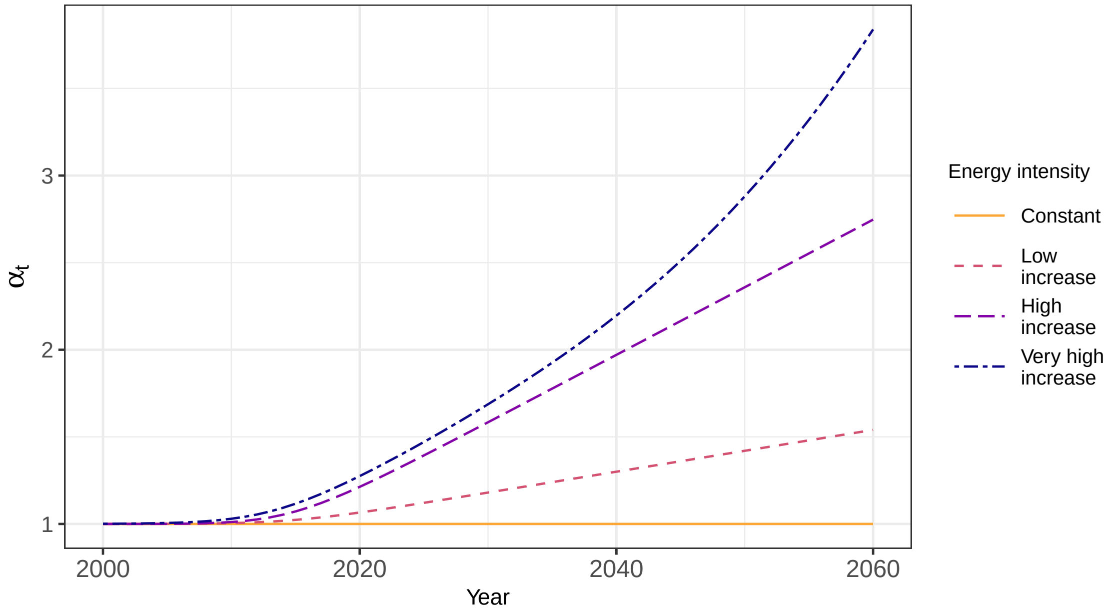

Figure 5.1: Values of the increasing energy intensities coefficient α for the three different considered scenarios and the baseline of no increasing energy intensities. Figure adapted from Aramendia et al. [26]. The very high increase in energy intensities scenario has been added for this article.

a given energy technology of capacity 1 MW, one can determine the final energy output over its lifetime e_{output} as:

$$e_{\text{output}} = 8760.\text{CF}.\text{L}, \tag{5.3}$$

where CF stands for the capacity factor of the energy technology (in share), and L for its average lifetime (in years). Then, the final energy input (over the lifetime of the energy technology) e_{input} in the absence of mineral depletion effects can be calculated as:

$$e_{\text{input}} = \frac{8760.\text{CF}.\text{L}}{\text{EROI}_{t=0}}, \tag{5.4}$$

where $\text{EROI}_{t=0}$ stands for the EROI of the energy technology that is currently observed, in the absence of mineral depletion effects — note that we are here defining EROI as the ratio of *final* energy output to *final* energy input over the lifetime of a technology (instead of using primary energy equivalents for the energy output and

Table 5.1: Summary of capacity factors, lifetimes, and EROI values used for each renewable energy technology assessed. Capacity factors and lifetimes are taken from de Castro and Capellán-Pérez [27]. We estimate a low, medium, and high EROI for each technology from the literature, particularly using [27, 31–35]. CF: Capacity Factor.

Technology	CF (%)	Lifetime (years)	Low EROI	Medium EROI	High EROI
Solar PV	14.2	25	4	8	15
Solar CSP	25.3	25	2	5	10
Wind onshore	24.2	20	5	10	20
Wind offshore	40.9	20	5	10	20

primary energy requirements for the energy input). The dynamic EROI, i.e. the EROI accounting for depletion effects, can then be determined as:

$$\mathrm{EROI}_t = \frac{e_{\mathrm{output}}}{e_{\mathrm{input}} + \Delta e_{\mathrm{mining},t}}. \tag{5.5}$$

Replacing e_{output}, one obtains:

$$\begin{aligned} \mathrm{EROI}_t &= \frac{e_{\mathrm{input}}\mathrm{EROI}_{t=0}}{e_{\mathrm{input}} + \Delta e_{\mathrm{mining},t}} \\ &= \frac{\mathrm{EROI}_{t=0}}{1 + \frac{\Delta e_{\mathrm{mining},t}}{e_{\mathrm{input}}}}. \end{aligned} \tag{5.6}$$

As the EROIs of renewable energy technologies are subject to debate in the literature (e.g. due to different system boundaries) and depend upon geographical conditions, we use a low, medium and high EROI value for each renewable energy technology for our calculations. We estimate a low, medium, and high EROI for each renewable energy technology from the literature (particularly, using [27, 31–35]) — we note that the chosen values are not critical to the results obtained in the analysis we conduct, although it was deemed important to show how the results obtained may vary using a low, medium, or high value as initial EROI. Table 5.1 summarises the EROI values we use as well as the capacity factor values and average lifetimes, which we take from de Castro and Capellán-Pérez [27].

Mineral depletion effects on the net energy returns of renewable energy technologies

Once the effects of mineral depletion on the EROI of renewable energy technologies have been quantified, the corresponding share of net energy returns can be simply calculated following Equation 5.7:

$$\begin{aligned}\eta_t &= \frac{\text{EROI}_t - 1}{\text{EROI}_t} \\ &= \frac{e_{\text{output}} - (e_{\text{input}} + \Delta e_{\text{mining},t})}{e_{\text{output}}},\end{aligned} \tag{5.7}$$

where η_t stands for the share of output energy available to society as net energy at a given time t, and where $\Delta e_{\text{mining},t}$, e_{output}, and e_{input} are determined from respectively Equations 5.2, 5.3, and 5.4. The variation in the share of net energy returned to society can then be calculated as:

$$\begin{aligned}\Delta\eta_t &= \frac{\text{EROI}_t - 1}{\text{EROI}_t} - \frac{\text{EROI}_{t=0} - 1}{\text{EROI}_{t=0}} \\ &= -\frac{\Delta e_{\text{mining},t}}{e_{\text{output}}}.\end{aligned} \tag{5.8}$$

We note that the variation in the share of net energy delivered to society is independent of the initial value of the EROI and that considering a given level of energy output, is only a function of the increasing energy consumption of mining processes.

Sensitivity analysis: Monte Carlo simulation of current energy intensities

Considering the uncertainty associated with the current energy intensities values f_m that we use for each mineral m, we follow the approach developed by Aramendia et al. [26] and conduct a Monte Carlo simulation (1000 runs) of the changes observed in η when the current energy intensity of each mineral follows independently a normal probability distribution function — see the dataset associated with the chapter, available through the Data Statement section.

5.2.2 Quantifying the potential of technological levers to offset the effects of mineral depletion

While the effects of mineral depletion are indeed likely to increase the future energy requirements needed to manufacture and operate renewable energy technologies, other drivers will tend to lower such energy requirements in the future. First, future increases in the efficiencies of metallurgical processes (i.e. metal manufacturing after the ore has been mined and concentrated) are likely to compensate to some extent the increasing energy intensities of mining [36] (see studies by the U.S. Department of Energy for analysis focused on e.g. iron, aluminium and titanium [37–39]), particularly considering that energy consumption for metallurgical processes is often significantly higher than energy consumption for mining processes [40, 41]. Second, future possible increases in recycling rates may entail an increase in the recycled input rates of materials (i.e. the share of input materials coming from secondary production [42, 43], sometimes also referred to as recycled content [44]), which will lower the energy requirements of renewable energy technologies, because the energy requirements of secondary material production (i.e. material recycling) are generally considerably lower than those of primary material production [41, 45]. Third, the material intensities of renewable energy technologies have been found to decrease in recent years for wind power and solar PV, and such a trend is expected to continue in the short term [11] — for instance, a decrease in the silicon and silver intensities of solar PV by respectively 25% and 30% is expected by the International Energy Agency (IEA) by 2030 [11, p. 56] — although Liang et al. [46] finds that this important aspect is often overlooked in studies. The variation of future energy requirements can hence be decomposed following Equation 5.9:

$$\Delta e = \Delta e_{\text{mining}} + \Delta e_{\text{refining}} + \Delta e_{\text{recycling}} + \Delta e_{\text{manufacture}}. \tag{5.9}$$

The subsequent paragraphs will explain how the effects of increasing efficiencies of metallurgical processes $\Delta e_{\text{refining}}$, increasing recycling rates $\Delta e_{\text{recycling}}$, and decreasing material intensities of manufacturing processes $\Delta e_{\text{manufacture}}$ are estimated, and will express the condition under which each term may be sufficient to compensate for the increasing energy intensities of mining as function of the α coefficient.

Effects of increases in metallurgical energy efficiencies

Equation 5.10 defines the variation in energy requirements due to increasing energy efficiencies of metallurgical processes:

$$\begin{aligned}\Delta e_{\text{refining}} &= \sum_m (1-\beta_m) i_m \varphi_m - \sum_m i_m \varphi_m \\ &= -\sum_m \beta_m i_m \varphi_m,\end{aligned} \tag{5.10}$$

with the factor β_m representing the metallurgical energy efficiency improvements (with $\beta_m \in [0,1]$) in manufacturing mineral m, and φ_m representing the energy intensity of the metallurgical process manufacturing mineral m. The values we use for φ_m are available in the dataset associated with the chapter (see Data Statement). For the sake of simplicity, we assume that efficiency improvements will be similar across all minerals, so that β is independent of the mineral m, and Equation 5.10 becomes:

$$\Delta e_{\text{refining}} = -\beta \sum_m i_m \varphi_m. \tag{5.11}$$

We can then estimate the β coefficient required to fully offset the effects of increasing energy intensities of mining in the absence of other compensating effects, by solving the equation $\Delta e_{\text{mining}} + \Delta e_{\text{refining}} = 0$, which leads to the following expression of β_{offset}:

$$\beta_{\text{offset}} = (\alpha - 1) \frac{\sum_m i_m f_m}{\sum_m i_m \varphi_m}. \tag{5.12}$$

Effects of increases in recycled input rates

Next, Equation 5.13 defines the variation in energy requirements as function of increasing recycled input rates:

$$\begin{aligned}\Delta e_{\text{recycling}} &= \sum_m \delta r_m i_m s_m - \sum_m \delta r_m i_m (\alpha f_m + (1-\beta)\varphi_m) \\ &= \sum_m \delta r_m i_m (s_m - (\alpha f_m + (1-\beta)\varphi_m)),\end{aligned} \tag{5.13}$$

where δr_m stands for the variation in the recycled input rate of mineral m (hence $\delta r_m \in [0,1]$), and s_m represents the energy intensity of recycling mineral m. The values we use for s_m are available in the dataset associated with the chapter (see Data Statement). We also assume for the sake of simplicity that recycled input rates increases will be homogeneous across all minerals, so that δr is effectively independent of the mineral, and Equation 5.13 becomes:

$$\Delta e_{\text{recycling}} = \delta r \sum_m i_m(s_m - (\alpha f_m + (1-\beta)\varphi_m)). \tag{5.14}$$

To determine the required increases in recycled input rates needed to offset the increases in energy intensities of mining in the absence of other compensating effects, one can solve the equation $\Delta e_{\text{mining}} + \Delta e_{\text{recycling}} = 0$, which leads to the following expression of δr_{offset}:

$$\delta r_{\text{offset}} = (\alpha - 1)\frac{\sum_m i_m f_m}{\sum_m i_m(\alpha f_m + (1-\beta)\varphi_m - s_m)}. \tag{5.15}$$

Effects of improvements in material intensities of manufacturing processes

The variation of energy requirements due to improvements in material intensities of renewable energy technologies manufacturing can be defined as:

$$\begin{aligned} \Delta e_{\text{manufacture}} &= \sum_m (1-\lambda_m) i_m(\alpha f_m + (1-\beta)\varphi_m) - \sum_m i_m(\alpha f_m + (1-\beta)\varphi_m) \\ &= -\sum_m \lambda_m i_m(\alpha f_m + (1-\beta)\varphi_m), \end{aligned} \tag{5.16}$$

where λ_m stands for the improvements in material intensity (hence $\lambda_m \in [0,1]$) of mineral m in the manufacture of a given renewable energy technology. We also assume that λ is independent the mineral m, so that it can be interpreted as the average improvement in manufacturing material intensities, and Equation 5.16 becomes:

$$\Delta e_{\text{manufacture}} = -\lambda \sum_m i_m(\alpha f_m + (1-\beta)\varphi_m). \tag{5.17}$$

Solving the equation $\Delta e = \Delta e_{\text{mining}} + \Delta e_{\text{manufacture}} = 0$ yields the value λ_{offset} required to fully offset the increasing energy intensities of mining in the absence of other compensating effects:

$$\lambda_{\text{offset}} = (\alpha - 1)\frac{\sum_m i_m f_m}{\sum_m i_m(\alpha f_m + (1-\beta)\varphi_m)}. \tag{5.18}$$

5.2.3 Methodological limitations

A first limitation of this study comes from the undifferentiated treatment of all minerals in terms of energy intensities of mining scenarios. Indeed, it is reasonable to think that mineral depletion dynamics will affect every mineral differently, and that the energy intensities of mining abundant minerals may not increase, or do so only negligibly, while scarce minerals will present steep increases in energy intensities. However, we note that applying increasing energy intensities derived from copper data (a rather scarce metal affected by the effects of mineral depletion) to the rest of minerals is likely to overestimate the effects of mineral depletion (some metals such as iron or aluminium are not likely to be significantly affected by these effects in the timespan considered, due to high deposit concentrations — in the range 30–50% for iron and around 15% for aluminium [30]). Hence, this methodological choice only makes the findings and conclusions of the study stronger, as the low effects of mineral depletion are demonstrated even in a hypothetical situation where all minerals would be (equally) affected by geological depletion.

Limited data availability, particularly regarding the energy intensities of mining f_m, of mineral refining φ_m, and of secondary mineral production s_m, is also a noteworthy limitation for this study. Indeed, there is significant uncertainty about the energy intensities of mining and mineral refining, and for some minerals we were not able to find energy intensities of secondary production. In response, we (i) conduct the Monte Carlo simulation when assigning the energy intensities of mining each mineral to a probability distribution function, and (ii) use rather unfavourable energy intensities for mineral refining and secondary production (see the dataset associated with the chapter, available through the Data Statement section), so that results regarding the capacity of metallurgical energy efficiencies and recycled input rates to offset mineral depletion effects are conservative.

An additional important limitation is that our methodology assumes that minerals remain available for renewable energy technologies, although the energy consumption associated with their extraction increases. Hence, this study does not capture the possible effects of limited mineral availability (which can be due to mineral depletion as well as geopolitical or economic factors) on the net energy returns of renewable energy technologies. Indeed, limited availability of specific minerals may incentive the substitution of the scarce minerals by other minerals (e.g. substituting silver with copper in solar PV), which can be expected to result in a drop in the performance of the technology, and hence and its net energy returns [27].

Last, it is worth noting that other technological factors that may help offsetting the effects of mineral depletion, such as increasing capacity factors, increasing lifetimes, or increasing module efficiencies for solar PV, are outside the scope of this study, although discussed briefly in Section 5.4.2.

5.3 Results

5.3.1 Quantifying the effects of mineral depletion on the net energy returns of renewable energy technologies

Effects on the share of net energy returned

Figure 5.2 shows the evolution of the share of net energy returns η over time (Equation 5.7), for each renewable energy technology and for each energy intensity scenario, in the case of a medium initial EROI (see Table 5.1). Figure 5.2 shows that the share of net energy returns is only marginally affected by the increases in the energy intensities of mining, even in the case of the highly increasing energy intensities scenario.

Then, Figure 5.3 shows the variation of the share of net energy returns $\Delta\eta$ (Equation 5.8) obtained by 2060, both for our default analysis (barplots), and results obtained when conducting the Monte Carlo simulation (boxplots) — note that the variation of the share of net energy returns in independent of the initial EROI adopted. Even in the very high increase in energy intensities scenario, the decline in the share of net energy returns stays very low (lower than 2 percentage points, except for wind offshore — lower than 3 percentage points). Wind offshore is the technology most affected by increasing energy intensities of mining, due to high chromium and nickel intensities (corrosion prevention) and copper intensities (connection to grid). Results obtained with the Monte Carlo simulation show that the decline in the share of net energy returns are lower than 3 percentage points for all simulations, with the exception of wind offshore, for which the decline is above 3 percentage points

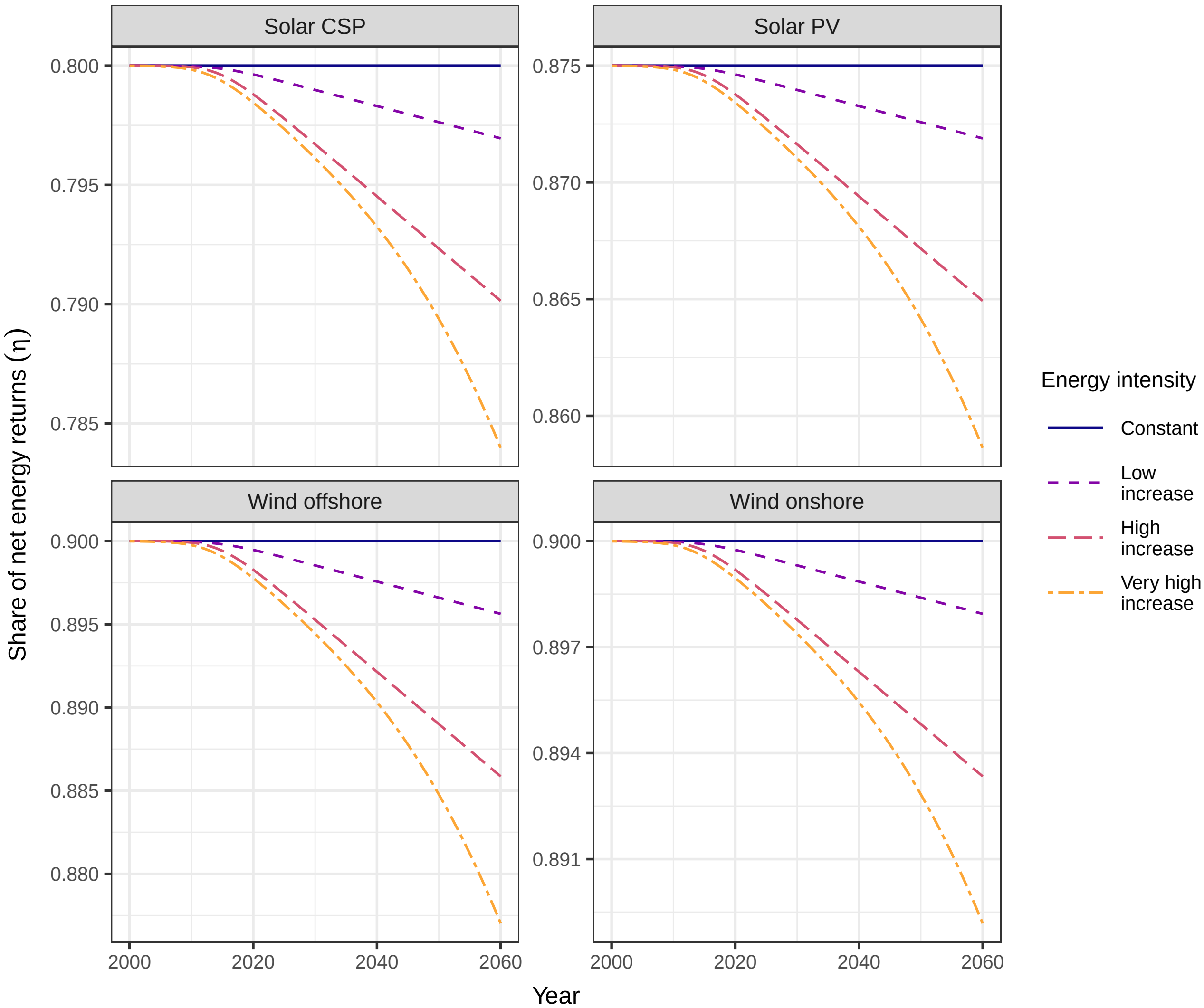

Figure 5.2: Evolution of the share of net energy returns η over time when adopting a medium initial EROI, for different energy intensities of mining scenarios.

in a few simulations (0.75% of simulations using the very high increase in energy intensities scenario). Hence, the Monte Carlo simulation shows that the uncertainty related to the current final energy intensities f_m of each mineral m is moderate, and unlikely to change the conclusions of this research — the influence of mineral depletion effects on net energy returns is found to be marginal in all simulations.

Results obtained when increasing and decreasing material intensities by 50% can be found in SI, Section D.2 and show robustness in the magnitude of $\Delta\eta$. The reason

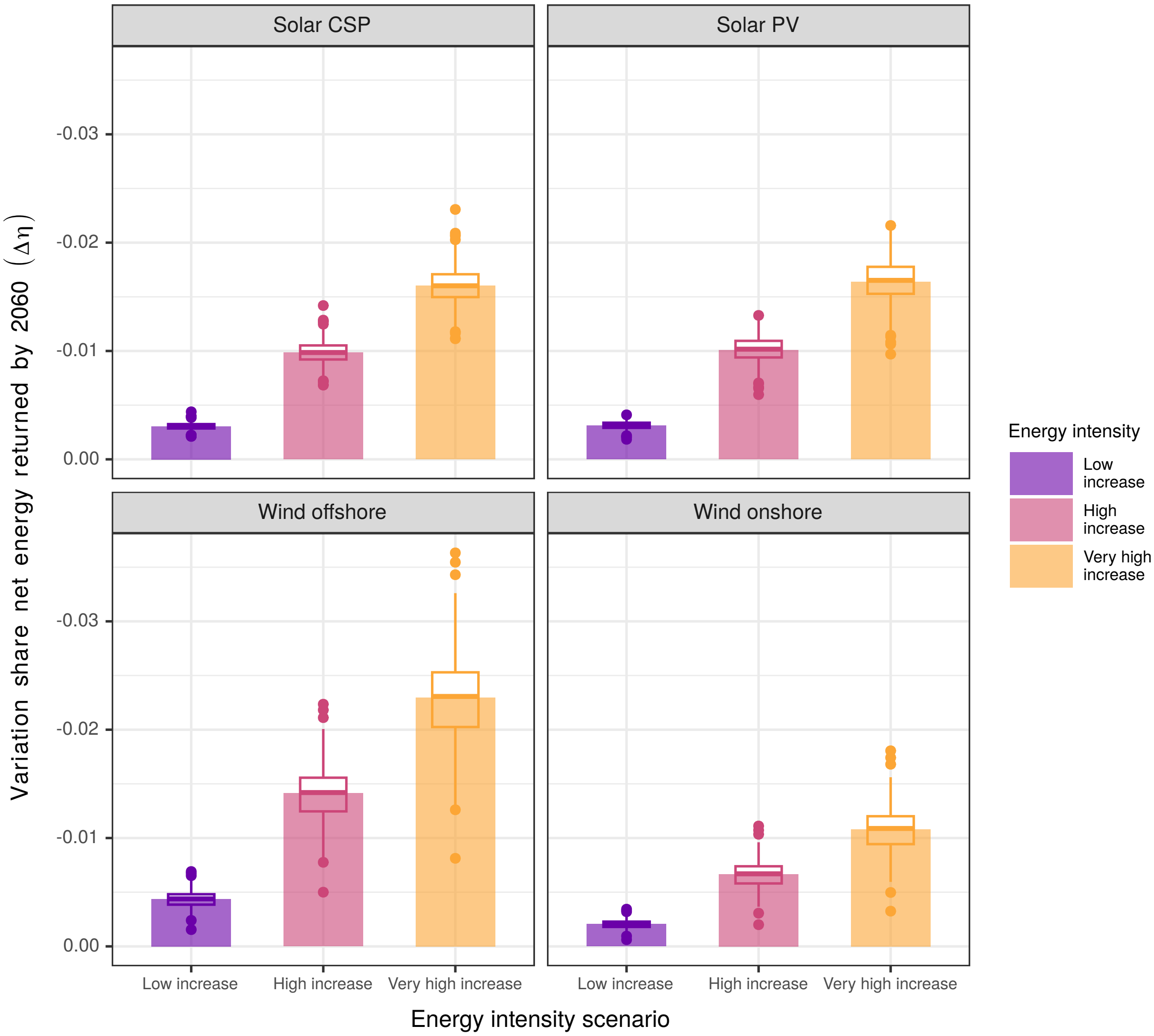

Figure 5.3: Variation in the share of net energy returns $\Delta\eta$ by 2060, for different energy intensities of mining scenarios. Barplots shows the default analysis, and boxplots show the results of the Monte Carlo simulation. Values are independent of the value of the initial EROI.

why the increasing energy intensities of mining have such moderate effects on the net energy returns of renewable energy technologies is that the energy inputs due to mining processes represent only a minor share of total energy inputs — Table 5.2 shows the share of energy inputs due to mining processes, for each renewable energy technology and each initial EROI value. Further, Figure 5.4 shows the contribution

Table 5.2: Initial share of energy inputs due to mining processes over total energy inputs for each renewable energy technology.

Technology	Initial EROI	Ratio $\frac{e_{\text{mining}}}{e_{\text{input}}}$ (%)
Solar PV	Low	2.3
	Medium	4.6
	High	8.6
Solar CSP	Low	1.1
	Medium	2.8
	High	5.6
Wind onshore	Low	1.9
	Medium	3.8
	High	7.6
Wind offshore	Low	4.0
	Medium	8.1
	High	16.2

of the energy inputs due to mining processes for each renewable energy technology by mineral (so that the sum across minerals will add up to unity). The minerals with highest weight in the contribution depend upon the considered technology, with iron (for steel production) being the highest for solar CSP, aluminium the highest for solar PV, chromium, nickel, copper, and iron (for stainless steel) being predominant for wind technologies. Such a breakdown should be considered carefully because of the uncertainty associated with the energy intensities of mining each mineral, and because of the different breakdown that would be observed for each subtechnology (e.g. monocrystalline, polycrystalline, CIGS, CdTe for solar PV). Indeed, the material intensities we use from de Castro and Capellán-Pérez [27] use weighted average of the market shares of each subtechnology in the case of solar PV for instance. Despite this uncertainty, Figure 5.4 shows that iron and aluminium are responsible for a very large fraction of the mining energy consumption for respectively solar CSP and PV. As the mining of these metals is unlikely to be significantly affected by increasing energy intensities, our estimations probably significantly overestimate the effects of mineral depletion on the net energy returns of solar CSP and PV. In the case of wind power technologies, the effects probably are overestimated as well, as iron and aluminium account for approximately 20% of the mining energy consumption, and chromium, which is also a metal mined at relatively high concentrations [29, p.99] — approximately 30% of the mining energy consumption.

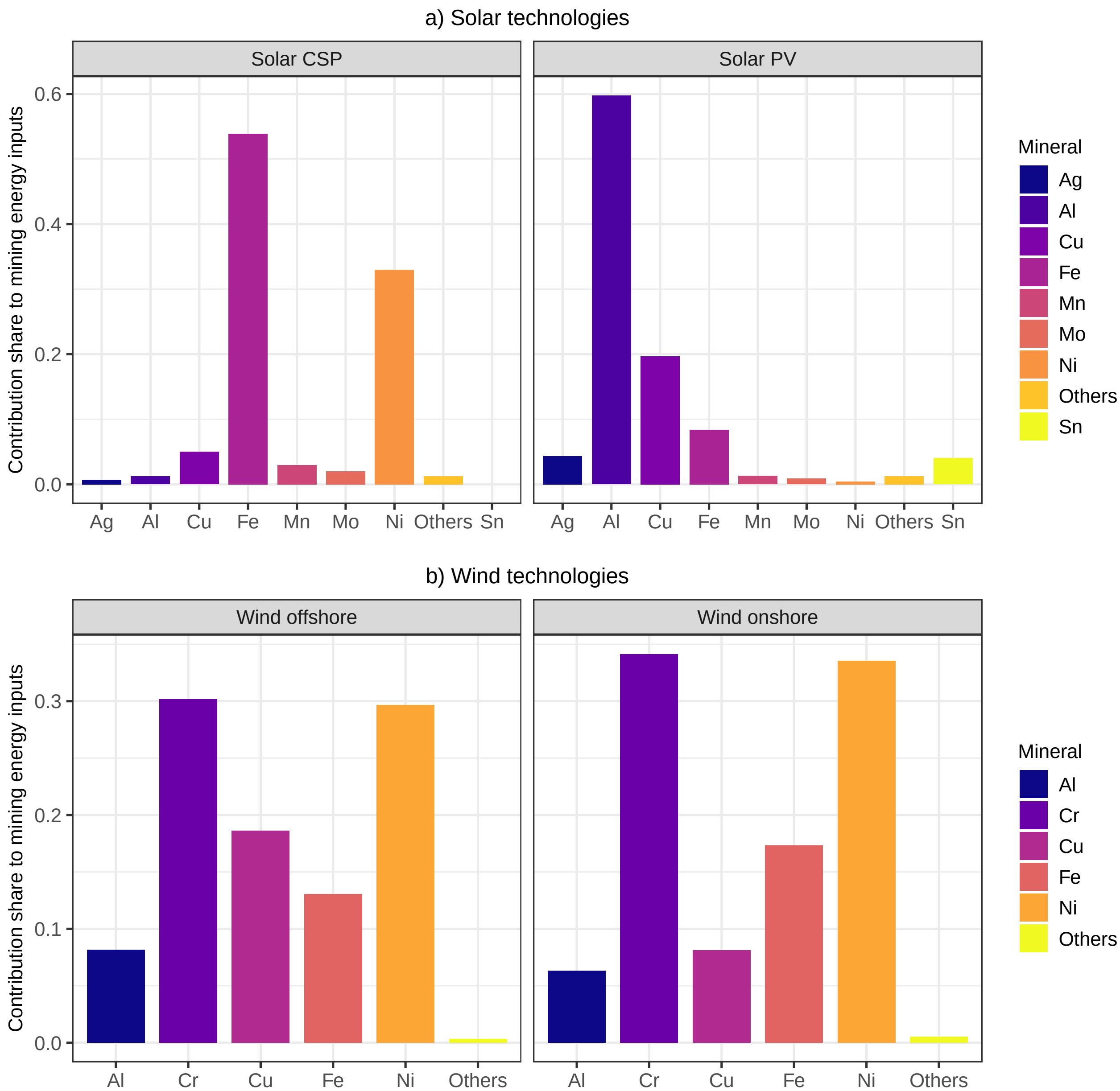

Figure 5.4: Breakdown of mining energy inputs by mineral for each renewable energy technology, in shares of total energy inputs due to mining processes.

Next, Figure 5.5 combines Equations 5.2 and 5.8 to determine the extent to which the increasing energy intensities of mining (represented by α) would have to increase to entail a given decrease in the share of net energy returns $\Delta\eta$ — such values are independent of the initial EROI. Figure 5.5 shows that even to reach a moderate decrease in the share of net energy returns of 5%, the value of alpha would need to reach a value of 7 for wind offshore, almost 10 for solar PV and solar CSP, and 14 for wind onshore[1], representing respectively a sevenfold, tenfold, and fourteenfold increase in the energy intensities of mining. Hence, the values of α that would be required to entail significant changes in the share of net energy returns of renewable energy systems are extremely high, and reaching such high increases in the energy intensities of mining would probably pose other critical challenges to the mining industry (for instance in terms of profitability, technological challenge of extraction, availability of deposits...) and to the economic system (for instance in terms of affordability of increasingly costly raw materials), prior to significantly affecting the net energy returns of renewable energy technologies. For comprehensiveness, the evolution of the shares of net energy returns η as function of the increasing energy intensities of mining (through the α coefficient) can be found in SI, Section D.3.

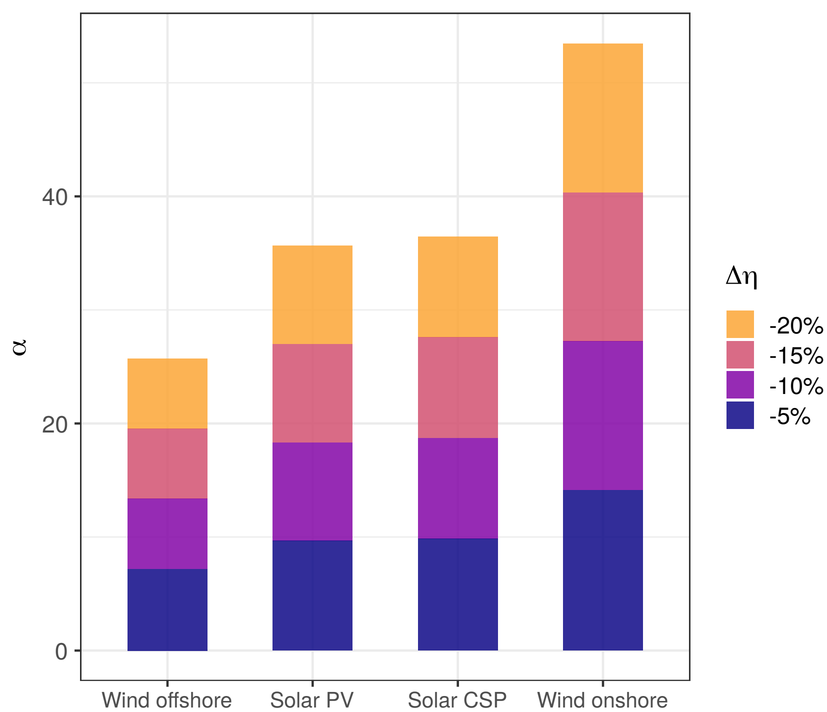

Figure 5.5: Required increases in energy intensities of mining (represented by α) to entail a given decrease in the share of net energy returns $\Delta\eta$. Values are independent of the value of the initial EROI.

[1]Precisely, 7.2 for wind offshore, 9.7 for solar PV, 9.9 for solar CSP, and 14.1 for wind onshore.

Effects on the Energy Return On Investment

Figure 5.6 shows the variation in the EROI of renewable energy technologies that can be expected by 2060 as a result of increasing energy intensities of mining, for each of the low, medium, and high EROI values, and each of the energy intensities of mining scenarios. Conversely to the variation in the share of net energy returns (Figure 5.3), the variation in the EROI of renewable energy technologies may be significant, particularly when using the medium or high initial EROI values and applying them the high or very high increase in mining energy intensities scenarios. In the most extreme case of wind offshore, when applying the very high increase in energy intensities scenario, the EROI may decrease from 5 to 4.5 (low initial EROI), from 10 to 8.1 (medium initial EROI), or from 20 to 13.7 (high initial EROI). Indeed, the lower the EROI, the higher the increasing energy inputs need to be to achieve a significant reduction in the EROI value, which is due to the non-linearity of the EROI metric (see SI, Section D.4), and to the fact that the lower are the energy inputs required, the higher is the contribution of mining processes to total energy inputs — see Table 5.2. It is noteworthy that the significant decreases in EROIs that can be observed when combining a medium or high initial EROIs with a high or very high increasing energy intensities scenarios are due to such a non-linear feature of the EROI metric, and do not translate into significant decreases in the share of net energy returns metric (Figure 5.3). This counter-intuitive result provides a reminder that the EROI metric should be considered carefully, and that assessing alternative metrics such as the share of net energy returns is a pertinent approach. The evolution of the EROIs as function directly of the increasing energy intensities of mining (through the α coefficient) can also be found in SI, Section D.3.

5.3.2 Quantifying the capacity of technological levers to offset the effects of mineral depletion

Figure 5.7 shows the improvements in technological factors (metallurgical energy efficiencies (β), recycled input rates (δr), and material intensities of manufacturing (λ)) that would be needed to offset a given value of increasing energy intensities of mining (represented by α), supposing that they are the only factor at play — the value of each parameter β, δr, or λ should be interpreted as the value required to offset mineral depletion effects assuming that the two other technological fac-

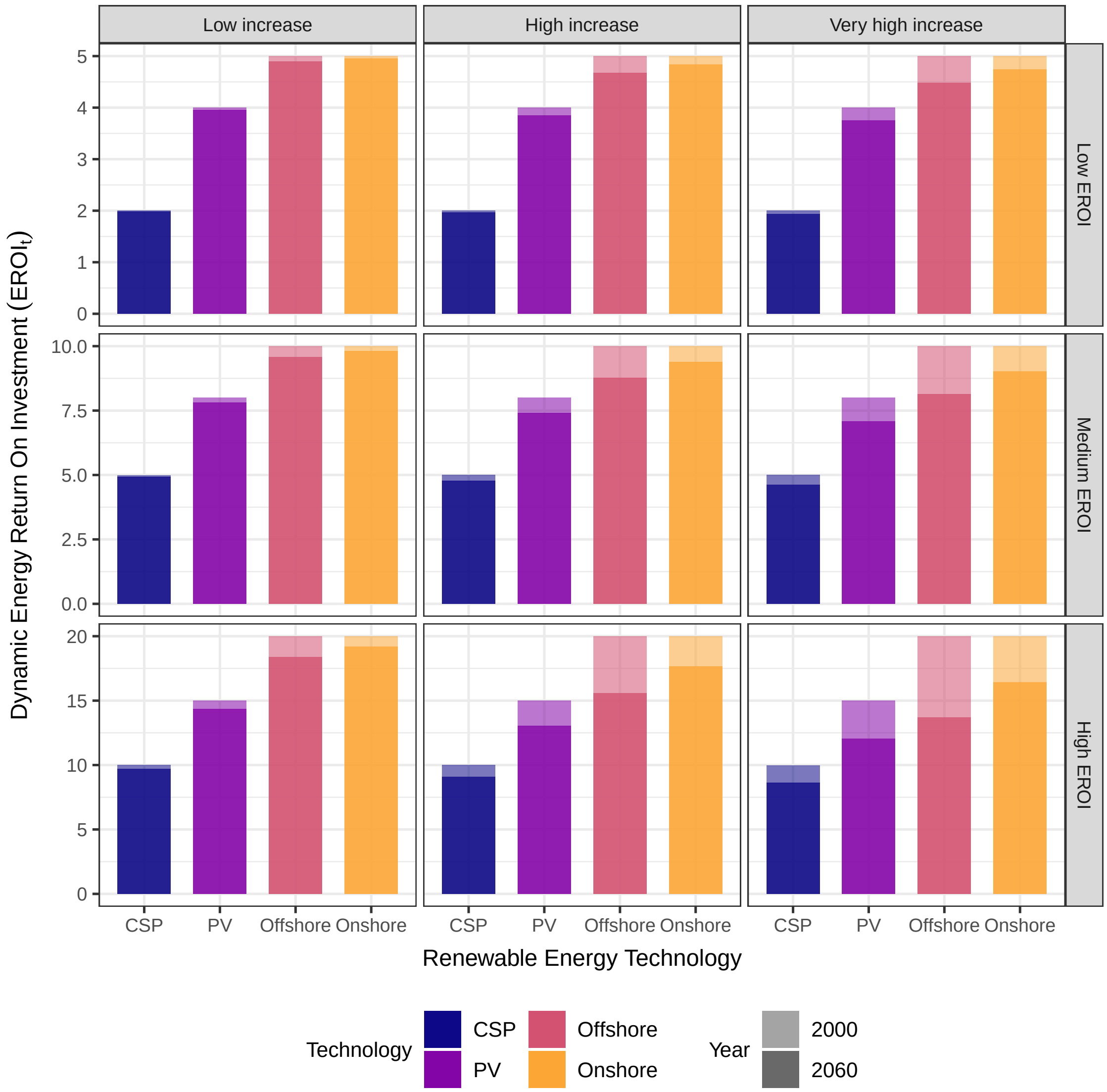

Figure 5.6: Variation in the Energy Return On Investment of renewable energy technologies by 2060 for each of the low, medium and high initial Energy Return On Investment values (rows), and each of the mining energy intensity scenarios (columns).

tors remain constant over time. The figure shows that at a moderate level of α (approximatively, $\alpha \leq 2.5$, or $\alpha \leq 5$ for solar CSP), there is a reasonable value for the technological factors that offsets the increasing energy intensities of mining. For instance, an increase in metallurgical energy efficiencies by approximately 25% would offset an α coefficient of 2.5 for solar PV, wind offshore and wind onshore —

only approximately 10% would be required for solar CSP. For comparison, the energy consumption of steelmaking and aluminium manufacturing in the US could be expected to decrease by respectively 24% and 26% if the best available technologies were systematically implemented (note that the practical minimums that could be obtained with R&D technologies are significantly lower) [37, 39]. An improvement in material intensities of manufacturing by approximately 15% would also be sufficient to offset such value of α for solar PV, wind offshore and onshore, and approximately 8% for solar CSP — which seems reasonable in the light of the expected decrease by 25% and 30% in respectively the silicon and silver intensities of solar PV by the IEA [11, p.56]. The potential of recycled input rates may be more limited, which is further discussed in Section 5.4.2. Such results show that when taken together, these technical levers can significantly offset the increasing energy intensities of mining. However, mineral depletion effects are increasingly hard to offset as the value of α increases, and beyond a given (unknown) level of increasing energy intensities of mining, these technological parameters will not be able to offset mineral depletion effects.

5.4 Discussion

5.4.1 Low effects of mineral depletion on the net energy returns of renewable energy technologies

This work has shown that the effects of mineral depletion on the net energy returns of renewable energy technologies are limited. Indeed, for each of the three mining energy intensities scenarios that we use, the decline in the share of net energy returns of each of the four renewable energy technologies remain lower than 3 percentage points (Figure 5.3). Significantly, such results are obtained without consideration of the technological levers that may contribute to offsetting increasing energy intensities of mining. The low influence of mining on the net energy returns of renewable energy technologies is due to the relatively low contribution of mining to total energy inputs for the manufacture and operation of renewable energy technologies (Table 5.2). It is noteworthy that our study assesses the impacts of mineral depletion on the net energy returns of renewable energy technologies independently of the ongoing debate regarding the actual and current net energy returns of such

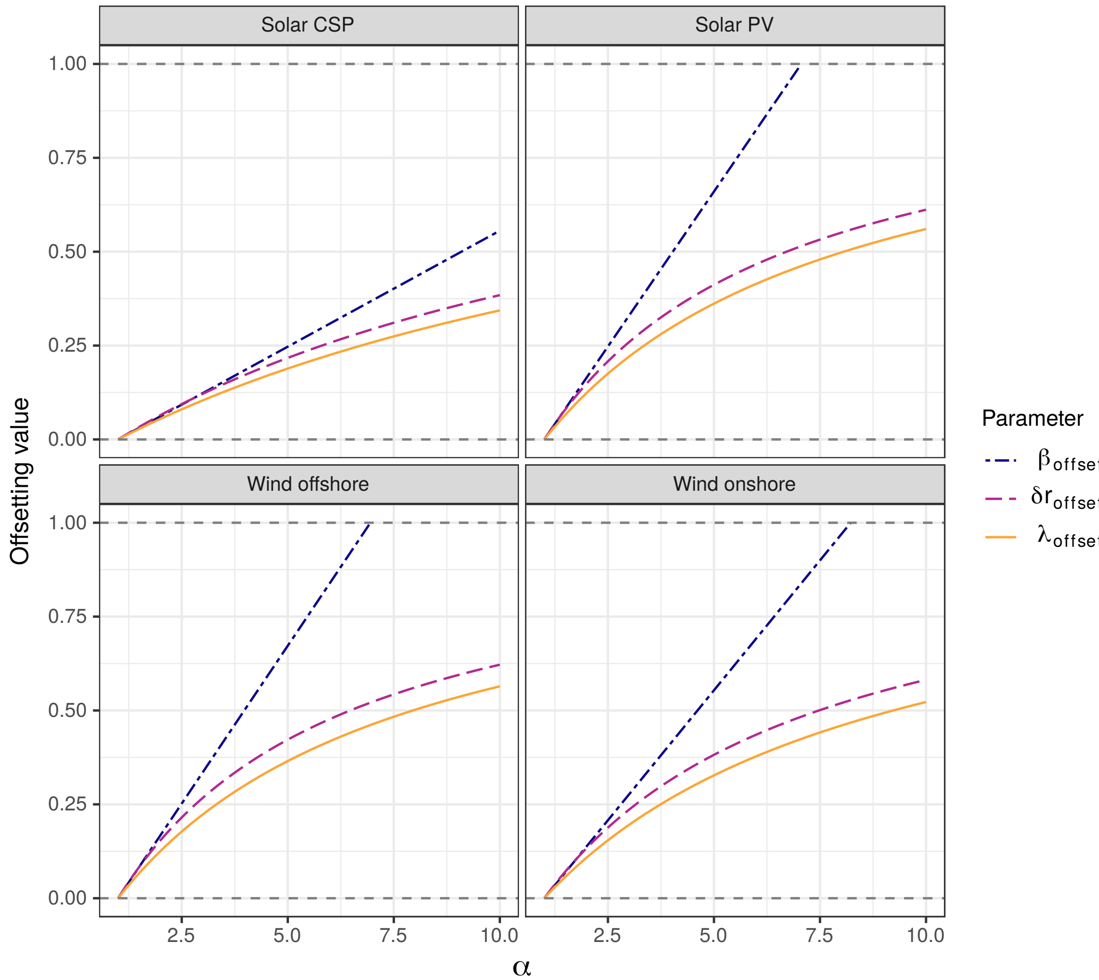

Figure 5.7: Required value for improvements in metallurgical energy efficiencies (β), recycled input rates (δr), and material intensities of manufacturing (λ) to fully offset increasing energy intensities of mining (α), considering that each other factor remains constant. Each of the β, δ_r, and λ parameters evolve in the range $[0, 1]$.

technologies (see for instance [47–50]). Consequently, the results obtained, in terms of variation of net energy returns, are independent from the current net energy returns of renewable energy technologies. While there are significant uncertainties related to this study, we have shown that the results are robust enough to back up the conclusions reached. First, we have shown using a Monte Carlo simulation that the uncertainties related to the energy intensities of mining each mineral are unlikely to substantially modify the results and conclusions (Figure 5.3). Second, we have also shown that even when material intensities of renewable energy technologies are increased by 50%, the change in the share of net energy returns remains of the same order of magnitude as in the core result (Figure D.1), and hence does not affect conclusions. Last, it is worth noting that the assumption of equally increasing energy intensities for all minerals (including abundant minerals, such as iron and aluminium, whose mining is unlikely to be significantly affected by increasing energy intensities in the medium term due to high enough deposit concentrations), is a pessimistic assumption that tends to overestimate the effect of mineral depletion, hence strengthening our conclusions.

Our results are consistent with the work of Harmsen et al. [21], which finds a decline in the EROI of wind turbines from approximatively 25.2 to 24.4 by 2050 (depending on the scenario), which represents a decrease of approximatively 0.1% in the share of net energy returns. However, the work by Harmsen et al. only considers copper; we show here that the conclusion does not differ when including the whole range of minerals upon which the renewable energy technologies considered depend. Comparing with the work of Fizaine and Court [20] is more difficult, as the work assesses the evolution of EROIs as function of ore grades, and EROIs decline and tend to zero as ore grades tend to zero. Our work expands and enhances the work by Fizaine and Court [20] by (i) clearly differentiating the energy requirements of mineral mining from those of mineral refining, which is crucial when focusing on the mining industry and on the effects of geological depletion, and (ii) providing a range of evolutions for the net energy returns of renewable energy technologies considering a range of realistic evolutions for the average future energy intensities of mining.

Results also show that the effects of mineral depletion on the net energy returns of renewable energy technologies only become substantial under extremely high increases in the energy intensities of mining (Figures 5.5 and D.2). Such high energy intensities of mining would however pose a range of serious constraints and challenges to both the mining industry and the broader economy. Indeed, the profitability of the mining industry may deteriorate as energy inputs (and inputs in general) increase dramatically, and the raw material monetary costs of the rest of industrial activities may increase considerably as a result of such high energy inputs required for mining processes. An increasingly difficult extraction of raw materials may also lead to a reallocation of productive capital and labour towards the mining sector, similarly to what has been described in previous works for the energy sector [51, 52]. Considering that all economic processes are based on raw materials inputs [53], and when possible, on cheap raw materials [54], such increases in monetary expenditures, capital and labour requirements of raw materials may have significant adverse effects on the economy, much before significantly affecting the net energy returns of renewable energy technologies.

5.4.2 Capacity of technological factors to offset mineral depletion effects

Results (Section 5.3.2) have shown that improving metallurgical energy efficiencies, recycled input rates, and material intensities of manufacturing are technological levers that, taken together, can contribute to reducing the energy inputs required for the manufacture and operation of renewable energy technologies, hence somewhat compensating for the increasing energy intensities of mining. Results show that under moderate increases in the energy intensities of mining (approximatively, $\alpha \leq 3$, or a yearly increase rate of 2.8% over the period 2020–2060), it seems reasonable to think that these technological factors can offset increasing energy intensities of mining. However, under higher mining energy intensities scenarios, it seems dubious that such effects may offset increasing energy intensities — the critical value of α can however not be determined from this exploratory study, although it is clear that beyond a given threshold, technological factors will not be able to compensate for mineral depletion effects.

In addition, it is important to consider that the improvements of all the considered technological factors are subject to constraints. Indeed, there are thermodynamic, as well as practical minimums, on the energy consumption of a given metallurgical process (see for instance the studies of the U.S. Department of Energy [37–39, 55]), which limit the extent to which energy intensities of mineral refining can effectively decrease. Moreover, efforts to decarbonise the metallurgical sector, for instance using hydrogen as an energy vector [56, 57], or carbon capture and storage techniques [58, 59], may imply an increase in the energy consumption of some specific metallurgical processes. In a similar vein, the future recycled input rates of minerals will also be limited by different factors. First come the available flow of end-of-life materials, that is function of the in-use stocks and lifetimes materials in society, and which is likely to act as a constraint on the recycled input rate that can be reached for each mineral, particularly in high mineral demand scenarios [60, 61]. Second, some of the uses of minerals are extremely hard to recover, when not impossible to recycle [62] — for instance recovering metals from superalloys — and the interdependency between different minerals adds complexity to recycling and metallurgical processes [63]. In such cases, recycling processes may require extremely high energy consumption to separate and purify the end-of-life materials in high quality metals, in some cases leading to energy requirements even higher than the ones for primary extraction [64]. Alternatively, the recycling of such hard to recover materials may be much more akin to downcycling, whereby the minerals obtained after recycling are of degraded quality, and hence may not be suitable for highly technological applications such as renewable energy technologies. Then, while material intensities of renewable energy technologies can be expected to decrease to some extent in the future [11], a minimum amount of materials will obviously be needed to obtain a reasonable performance, implying that there is a lower bound limit on the future material intensities of renewable energy technologies, the value of which remains unknown.

Last, it is worth noting that other technological factors that have not been considered in this study may also come into play and contribute to offsetting mineral depletion effects. Particularly, the capacity factors of renewable energy technologies, which have been significantly increasing in recent years, notably in the case of wind turbines (onshore, as offshore is a relatively new technology) [65], are a crucial technological factor in respect to the energy output of renewable energy technologies. In the case of solar PV, the efficiency of modules has considerably increased in recent years [11, 66], and may be a key technological factor determining the energy output of solar panels.

5.4.3 Other material constraints for the energy transition should not be overlooked

It is worth noting that mineral requirements pose a wider range of challenges to the energy transition, which should not be reduced to the net energy question. Indeed, other important challenges for the energy transition relate to the future mineral availability of critical minerals. The question of whether mineral endowments will be sufficient to meet a surging mineral demand remains under discussion, with different studies showing that future mineral requirements are likely to significantly exceed known reserves for specific minerals (see e.g. [14, 16, 67, 68]), while some authors point to the fact that reserves will keep increasing as technological progress will make new deposits available (see e.g. [69–71]) — current dynamics show that indeed, estimated reserves and resources tend to increase over time as a result of exploration and technological progress [72], but the question of how such a trend will evolve is complex [73]. Additional concerns are related to the risk of supply bottlenecks [74–76], particularly in the context of high geographical concentration for specific mineral deposits and geopolitical tensions [77]. Last, the environmental impacts, for instance in terms of biodiversity loss [78, 79] and pollution [80, 81], as well as social impacts [82, 83] of mining activities should not be diminished, and should be part of the considerations for the mining industry in the context of a sustainable and fair energy transition, particularly as mineral depletion dynamics will increasingly steer extraction towards lower quality deposits, thereby increasing environmental and social impacts [84].

5.4.4 Implications of the non-linear behaviour of the EROI metric

Our findings also emphasise the importance of the metric used when conducting net energy analysis. Indeed, the results we obtain when assessing the variation of EROI as function of increasing energy intensities can give, in some cases, the impression of high impacts of increasing energy intensities of mining on net energy returns. For instance, in the case of wind offshore, when applying the very high increase in energy intensities scenario, the EROI decreases from 10 to 8.1 with a medium initial EROI and from 20 to 13.7 with a high initial EROI. Such significant decreases in EROI values however translate in a decrease lower than 3 percentage points in the shares of net energy returns, which is what ultimately matters to society. Such a result is due to the non-linearity of the EROI metric, which is further discussed in SI, Section D.4. An implication for the field of net energy analysis is the fact that EROI values should be handled with care, and analysts would benefit from translating such values in terms of the corresponding share of net energy returns.

5.5 Conclusion

In this study, we have estimated the effects of mineral depletion on the net energy returns of four renewable energy technologies (solar photovoltaic, concentrated solar power, wind onshore, and wind offshore). Results show that such effects will have a very limited impact on the net energy returns of renewable energy technologies, which is due to the fact that the energy requirements for mining processes only account for a minor fraction of the energy inputs to renewable energy technologies. The future energy intensity scenarios that we use lead to a decrease in the share of net energy returns by 2060 lower than 3 percentage points — significantly lower in most cases. Only under extremely high future energy intensities of mining are the net energy returns of renewable energy technologies substantially affected, and reaching such high energy intensities would pose serious challenges to the mining industry, e.g. in terms of economic profitability, and to the broader economy, e.g. in terms of economic costs of raw minerals.

In addition, we have shown using a Monte Carlo simulation that results are robust to the uncertainties related to the energy intensities of mining for each mineral (the decrease in the share of net energy returns remains lower than 3 percentage points except for very few simulations in the case of wind offshore). The paper has also discussed, with a simple approach, the potential of three different technological factors (metallurgical energy efficiencies, recycled input rates, and material intensities of manufacturing) to offset the effects of mineral depletion. Results show that such technological factors may offset reasonable increases in energy intensities of mining, but that they will not be able to offset increasing energy intensities beyond a given (unknown) level — although the effects of increasing energy intensities may remain low beyond such a threshold.

To conclude, this work has shown that concerns regarding the impacts of mineral depletion on the net energy returns of renewable energy technologies may be unfounded. Although such a negative dynamic indeed exists, its quantification leads to very limited impacts on the net energy returns of renewable energy technologies. Taking these results together with recent works indicating that the net energy returns of renewable energy technologies are of similar order of magnitude to those of traditional fossil fuel energy questions the narrative according to which the energy transition would necessarily imply negative net energy impacts.

Data statement

The dataset associated with this chapter can be found in the online repository associated with this thesis, hosted at the University of Leeds Data Repostory: https://doi.org/10.5518/1322.

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Chapter 6

Discussion and conclusion

Emmanuel Aramendia

In this chapter, I first summarise the main findings of each thesis chapter, as well as its contributions to the literature (Section 6.1). I also discuss the answers to the research questions presented in Introduction, Section 1.4. Second, I discuss the findings in relation to the broader question of the net useful energy implications of the energy transition, considering the broader literature (Section 6.2). Third, I discuss the relevance of the findings in relation to the key question of the transition to a post-growth economy (Section 6.3). Last, I present in the final section the concluding remarks to the thesis (Section 6.4).

6.1 Findings and contributions to the literature

I have argued in this thesis that energy is crucial for human societies. More specifically, I have argued that it is the net energy (the energy available once the energy needs of the energy system itself are subtracted) at the useful stage (the energy contributing to delivering a service after transformation in an end-use device) available to society that is valuable for productive and socially beneficial purposes. In addition, I have argued that the ongoing process of mineral depletion, whereby the energy requirements of mining a unit mass of valuable mineral can be expected to increase substantially, require me to expand the net energy framework to capture the energy requirements of mining processes. As such, the overarching aim of this thesis was **to gain a better understanding of the net useful energy implications of the global energy transition, in the context of mineral depletion**. Specifically, the following research questions have been addressed through the four core chapters:

- Q1: What will be the future energy consumption of the mining industry as a result of the energy transition, in the context of mineral depletion?
- Q2: What are the useful stage energy returns of fossil fuel-based energy carriers, and how do these relate to those of renewable energy technologies?
- Q3: How will the energy returns of renewable energy technologies evolve in the context of mineral depletion?

The following sections detail the contributions of each thesis chapter to these research questions, as well as to the broader literature.

6.1.1 Developing a Multi-Regional Physical Supply Use Table framework to improve the accuracy and reliability of energy analysis

Building on the work of Heun et al. [1], Chapter 2 has developed a Multi-Regional Physical Supply Use Table (MR-PSUT) framework to represent the Energy Conversion Chain across borders, from the primary energy extraction stage to the final use of energy. Amongst **the key contributions to the literature** of the chapter is **first**, the addition of a resource matrix. The addition of such a matrix allows the introduction of a new set of matrices and provides the framework with symmetry, thereby allowing analysts to reverse input-output calculations.[1] **Second**, the chapter has introduced open source `R` tools developed collaboratively (see Intellectual property and publication statements) which allow analysts to build a MR-PSUT framework in a highly automated and adaptable way from the International Energy Agency's World Energy Extended Balances dataset [5], which is the most comprehensive energy database available to date, and to conduct a wide range of physical energy input-output analyses.

I have shown in Chapter 2 how the framework can be applied to (i) the accounting of greenhouse gas emissions, by ascribing an emission coefficient to the fossil fuels

[1]Since the publication of the chapter, the authors have become aware that the resource matrix introduced is similar to the Ghosh model initially formulated by Ghosh in 1958 [2], but sparsely used by the input-output community due to its inability to account for the heterogeneity and interdependency of primary inputs [3, 4], and therefore reinterpreted as a price model [3]. Such a limitation also constitutes a caveat for the use of the resource matrix introduced in Chapter 2, but the fact that the introduced model only represents energy products, hence with some degree of homogeneity, mitigates the caveat.

extracted from the ground, and (ii) energy security analysis, by tracking energy flows across borders, and identifying the origin of the final energy consumed in each region. The application to energy security seems to be of high value considering the current international context. Further work applying the framework to energy security could benefit from refining the Supply Use Tables constructed by using bilateral trade data (see e.g. [6]).[2] Second, the application to energy security could also be enhanced by analysing energy "throughflows" [7], i.e. by analysing the intermediary processes required to deliver the primary energy extracted as final energy. In the case of oil, the supply chain of which is complex, one could for instance analyse the location of refining processes prior to consumption in a given country, in addition to the location of primary extraction.

Further, the recent literature shows the wide range topics for which a MR-PSUT framework can be used. Guevara et al. for instance applies a MR-PSUT framework to the assessment of the effects on energy-related greenhouse gas emissions of the North Atlantic Free Trade Agreement [8]. Rocco et al. describes the application of a MR-PSUT framework to the assessment of the energy and economic impacts of large-scale policy shocks, with the example of Brexit [9]. The coupling of a MR-PSUT with an economic input-output model, as demonstrated by Guevara and Domingos with the multi-factor energy input-output model [10], is a promising way to bridge the gap between energy and economic modelling. Both the methodological novelties introduced in Chapter 2 and the development of a set of open source `R` packages, which provide the research community with robust tools for energy input-output analysis, constitute a valuable contribution to this emerging field of study.

Contributions of the chapter to the thesis

Although this chapter does not directly address any of the reseach questions, it has been a cornerstone of the thesis. First, Chapters 3 and 5 used the framework to determine final demand sector-specific final-to-primary energy ratios for the mining industry. Second, and most importantly, the MR-PSUT framework developed is the backbone of the calculations conducted in Chapter 4 to determine the useful stage Energy Return On Investment (EROI) of fossil fuels, and therefore a crucial enabler of the determination of the final stage EROI equivalent for which renewable energy

[2] Instead of the Global Market Assumption I use in Chapter 2 to demonstrate the framework.

systems would deliver the same net useful energy as fossil fuels.

6.1.2 Global energy consumption of the mineral mining industry: exploring the historical perspective and future pathways to 2060

I have argued that there is a gap in the literature to the extent that the global energy consumption of the mining industry has not yet been comprehensively quantified. Quantifying such energy consumption and its possible future evolution is however crucial as the energy requirements of mining are expected to increase as a result of mineral depletion, and as low-carbon energy systems are much more material intensive than traditional fossil fuel-based energy systems [11, 12].

In response, **the key contribution to the literature** of Chapter 3 is to estimate the historical global energy consumption of the mining industry, as well as future possible pathways. More specifically, the chapter provides, to my knowledge, the first bottom-up assessment of the mining industry's final energy consumption globally (1971–2015), and has used 1.5°C consistent socio-economic scenarios to conduct for the first time an exploratory study of future possible pathways for the mining industry's final energy consumption, taking into consideration both the material requirements of the energy transition, and the increasing energy requirements of mining due to mineral depletion. Typical final energy requirements by unit mass of mineral mined (energy intensities of mining) have been estimated for a wide range of minerals combining the literature with the MR-PSUT framework introduced in Chapter 2, thereby providing the research community with a valuable dataset of typical final (and primary) energy intensities of mining.

Q1: What will be the future energy consumption of the mining industry as a result of the energy transition, in the context of mineral depletion?

The chapter finds that the mining industry is currently responsible for approximately 1.7% of global final energy consumption (value for 2015). However, the mining industry's final energy consumption is likely to increase significantly, by a factor in the range 2–8 by 2060, until reaching values representing 4 to 12% of forecasted global final energy consumption for the socio-economic scenarios used for projections. Such an evolution will be highly dependent on (i) the future economic trajectory, (ii) the evolution of the energy intensities of mining, and (iii) future recycling rates. In addition, the chapter finds that the chief determinant of the mining industry's final energy consumption will be future economic activity; only under post-growth pathways does the energy consumption of mining stabilise at a level close to its current value. In regards to the energy transition, the chapter finds that the final energy consumption related to mineral demand for energy transition technologies will remain minor (probably below 15% of the total final energy consumption of mining activities) compared to the final energy consumption entailed by mineral demand for the rest of economic activities.

Additional contribution: the insufficient coverage of material flows and associated energy requirements

I also find in Chapter 3 that mineral material flows and their associated energy requirements are insufficiently represented in energy-economy models. Most models only cover few materials (cement and steel are generally the ones best covered), do not explicitly model in-use stocks and recycling rates, and do not appropriately capture the feedback caused by material flows on energy consumption. Significant improvements are however under way in the IMAGE (see e.g. [13, 14]) and MEDEAS [15] Integrated Assessment Models. This insufficient representation may limit the ability of energy-economy models to determine future material demand and primary material extraction, as well as to determine the energy consumption and greenhouse gas emissions associated with materials cycles. Considering that materials are responsible for a large fraction of global energy consumption and greenhouse gas emissions, their limited representation may be a critical blind spot in energy-economy models and may hamper efforts to build consistent mitigation pathways. To overcome this challenge, I suggest that models should pay particular attention to (i) representing material demand as function of economic activity or bottom-up human activities, (ii) explicitly modelling in-use material stocks and end-of-life flows, as well as recycling rates, and (iii) explicitly representing the energy requirements associated with material flows.

6.1.3 Estimation of fossil fuels useful stage Energy Return On Investment and implications for renewable energy systems

I have argued that conducting the analysis to the useful stage of energy use is crucial to understand the net energy implications of the energy transition, due to the differences in the final-to-useful efficiencies between energy carriers. **The key contribution to the literature** of Chapter 4 is to attempt a useful stage-based comparison between the net energy returns of fossil fuels and those of renewable energy systems. I had to follow an indirect approach to conduct such a comparison. First, Chapter 4 has used the MR-PSUT framework introduced in Chapter 2, in combination with the International Energy Agency's World Energy Extended Balances [16], the Exiobase Multi-Regional Input Output model [17, 18], and a recently developed global primary-final-useful database [19] to determine the useful stage EROIs of fossil fuels, both at the global and national levels. Useful stage EROIs are determined both at the economy-wide level as well as for different end-uses, accounting for the fact that final-to-useful efficiencies differ significantly across end-uses. Second, Chapter 2 has determined for the first time the final stage EROI of renewable energy systems for which such systems would deliver the same amount of net useful energy as fossil fuels (i.e., the final stage EROI equivalent). Such calculations are conducted both globally and at the national level, and for different end-uses.

Q2: What are the useful stage energy returns of fossil fuel-based energy carriers, and how do these relate to those of renewable energy technologies?

The chapter finds that the average useful stage EROI of fossil fuels in 2019 is of approximately 3.3, which is significantly lower than the average final stage EROI — approximately 8.3. In addition, the chapter finds that conversely to final stage EROIs, which have slightly declined from an average value of 9.6 in 1971, useful stage EROIs have slightly increased from an average value of 2.9 in 1971, due to increasing final-to-useful efficiencies (with the exception of fossil gas EROIs, which show a decreasing trend over time). Values and trends however hide significant differences between fossil fuels, with useful stage EROIs ranging from 2.0 for oil products to 9.1 for fossil gas in 2019. Useful stage EROIs also vary widely across end-uses, from values as low as 1.5 for road propulsion to values as high as 12.0 for low temperature heating.

Second, Chapter 4 finds that the final stage EROI for which renewable energy systems would deliver the same amount of net useful energy as fossil fuels is as low as 4.5, although such a value is highly dependent on the fossil fuel and end-use considered. The comparison of the EROI equivalent determined with recent EROI estimates for solar photovoltaic and wind power in the literature suggests that their actual final stage EROIs are well above the EROI equivalent value. Hence, the useful stage energy returns of renewable energy systems seem to be on average higher than those of fossil fuel-based energy carriers.

6.1.4 Exploring the effects of mineral depletion on renewable energy technologies net energy returns

I have argued that considering the high material intensities of renewable energy systems and the increasing energy requirements of mining, it is important to understand the extent to which the effects of mineral depletion can affect the net energy returns of renewable energy systems. **The key contribution to the literature** of Chapter 5 is to explore such effects, building on the methodology developed by Fizaine and Court [20]. Indeed, the chapter uses the final energy intensities of mining developed in Chapter 3 to explore the effects of mineral depletion, modelled through increasing energy intensities of mining, on the net energy returns of four renewable energy technologies: solar photovoltaic, concentrated solar power, onshore wind, and offshore wind. The chapter substantially contributes to the existing literature [20, 21] by simultaneously (i) differentiating the mining and metallurgical stages of the metal production process, (ii) covering a wide range of minerals and metals, and (iii) considering plausible scenarios, based on empirical data, for the evolution of energy intensities of mining, which were developed in Chapter 3.

Q3: How will the energy returns of renewable energy technologies evolve in the context of mineral depletion?

Chapter 5 finds that the effects of mineral depletion on the energy returns of renewable energy technologies are likely to remain marginal, because the energy requirements of mining raw materials only account for a minor portion of the energy inputs required to manufacture and operate renewable energy technologies. Indeed, the share of net energy returned (i.e. the share of the energy output that is available after reinvestment in the energy system itself) declines by less than 3 percentage points for all the renewable energy technologies and energy intensities scenarios that the chapter explores. The chapter validates the robustness of the findings through appropriate sensitivity testing on the final energy intensities of mining each mineral, as well as on the material intensities of renewable energy technologies. Moreover, the chapter's assumption of equally increasing energy intensities for all minerals is pessimistic, as the mining of relatively abundant minerals, such as iron and aluminium, is unlikely to be significantly affected by increasing energy intensities in the medium term, thereby strengthening further the findings.

6.2 The net useful energy implications of the energy transition

6.2.1 Synthesis of key findings and limitations

Key findings

Four key findings can be identified from this thesis. **First**, Chapter 4 has shown that when expanding the analysis to the useful stage, **the net energy returns of renewable energy systems are likely to be higher than those of fossil fuel-based energy carriers**. Such a finding significantly expands previous work at the final energy stage [22–24], and contradicts the widespread view according to which fossil fuels have higher net energy returns than renewable energy systems. Further, the findings suggest that the energy transition may entail net useful energy gains, or alternatively, may allow for significant final energy savings while delivering the same amount of net useful energy (savings quantified above 50% of final energy consumption in Appendix C). The results are however highly dependent on the fossil fuel and end-use considered. Indeed, the (useful stage) net energy returns range from values as low as 2.0 and 1.5 for oil products and road transportation, respectively, to values as high as 9.1 and 12.0 for fossil gas and low temperature heating, respectively (values for 2019). The net useful energy gains, or potential final energy savings, are hence highly dependent on the fossil fuel being substituted and end-use of substitution.

Second, Chapter 5 shows that **the effects of mineral depletion should only marginally affect the net energy returns of renewable energy systems** despite the high material requirements of such systems, because mining processes only account for a minor fraction of the energy requirements of manufacturing and operating renewable energy systems. Indeed, the effects of mineral depletion are expected to decrease the share of net energy returns of renewable energy systems by less than three percentage points. The chapter builds on previous work [20, 21] and provides a novel and comprehensive analysis that considers the energy requirements of mining a wide set of minerals alongside a set of realistic scenarios regarding their future evolution. Such findings indicate that the results I obtain in Chapter 4 are robust to the effects of mineral depletion, and can be expected to hold over time, particularly considering that technological improvements (only partially covered in Chapter 5), such as increased capacity factors of wind turbines due to higher and bigger turbines, or higher module efficiencies of solar PV, will tend to increase the net energy returns of renewable energy systems [25].

Third, when taken together, the previous points suggest that **most energy-economy models adopting a net energy perspective may find overly pessimistic implications of the energy transition**, due to the misleading assumption that renewable energy systems present much lower net energy returns than fossil fuels [26–30]. Indeed, many models inconsistently mix the primary stage net energy returns of fossil fuels with those of renewable energy systems at the final stage, thereby using unrealistically high values for fossil fuels. Further, the results show that even for those models that consistently conduct the analysis at the final stage for both fossil fuels and renewable energy systems (see e.g. [15, 31]), the critical effect of the difference in final-to-useful efficiencies between energy carriers, which would favour renewable energy systems, may be overlooked. Capturing such an effect requires to conduct the analysis at the useful stage, and would provide a more optimistic picture of the net energy implications of the energy transition.

Fourth, Chapter 3 shows that **the future energy requirements of mining will increase significantly** (an increase in the range 2–8 is forecasted compared to 2015), and will be mostly driven by future economic output, and only to a lesser extent, by the energy transition. Such increasing energy requirements will exert a drain on the net useful energy available to society. However, **the final**

energy savings allowed by the energy transition should be sufficient to compensate — alternatively, additional gross energy consumption may be utilised, although it would make more difficult the achievement of climate change targets.

Taken together, the findings of this thesis indicate that **there is no reason to believe that the energy transition will adversely impact the net useful energy available to society**, even taking into consideration the adverse effects of mineral depletion.

Limitations and avenues for further work

There are however significant limitations to this work, which could be overcome with further research. First, this thesis obviates the dynamic effects of the energy transition on the net useful energy supply. Indeed, a successful transition to reach climate targets would imply very large investments in the energy system over a very short time, which would have considerable impacts on the net useful energy supply in the short term — particularly as renewable energy systems require large *upfront* investments. Previous work has shown that this dynamic may entail a temporary decrease of the net energy available at the final energy stage [32, 33], which may also be expected at the useful stage, although the potential net useful energy gains pointed in Chapter 4 may mitigate this effect. Hence this thesis findings seem to be valid over the *long term*, and do not elucidate what the *short term* implications of the energy transition may be.

Second, the energy requirements of a renewable energy system are only partially covered, as such a system would also need additional investments, for instance to expand the grid to electrify end-uses and to connect decentralised generation, as well as to deal with intermittency, which would require significant amounts of storage capacity, as well as some degree of generation overcapacity. Following previous authors [34, 35], I have argued that such energy requirements are function of the energy system as a whole (Chapter 4), and cannot be ascribed to a given technology in particular. However, such investments, which are outside the scope of this thesis, will also have implications in terms of net useful energy.

Third, this thesis has assumed a specific set of "default" machines for the electrification of end-uses, i.e. a specific electrification scenario (see Data statement). The thesis has however not looked in detail into the technical question of the electrification of end-uses. Not all end-uses may be electrified, and hence the renewable energy technologies (solar and wind power) under study in Chapters 4 and 5 may not be suitable for the delivery of all end-uses. For instance, the decarbonisation of steelmaking may involve the use of low-carbon hydrogen [36], for some processes the use of gas or liquid fuels may be necessary, so that decarbonisation may require the use of biogas or biofuels. The net energy returns of these alternative decarbonised energy carriers, which are likely to be lower than those of solar and wind power,[3] need to be analysed for a comprehensive analysis of the net energy implications of the energy transition.

Last, the energy requirements of the energy system itself are only a portion of the energy investments required for a low-carbon transition. Much more energy investments are needed, for instance, to insulate buildings, manufacture heat pumps and electric vehicles, or expand the rail system and cycling infrastructure. Where the boundary should be set in net energy analysis is a thorny question, identified since the very early days of the field [38]. Should such energy requirements be subtracted from the net energy available to society? If so, why should the energy investments associated with manufacturing an electric vehicle or a heat pump, or expanding the rail system, be accounted as a net energy sink, while those associated with the manufacture of a SUV, or with expanding an airport, are not? A comprehensive net energy accounting would have to include all the energy requirements associated with the low-carbon energy transition, as well as those avoided, associated with the alternative high-carbon pathway. Considering the wide range of activities that would need to be either downscaled or altogether phased out in a low-carbon transition, such a transition need not have any adverse impacts on the net useful energy available. The issue seems to lie more in the allocation of net useful energy to different end-uses, and on its fair distribution, than in the absolute amount of net useful energy available.[4]

[3]Regarding green hydrogen, it should be manufactured from solar and wind power, hence leading to lower net energy returns (due to losses in each conversion process). Regarding biomass in general, the literature suggests low net energy returns [22, 37].

[4]Further, from a political economy standpoint, one could say that the function of any economic activity in a capitalist system is to generate a monetary surplus, which is then distributed to capitalists (through profits) and workers (through wages). If the energy investments needed for the low-carbon transition allow to generate a monetary surplus, and to distribute it to workers through wages in the same way than traditional economic activities, then there does not need to be any adverse economic implications of allocating more energy to the low-carbon transition.

6.2.2 The final stage net energy potential of renewable energy technologies

Besides the question of the net energy returns of renewable energy systems, the question of their energy potential has been an important topic under investigation, and for some authors, a reason for concern [39]. The recent work of Dupont et al. adopts the perspective of declining marginal returns to determine the global potential of wind power [40] and solar energy [41]. With such a perspective, the sites of higher quality are used first, and sites of decreasing qualities need to be used as renewable energy technologies are scaled up. The authors develop curves linking the EROI of the marginal renewable energy power capacity installed as function of the cumulative deployment of technologies, expressed in terms of final energy production, akin to the curve presented in Figure 6.1.

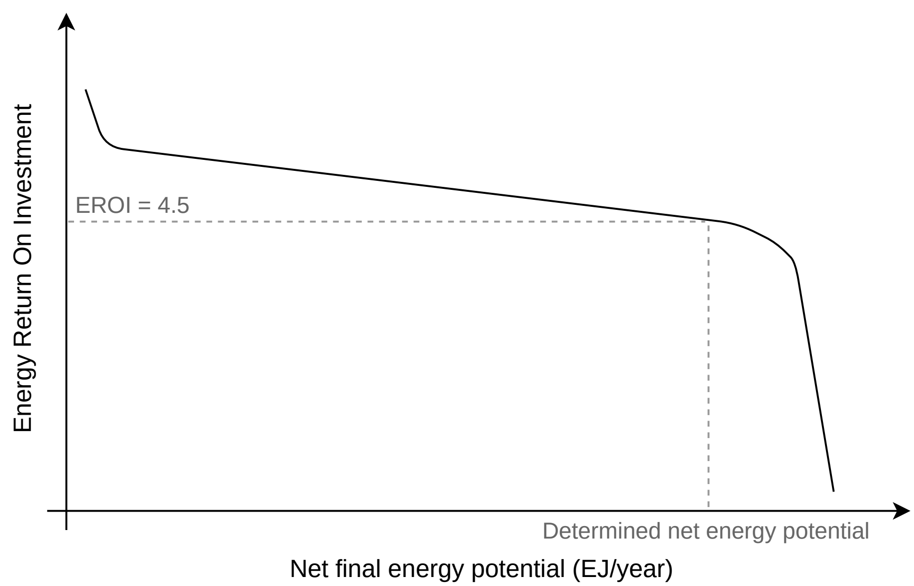

Figure 6.1: Example of curve linking the marginal final stage Energy Return On Investment (EROI) to the cumulative deployment of a renewable energy technology, and graphical identification of the yearly net final energy potential as function of the minimum condition on the final stage EROI. Shape inspired from [40, 41].

The final stage EROI equivalent values that are determined in Chapter 4 can be used to determine, based on the curves constructed by Dupont et al. [40, 41], the cumulative deployment of renewable energy technologies for which their marginal

EROI equals the calculated equivalent value (4.5), value at which renewable energy technologies deliver the same amount of net useful energy than fossil fuels. Using these curves, and following the reasoning shown in Figure 6.1,[5] I estimate the yearly net final energy potential that can be obtained at net energy returns (measured at the useful stage) higher or equal than those of fossil fuels for wind power and solar energy to be 750 EJ and 1100 EJ, respectively.

As a comparison, the global final energy demand forecasted for the Beyond 2 Degrees Scenario (B2DS) from the International Energy Agency is 376 EJ in 2050, and the forecasted global electricity demand is 131 EJ. Figure 6.2 shows the range of final energy demand forecasts for 1.5 and 2°C scenarios in the 2018 Intergovernmental Panel on Climate Change Special Report on 1.5°C [42]. The yearly potential estimated from the estimated EROI equivalent and the cumulative deployment curves developed by Dupont et al. is therefore significantly higher than the expected future final energy demand, at least in scenarios limiting future global warming to 1.5 and 2°C.

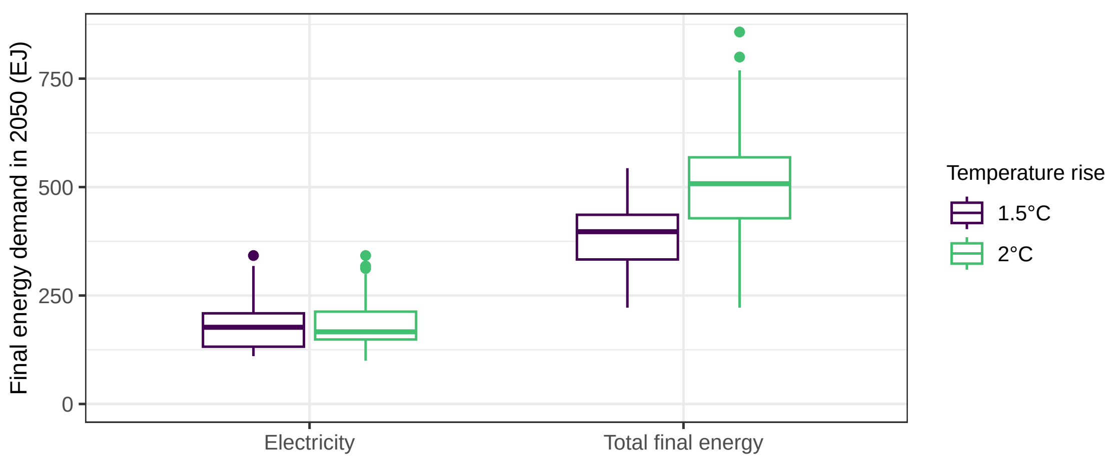

Figure 6.2: Total final energy demand and electricity demand in 2050 in scenarios consistent with 1.5 and 2°C of average global warming. Scenarios from the Intergovernmental Panel on Climate Change Special Report on 1.5°C [42]. Data taken from [43].

[5]We use Figure 8.c in [40] and Figure 7 in [41] to determine the yearly potential of respectively wind power and solar energy. The EROI equivalent used had to be adapted to account for energy inputs in terms of primary energy (using 0.68 as average final-to-primary energy factor) and to exclude transmission and distribution losses (using 7.6% as grid losses as discussed in Appendix C.1.4). So, the equivalent EROI values determined are divided by 0.924 and multiplied by 0.68.

Such a finding is relatively robust to the EROI equivalent value determined for renewable energy systems in Chapter 4: an EROI equivalent value of 10 would for instance point to a yearly net final energy potential of 650 and 900 EJ for respectively wind power and solar energy — still significantly more than sufficient to cover demand in the B2DS scenario. The potentials I find should however be considered with caution, as different methodologies may lead to very different estimations [44, 45]. Additionally, the question of land requirements is highly relevant in a context of global competition for land, particularly in the case of solar energy [46, 47]. Indeed, the question may not be so much what the absolute potential for renewable energy is, but what society will need to give up to devote additional land to renewable energy systems (as well as the distribution of costs and benefits). However, as one third of global cropland is devoted to livestock-based diets [48], and as dietary changes can considerably reduce cropland use [49], it seems clear that there is scope to free substantial amounts of land for energy purposes, provided appropriate dietary changes are undertaken. Further, agrivoltaics may have the potential to minimise the land requirements of solar energy and to increase the yield of both crops and solar modules [50, 51].

Last, it is worth noting that the evidence for such a pattern of decreasing marginal EROIs as function of cumulative deployment of renewable energy systems is limited. Indeed, technological change, for instance increasing solar cell efficiencies, or the use of higher, and bigger turbines, may compensate for the use of sites of lowering qualities — the International Renewable Energy Association reports for instance how the capacity factors of wind turbines have significantly increased over time [25]. Additionally, whether the sites of higher quality will be used first is questionable, as economic affordability seems to be a determining factor of the location of deployment of renewable energy systems, with highest rates of deployment occuring in wealthy countries, and not necessarily where energy returns are the highest (e.g. solar panels in Northern European countries). However, the thought experiment I have just done shows that even assuming declining marginal EROIs, the EROI equivalent values determined in Chapter 4 are low enough to allow for the deployment of more than enough (based on 1.5 and 2°C scenarios) renewable energy while providing higher net useful energy returns than the current fossil fuel-based energy system.

6.2.3 Synthesizing the net energy implications of the energy transition

To summarise, this thesis finds that when expanding the analysis to the useful stage of energy use, the energy transition does not imply a reduction in the net useful energy available to society, at least in the long term. Indeed, this thesis has shown that the useful stage net energy returns of renewable energy systems are likely to be higher than those of fossil fuel-based carriers (Chapter 4), thereby suggesting that in the long term, the energy transition may entail net useful energy gains (i.e. increasing net useful energy delivered to society), or alternatively, final energy savings (quantified in Appendix C.3). Further, I find that although mineral depletion may significantly increase the energy requirements of mining activities (Chapter 3), the net energy returns of renewable energy technologies will only be marginally affected (Chapter 5).

The increasing energy requirements of mining activities found in Chapter 3, can however be compensated by the net useful energy gains entailed by the uptake of renewable energy systems, or alternatively, by expanding further the scale of renewable energy systems. Indeed, the results obtained in Chapter 4 allow me, based on previous work [40, 41], to estimate the yearly net final energy potential that can be harvested at net energy returns (measured at the useful stage) higher or equal than those of fossil fuels. I estimate such potential for wind power and solar energy at 750 EJ and 1100 EJ, respectively — although the values should be handled with caution. Such values are colossal, and significantly higher than the final energy demand forecasts of 1.5 and 2°C consistent climate pathways, hence suggesting that besides presenting high enough useful stage net energy returns, the potential for wind and solar power generation is more than sufficient to provide decent living standards for all.

However, considering that most renewable energy systems energy requirements are upfront (related to capital investments), and that decarbonisation must happen at an extremely fast pace, a temporary decline in the net useful energy available to society may be expected in the short term, as recently shown at the final energy stage [32, 33]. Furthermore, additional energy requirements will be needed for investments in decarbonisation, for instance to insulate houses, to produce electric vehicles, or to expand and modernise the rail system, hence suggesting that the allocation of energy may need, in the short term, to be increasingly directed towards long-term investments instead of discretionary use — the alternative being an increase in the scale of fossil fuel use to allow for both to happen simultaneously, which would put at high risk the 2°C climate target.

To conclude, this thesis suggests that over the long term, and conversely to the widespread view that the net energy implications of the energy transition may be problematic to society, a renewable energy system may provide decent living standards for all. The implications may even be positive, as net useful energy gains may be expected as a result of the transition, thereby allowing to either expand further the scale of society's productive activities, or alternatively, to reduce final energy consumption. Such findings provide critical insights regarding the transition to a post-growth and well-being economy, which I discuss in the following section.

6.3 Insights regarding the transition to a post-growth and well-being economy

Considering the urgency to reduce greenhouse gas emissions and the magnitude of reductions to achieve, the transition to a post-growth economy is increasingly advocated as a way to quickly curtail greenhouse gas emissions. A post-growth economy would put human well-being at the core by focusing on a wide range of indicators, so that decent living standards are provided to all, while limiting the scale of production and consumption.

6.3.1 The feasible path to decent living standards for all

The widespread belief that renewable energy systems have net energy returns substantially lower than fossil fuels has nourished the view that such systems would not sustain a modern, energy-intensive lifestyle and civilisation [52, 53],[6] and in the most pessimistic cases, that systemic collapse of the civilisation is unavoidable [58]. This thesis shows that when expanding the analysis to the useful stage, renewable energy systems have higher net energy returns than fossil fuels, because of the very

[6] See [54–57] for examples of this view in the wider ecological economics literature.

low average final-to-useful efficiencies of fossil fuel-based energy carriers.[7] Furthermore, the estimation of the renewable energy potential that I derive from the useful stage analysis in Section 6.2.2 suggests that very large amounts of energy can be harvested through renewable energy systems at high enough net energy returns.

Hence, and conversely to the view that the transition towards renewable energy will imply a significant drop in living standards, this thesis suggests that transitioning to a renewable energy system is fully compatible with the delivery of a sufficient level of net useful energy to provide decent living standards for all [60–63]. Such a finding is crucial for the transition to a post-growth economy, where the aim of endless growth would be replaced by the aim to improve quality of life, captured through a wide set of socio-economic indicators [64, 65]. Particularly, analysing the final energy requirements of decent living standards through the lens of energy services [66, 67], and not only of energy efficiency, would strengthen this compatibility, as high living standards may be achieved at much lower levels of energy use than current ones.

Further, the question of inequality in the consumption of energy is an elephant in the room: the very large inequality between, but also within countries in terms of energy consumption [68] and carbon footprint [69, 70] suggests that a reduction in the energy consumption of the most affluent[8] would make available substantial amounts of energy to the most disadvantaged people. Recent research even suggests that reducing inequality may reduce aggregate energy consumption [72]. Hence, the transition to a renewable energy system alongside a well-being economy seems definitely feasible, although there is an urgent need to develop mitigation pathways that provide a sufficient level of energy services for all, as well as to further investigate the conditions under which high living standards can be satisfied at low levels of energy use [73–75].

The findings therefore support the technical possibility of a transition to a well-being economy alongside the transition to a low-carbon energy system. However, considering the magnitude of emissions reduction to be achieved in a short timespan, and the complex set of interwoven crisis that the world is facing, with global environ-

[7]As discussed in the thesis, previous work already demonstrated than conducting the analysis at the final energy stage shows that the final stage net energy returns of renewable energy systems and fossil fuels are of similar magnitude [24, 59].

[8]Such energy consumption is particularly outsized in the case of the ultra-rich [71].

mental pressures are already exceeding 5 of the 9 planetary boundaries' safe levels[9] [76, 77], there is increasing support for a transition towards a post-growth economy in developed countries. While the findings of this thesis support the possibility to undertake such a transition, they also raise critical caveats for the post-growth community.

6.3.2 Caveats for the post-growth community

The introduction of this thesis has emphasised the high reliance of human activities on energy consumption. Particularly, economic output seems tightly coupled to the level of energy consumption, as shown in Figure 1.1. The limited evidence of absolute decoupling between energy consumption and economic growth at the global level, or at the national level when considered on a consumption-based perspective [78–80], strengthen the view that economic activity fundamentally relies on energy consumption, and that increasing economic output is likely to require increasing energy consumption. More specifically, I have argued throughout this thesis that it is the *net useful* energy available to society that is fundamental to productive and socially beneficial processes and activities.

Recent literature has indeed emphasised the critical role of energy at the useful stage (see Section 1.2.3), often quantified through the lens of exergy analysis, in the production process and as a key driver of economic growth [81–83]. Further, the increase in aggregate final-to-useful energy efficiencies has been identified as a crucial factor explaining economic growth [84], following a mechanism somewhat similar to the rebound effect, whereby increasing efficiencies translate in lower costs, and eventually result in higher production and consumption [85–87]. Such findings fill the hole left by traditional neoclassical theory, which views unexplained technological progress as the key driver of economic growth [88], in line with the early formulation of the Solow-Swan growth model [89–91]. This thesis has shown that not only renewable energy systems may have the potential to deliver large amounts of final energy with reasonably high net energy returns, but that additionally, the energy transition may come with significant increases in the average final-to-useful energy efficiencies, as low efficiency fossil fuels-based carriers are progressively substituted with high efficiency electricity (Chapter 4). Hence, a quick energy transition to-

[9] Safe levels are currently quantified for only 8 out of the 9 planetary boundaries.

wards a renewable energy system may entail further economic growth, potentially putting additional strain on ecosystems and hindering ambitious climate change mitigation.[10]

This outlook raises critical strategic questions for the post-growth community, which has traditionally thought that the transition to renewable energy systems may hinder economic growth due to the low net energy returns of such systems (see e.g. [55, 57]). This thesis suggests that besides the short-term Keynesian stimulus that the needed investments in a low-carbon energy system may have [92], the energy transition may also lay down the foundations for further economic growth in the medium and long term. In other words, the energy transition may foster the "green growth" agenda, whereby efforts to mitigate climate change and the uptake of low-carbon technologies become a driver of economic growth [93] — in the vein of some formulations of the Green New Deal [54], such as the European Green Deal.[11] If the post-growth community is to concur with the need for a quick and dramatic investment in low-carbon technologies, and hence with some sort of Green New Deal, as I argue it should, then the critical question of how to reconcile such an investment with a post-growth transition — i.e. of how to secure a "Green New Deal without growth" [54] — must be faced.

Considering that there is no evidence that the energy transition should naturally impose limits on the scale of production and consumption, I believe that an implication for the post-growth community is the need to strive for the inclusion of the key concept of *limits* in public policy. The definition of societal boundaries, i.e. of collectively defined self-limitation through a democratic process seems to be an essential element of a post-growth transition. [95]. A recent example of such a democratic process is the Citizens Climate Convention in France [96, 97], which argued for strong climate change mitigation measures, although these were turned down by the government. The concept of consumption corridors, whereby minimum consumption standards are secured for all while preventing than overconsumption "threatens the opportunity for a good life for others" [98], can be highly valuable for the democratic definition of collective limits. Policies to operationalise societal, col-

[10] The recent drop in the costs of renewable electricity generation, which is now becoming cheaper than traditional fossil fuel-based electricity, also points in that direction, as low generation costs mean that the economic conditions for a large renewable energy supply are also met [25].

[11] The president of the European Commission Ursula von der Leyen states that "The European Green Deal is our new growth strategy. It will help us cut emissions while creating jobs" [94].

lectively defined limits, could be diverse: outright bans and command-and-control policies, setting a cap on national greenhouse gas emissions, or even the more radical rationing option, as a way to ensure both an effective and fair reduction of emissions through the equitable downscaling of consumption [99]. Further, the need for setting collectively defined limits raises the question of the relationship to capitalism, which is inherently a growth-oriented system [100, 101], whereby the aims of profit maximisation and endless accumulation are prioritised.

6.3.3 Reflections on the economic system and the energy transition

The ecological economics community argues that in developed countries, the levels of production and consumption are sufficient to provide everyone with good lives, i.e. that there is “already enough” [101], although there are clear distributional issues. While some have raised concerns regarding the net energy implications of the energy transition, I find in this thesis that over the long-term, an energy system based on renewable energy shall supply sufficient net useful energy to provide everyone with decent living standards, particularly as there is increasing evidence that these can be provided at much lower than current levels of energy use [62, 75].[12] Short-term dynamics, which are outside the scope of this thesis, are however complex, and may imply a temporary decrease in the net useful energy available to society due to the quick and large scale investments required should ambitious climate mitigation action be undertaken.

Two critical questions remain wide open, and urgently need to be addressed. First is the question of how to achieve a quick and large enough investment in the low-carbon energy transition to reach climate targets. Second is the question of how to ensure that the net useful energy available is allocated to the appropriate end-uses, and that the produced goods and services are distributed in an equitable manner that provides decent living standards for all. While the answers are complex, it seems to me highly questionable that a capitalist system, understood as a system whereby the means of production and the investment decisions are private, and whereby the pursuit of maximum profit and endless accumulation drives economic agents, may be able to tackle these issues in a satisfactory way.

[12] See [102–104] for additional examples.

First, a critical issue is the fact that under capitalism investment decisions are private, and are conducted with the aim of maximising profits. The Intergovernmental Panel on Climate Change notes the serious misallocation of capital and investment, with climate change mitigation and adaptation drastically underfunded, while fossil fuel extraction projects remain abundantly funded [105] — the situation may even worsen as the profitability of fossil fuel extraction is soaring in the wake of the war in Ukraine. Achieving 1.5 or 2°C pathways requires a drastic reallocation of capital, either by strongly directing private investments, or by some sort of socialisation of investment.

Second, situations of dire destitution and low access to energy services remain pervasive despite the fact that there is “already enough” [101]. Indeed, under capitalism, resources are allocated towards the most profitable end-uses, meaning in practice that the *wants* of the wealthy are prioritised over the *needs* of the destitute. Such economic inequalities translate in dramatic inequalities in the use of energy and in the emission of greenhouse gases [68, 70]. Reallocating energy use (and more broadly, resource use) towards fulfilling human needs and providing decent living standards for all seems crucial for ambitious and fair climate action, so that the scale of production and energy consumption can be curtailed. Whether capitalism is compatible with such a change in priorities is highly doubtful.

6.4 Conclusion

I have shown in this thesis that extending the analysis to the useful stage of energy use is crucial to understand the net energy implications of the energy transition. The useful stage energy analysis I have conducted shows that the net energy returns of renewable energy systems are likely to be higher than those of fossil fuel-based energy carriers. Further, I find that such a finding is robust to the effects of mineral depletion on the net energy returns of renewable energy systems, which are likely to remain minor. These insights contradict the widespread view that renewable energy systems have lower net energy returns than fossil fuel-based energy carriers, and that the energy transition will entail a decrease in the net energy available to society. Further, I have quantified the final energy potential of renewable energy systems that can be harvested at net energy returns higher or equal than those of fossil fuels. I find such potential to be very large, about one order of magnitude higher than the final energy consumption forecasted in 2050 by most low-carbon (1.5 and 2°C consistent) energy transition scenarios. Three key implications can be derived from these results.

First, most current energy-economy models may find overly pessimistic implications of the energy transition, due to the misleading assumption that renewable energy systems present much lower net energy returns than fossil fuels. Conducting the analysis to the useful stage appears crucial to appropriately capture the net energy implications of the energy transition. Further, I find that there is still significant scope to improve the biophysical consistency of most energy-economy models, which do not explicitly describe the material requirements and associated energy requirements of energy systems, and more generally, of economic activities. Such omission may be a critical blind spot and may hamper efforts to build consistent mitigation pathways.

Second, the results also suggest that the energy transition may lay down the foundations for long-term economic growth, and may therefore foster the green growth agenda. Indeed, the energy transition may (i) increase the average efficiency with which final energy is converted into useful energy, which has been shown to be a major driver of economic growth, and (ii) deliver very large amounts of final energy, thereby allowing society to expand further the scale of productive activities. Further, recent data suggest that renewable energy systems may provide energy at a lower cost than traditional fossil fuel-based energy systems. The findings therefore raise crucial questions for the post-growth community, which has traditionally believed that the energy transition will support the transition to a post-growth economy.

Third, the findings of this thesis imply that renewable energy systems have the potential to deliver more than sufficient net useful energy to provide everyone with decent living standards, and to allow society to transition to a well-being, post-growth economy, provided that net energy is allocated to the appropriate end-uses, and fairly distributed. From an ecological economics standpoint, providing everyone with sufficient net useful energy to meet decent living standards would however require a deep change of economic system, so that the the *wants* of the wealthy are not prioritised over the *needs* of the destitute.

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Appendix A

Supporting Information to Chapter 2: Developing a Multi-Regional Physical Supply Use Table framework to improve the accuracy and reliability of energy analysis

Emmanuel Aramendia, Matthew K. Heun, Paul E. Brockway, Peter G. Taylor

A.1 Nomenclature

The paper adopts the following conventions: boldface capital letters (e.g., **U**) represent matrices, while boldface lowercase letters (e.g., **g**) identify column vectors. Where possible, symbols for matrices and vectors follow the Eurostat naming convention [1]. Table A.1 lists the nomenclature for this paper.

Table A.1: Nomenclature

Symbol	Description
Letters	
E	Refers to primary energy. Subscripts denote the demanding region, supplying region, and energy source type.
F	Refers to final energy. Subscripts denote the demanding region, supplying region, and final end-use sector.
c	Refers to the share of exports. Subscripts denote the region and product it refers to.
k	Refers to the line k of a matrix.
i	Refers to a given industry.
l	Refers to the column l of a matrix.
n	Refers to the number of regions considered.
p	Refers to a given product.
s	Refers to a given supplying region.
r	Refers to a given resource stock.
t	Refers to a given energy source type.
u	Refers to a given end-use sector.
x	Refers to exports. Subscripts denote the region and product if refers to.
Greek letters	
λ	Downscaling or upscaling factor for modifying the supply mix. See Table 2.2.
τ	Refers to a given demanding region.
Acronyms/abbreviations	
EIO	Energy Input Output
EU27, or EU	European Union
GDP	Gross Domestic Product
IEA	International Energy Agency
MIOT	Monetary Input Output Table
MR-PSUT	Multi-Regional Physical Supply Use Table
PIOT	Physical Input Output Table
PSUT	Physical Supply Use Table
TPES	Total Primary Energy Supply
US	United States
Subscripts	
p	Refers to a given product.
s	Refers to a given supplying region.
t	Refers to a given energy source type.
τ	Refers to a given demanding region.
u	Refers to a given end-use sector.
feed	Refers to feedstock share of a matrix.
eiou	Refers to the EIOU share of a matrix.
Superscripts	
-1	Denotes square matrix inverse
T	Denotes transpose of a vector or matrix
$'$	Denotes a new version of a vector or matrix induced by a new final demand $\mathbf{Y}'$.
$''$	Denotes a new version of a vector or matrix induced by a new resources matrix $\mathbf{R}'''$.
Superannotations	
$\widehat{\mathbf{v}}$	Denotes a square diagonal matrix formed by placing the elements of $\mathbf{v}$ on the diagonal of $\mathbf{I}$
$\mathbf{Z}^*$	Denotes the symmetric $\mathbf{Z}$ matrix used to reverse the Input Output structure. See Table 2.6.

Symbol	Description
Column vectors	
$\mathbf{e}_{\mathrm{c}}$	Vector of CO_2 emissions by resource-product, due to its combustion (p × 1).
$\mathbf{e}_{\mathrm{f}}$	Vector of CO_2 emissions by resource-product, due to methane flaring and leakages (p × 1).
$\mathbf{f}$	Total input by industry (i × 1).
$\mathbf{f}_{\mathrm{c}}$	Induced CO_2 emissions by final demand sector due to the combustion of fuels (s × 1).
$\mathbf{f}_{\mathrm{f}}$	Induced CO_2 emissions by final demand sector due to methane flaring and leakages (s × 1).
$\mathbf{f}_{\mathrm{CO_2}}$	Total induced CO_2 emissions by final demand sector. (s × 1).
$\mathbf{g}$	Total industry output vector (i × 1).
$\mathbf{h}$	Total output by resource-products vector (p × 1).
$\mathbf{i}$	Identity column vector (flexible numbers of rows, one column).
$\mathbf{k}_p$	Vector selecting resource-products. (p × 1)
$\mathbf{k}_s$	Vector selecting resource-stocks located in region s (r × 1).
$\mathbf{k}_t$	Vector selecting resource-stocks of type t (r × 1).
$\mathbf{m}_{\mathbf{e}}$	Vector of primary energy multipliers (p × 1).
$\mathbf{m}_{\mathrm{CO_2}}$	Vector of total CO_2 emissions multipliers (p × 1).
$\mathbf{m}_{\mathrm{c}}$	Vector of CO_2 emissions multipliers due to combustion (p × 1).
$\mathbf{m}_{\mathrm{d}}$	Vector of CO_2 emissions multipliers due to downstream energy use (p × 1).
$\mathbf{m}_{\mathrm{eiou}}$	Vector of CO_2 emissions multipliers due to energy industry energy use (p × 1).
$\mathbf{q}$	Total output by product vector (p × 1).
$\mathbf{q}_{\mathrm{c}}$	Total output by product vector, calculated with a consumption perspective (p × 1).
$\mathbf{q}_{\mathrm{s}}$	Total output by product vector, calculated with a supply perspective (p × 1).
$\mathbf{r}$	Total output by resource-stocks vector (r × 1).
$\mathbf{y}$	Final demand vector (p × 1).
Matrices	
$\mathbf{A}$	Direct requirements matrix (p × p).
$\mathbf{C}$	Product shares matrix (p × i).
$\mathbf{D}$	Market shares matrix (i × p).
$\mathbf{B}$	Balancing matrix (flexible column size, product row size).
$\mathbf{I}$	Identity matrix.
$\underset{\mathrm{p\times p}}{\mathbf{L}}$	Total requirements matrix (p × p).
$\underset{\mathrm{i\times p}}{\mathbf{L}}$	Total requirements matrix (i × p).
$\mathbf{M}_e$	Matrix of embodied resource-products by demanded product (p × p).
$\mathbf{O}$	Resource shares matrix (r × p).
$\mathbf{R}$	Resources extraction matrix (r × p).
$\mathbf{R}_r$	Corresponding resources matrix for demanding country r (r × p).
$\mathbf{R}_s$	Resources extraction matrix for supplying country s (p × s).
$\mathbf{U}$	Use matrix. (p × i).
$\mathbf{U}_{\mathrm{eiou}}$	Part of **U** that is used for energy purposes (p × i).
$\mathbf{U}_{\mathrm{feed}}$	Part of **U** that is used as feedstock, i.e. for transformation purposes (p × i).
$\mathbf{V}$	Make matrix. (i × p).
$\mathbf{W}$	Value added matrix (p × i).
$\mathbf{Y}$	Final demand matrix (p × s).
$\mathbf{Y}_r$	Final demand matrix for demanding country r ($p \times s$).
$\mathbf{Y}_s$	Induced final demand matrix by supplying country s (p × s).
$\mathbf{Z}$	Direct requirements matrix (p × i).
$\mathbf{Z}_{\mathrm{eiou}}$	Direct requirements matrix for energy industry own use (p × i).

A.2 Additional example: downstream effects analysis

To showcase how the framework also enables analysts to assess downstream consequences (i.e. induced final demand) of a given quantity of extracted resources, we track down the final uses of the primary extraction of oil products in different regions. Thus, for each supplying region s, we define a new matrix $\mathbf{R}_s$ in which only oil products extracted in region s are kept. We calculate the corresponding $\mathbf{Y}_s$ matrix of induced final demand, no matter the region of final demand, following Table 2.7. Then, we adapt Equations 2.4 and 2.5, so that the induced final energy consumption in region τ, and noted $F_{\tau,s}$, is calculated as:

$$F_{\tau,s} = \mathbf{i}\widehat{\mathbf{k}}_\tau \mathbf{Y}_s \mathbf{i}, \tag{A.1}$$

where $\mathbf{k}_\tau$ selects final demand sectors corresponding to region τ. Then, the induced final energy by final demand sector u, independently of the region τ of end-use, is calculated as:

$$F_{\tau,u} = \mathbf{i}\widehat{\mathbf{k}}_u \mathbf{Y}_s \mathbf{i}. \tag{A.2}$$

where $\mathbf{k}_u$ selects final demand sectors u, no matter the end-use region τ.

Figure A.1 shows the destination regions of extracted oil products. For countries that are net importers of most oil products, for instance the EU, Brazil, or China, almost all domestically extracted oil products are consumed domestically. Conversely, for regions such as Mexico and the Russian Federation, most of the domestic extraction is exported. The US has evolved from being a net importer of oil products (exporting only some particular oil products in small quantities) to being a net exporter of oil products, which exports roughly 15% of its oil products extraction, due to the recent tight oil boom.

A.3 Description of Eurostat Input-Output models

Table A.2 presents the different Eurostat models [1], and discusses their validity in relation to the energy PSUT developed in this paper.

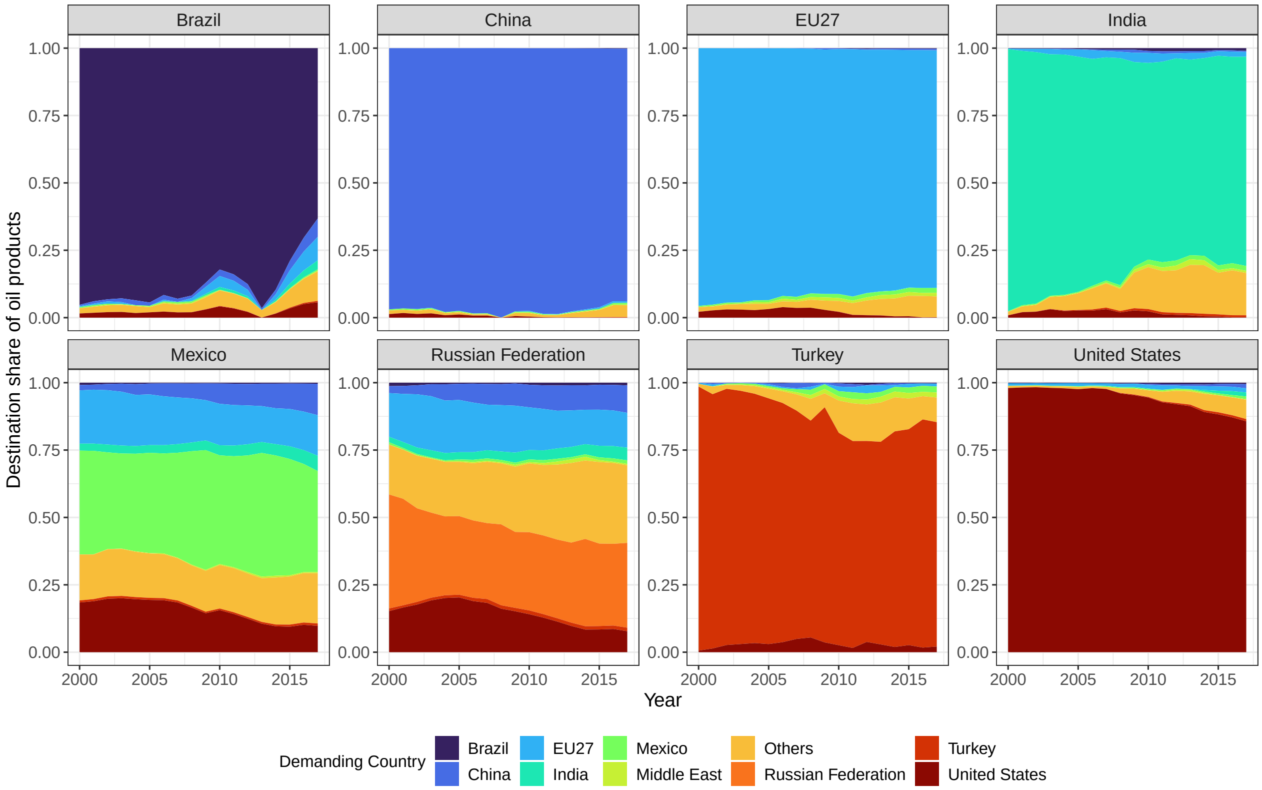

Figure A.1: Destination region shares of domestically produced oil products.

Of these models, all industry-by-industry models can first be dismissed, as the unit of interest is here the energy product. Indeed, the final energy demand by sector (e.g. Transport, Residential, Iron and steel...) is formulated in terms of energy products, and not in terms of industry output. Of the remaining models, the one that describes best the energy industry is the Industry Technology Assumption, which considers that "all products produced by an industry are produced by the same input structure", and which is most appropriate when dealing with numerous cases of joint and by-products [1].

Table A.2: List of different Eurostat models. Reasoning, arguments, and quotes from Eurostat [1, Chapter 11].

Eurostat Model	IO-structure	Assumption	Validity for PSUT
Model A	Product-by-product	Product Technology Assumption: "each product is produced in its own specific way, irrespective of the industry where it is produced," equivalent to "a product has the same input structure in whichever industry it is produced."	This assumption is adapted for cases of subsidiary production, i.e. where products produced by a same industry can be independently produced, and one of them can be defined as a primary product. In addition, a primary producer industry needs to be defined for each product. Considering the numerous cases of joint production in the energy industry (e.g. oil refineries, blast furnaces, etc.), the assumption is not appropriate.
Model B	Product-by-product	Industry Technology Assumption: "each industry has its own specific way of production, irrespective of its product mix," equivalent to "all products produced by an industry are produced by the same input structure."	The assumption is particularly relevant for cases of joint and by-production, where different outputs products from a given industry are produced indistinctly from a given structure of inputs. The assumption is appropriate for describing the energy industry.
Model C	Industry-by-industry	Industry Sales Structure Assumption: "each industry has its own specific sales structure, irrespective of its product mix."	The assumption does not seem appropriate, as joint products are used for different purposes; for instance, oil and gas extraction produces natural gas, crude oil, natural gas liquids, each of which will have a different use. In addition, the assumption leads to an industry-by-industry structure, which is not consistent with a final demand in terms of energy carriers.
Model D	Industry-by-industry	Industry Product Sales Structure Assumption: "each product has its own specific sales structure, irrespective of the industry where it is produced."	The assumption may be consistent with the energy industry structure, but it leads to an industry-by-industry structure, which is not consistent with a final demand in terms of energy carriers.

Table A.3: Continuation of Table A.2. List of different Eurostat models. Reasoning, arguments, and quotes from Eurostat [1, Chapter 11].

Eurostat Model	IO-structure	Assumption	Validity for PSUT
Model E	Product-by-product	Hybrid Technology Assumption: "combines the product technology assumption and the industry technology assumption to avoid negatives in product-by-product input-output tables."	As the Product Technology Assumption is not appropriate, neither is the Hybrid Technology Assumption.
Model F	Product-by-product	Almon procedure: "mathematical algorithm designed for compiling product-by-product input-output tables which are based in essence on the product technology assumption but avoids by step-by-step procedure negatives in the derives input-output tables."	As the Product Technology Assumption is not appropriate, neither is the Almon procedure.

A.4 Specification of U and Y with the Global Market Assumption

To specify the **U** and **Y** matrices following the global market assumption and the imports proportionality assumption, we follow the four following steps:

1. We determine, for each product p and each region τ, the share of imported products compared to domestically consumed products (i.e. consumed in either **U** or **Y**, excluding exports). With that share, we ascribe a portion of used product p to domestically produced products following the imports proportionality assumption. The remaining portion of used products are ascribed to imported products.

2. We determine the global market suppliers for a product p; i.e. we determine the contribution of each region $s \neq \tau$ to the global exports of product p, noted $c_{s,p}$, and defined as:

$$c_{s,p} = \frac{x_{s,p}}{x_p}, \tag{A.3}$$

   where $x_{s,p}$ and x_p stand respectively for exports of product p by region s, and for global exports of product p. (Hence $\sum_s x_{s,p} = x_p$.) Then, we use the determined global market shares $c_{s,p}$ to ascribe, for each product p in each region τ, the imported products to their region of production.

3. The columns corresponding to exports are removed from the regional final demand **Y** matrices.

4. The regional **U** and **Y** matrices with specified product, industry, and sector names are combined in respectively a multi-regional **U** and **Y**, filling coefficients that do not belong to any regional matrix with zeros.

A.5 Comparison of Total Primary Energy Supply (own calculations) with Total Energy Supply (IEA data)

Figure A.2 shows the TES for each region according to the IEA World Energy Extended Balances, i.e. without treatment. A few remarks can be drawn from the figure. First, a share of the TES is composed by non primary energy products, such as electricity, heat, gasoline, coke oven coke, which means that the energy accounted for is not fully primary energy. The share of non-primary energy is significant in the case of for instance Brazil, Mexico, and Russia. Second, the fact that some of the products are non-primary products does not always enable identification of the type of energy source. For some traded products, such as coke oven coke, the energy source, namely coal, is obvious. But in the case of imported electricity or heat, such identification is not possible. Third, in the case of regions that are net exporters of energy products, there is a negative component for exported energy products that should be subtracted from the total TES. Each of these issues are solved when adopting the TPES calculation shown in Section 2.3.2. We note, however, than once subtracting exported energy products, the TES of each region is of similar magnitude than the TPES reported in Figure 2.4.

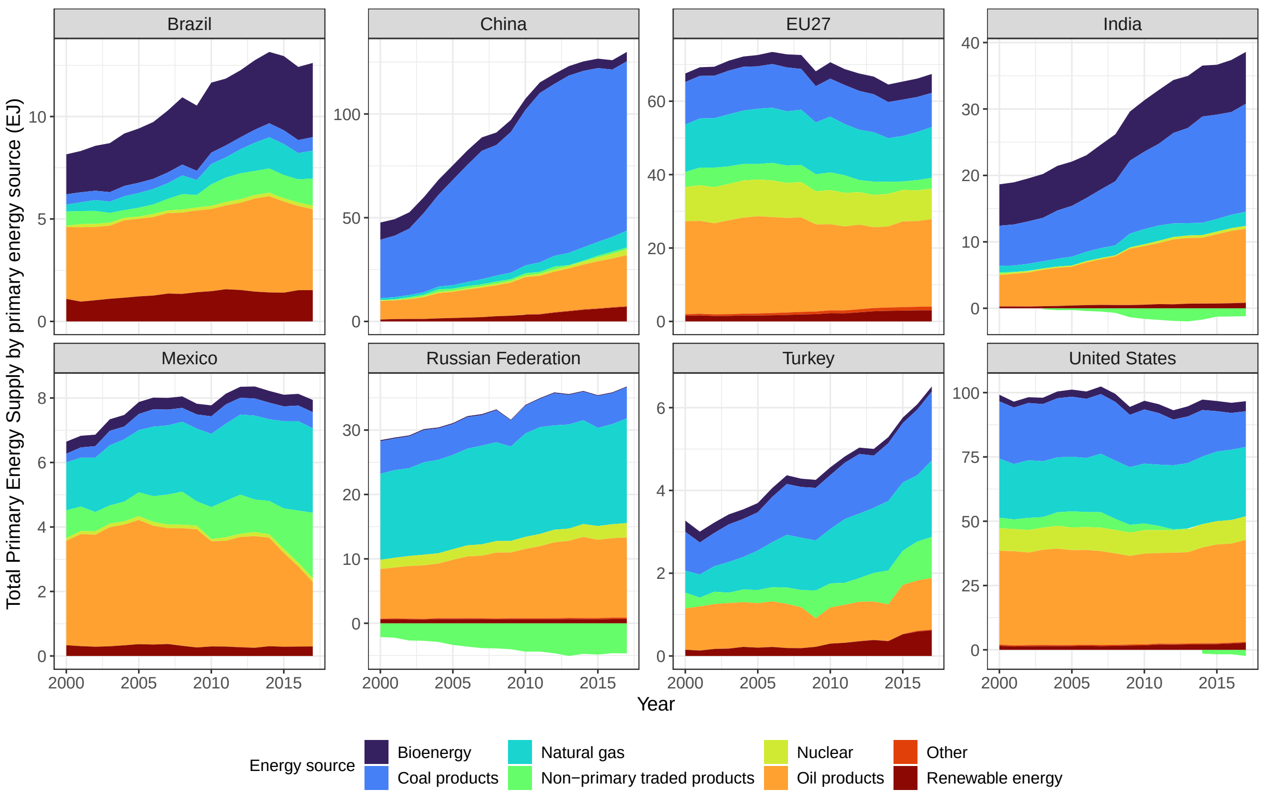

Figure A.2: Total Energy Supply according to the International Energy Agency World Energy Extended Balances [2] for different regions, broken down by primary energy source, when possible.

A.6 Vector of energy-related CO_2 emissions

Table A.4 presents the combustion and extraction emissions used to construct the $\mathbf{e}_c$ and $\mathbf{e}_f$ extension vectors.

Table A.4: Values of energy-related CO_2 emissions by resource product (CO_2 equivalent), both for the combustion and extraction processes. Values for combustion emissions are taken from the IEA [3, p.I.24], and values for extraction emissions are deduced from the IEA [4, pp.490–491]. Units: kgCO_2e/GJ.

Resource product	Combustion emissions	Extraction emissions
Anthracite	26.8	0
Coking coal	25.8	0
Crude oil	20	1.7
Lignite	27.6	0
Natural gas	15.3	2.3
Natural gas liquids	17.5	2.7
Other bituminous coal	25.8	0
Sub-bituminous coal	26.2	0
Other hydrocarbons	20	1.7
Oil shale and oil sands	29.1	2.5
Peat	28.9	0
All other products	0	0

A.7 References

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[3] IEA. *Statistics: CO2 emissions from fuel combustion.* Tech. rep. International Energy Agency, 2019.

[4] IEA. *World Energy Outlook 2018.* Tech. rep. International Energy Agency, 2018.

Appendix B

Supporting Information to Chapter 3: Global energy consumption of the mineral mining industry: exploring the historical perspective and future pathways to 2060

Emmanuel Aramendia, Paul E. Brockway, Peter G. Taylor, Jonathan Norman

B.1 The mineral extraction process

The subsequent summary of the mineral extraction process is based on [1, Chapters 7 and 8], which provides an excellent overview of the different extraction processes.[1]

Ore extraction. The ore of interest is extracted from the ground, lifted and hauled until the processing facility, where it is further processed.[2] The extracted ores that are not of sufficient economic interest constitute the overburden, and are left unexploited in the mining site.

Ore beneficiation. The extracted ore is then concentrated. The beneficiation (or concentration) process consists of separating the mineral of interest from the other minerals, i.e. the *gangue*. Usually, the process involves crushing and grinding the ore (process known as ore *comminution*), until reaching the ore's *liberation* size, at which the particles of interest are released from the rest of the ore. The ore

[1] Regarding energy consumption, we note that the prevalent extraction stage depends on the mineral extracted as well as on the extraction route. See e.g. [2, 3] for a breakdown for different minerals.

[2] This step is skipped when the technique of *in situ* mineral leaching is used to directly recover the mineral of interest.

concentrate is then obtained by separating the mineral of interest from the gangue, which ends up as *tailings*, i.e. processed "waste" ore. The ore concentrate is an ore consisting mostly of the mineral of interest, but in which considerable impurities remain.

Concentrate refining. It is usually the case for metals that the ore concentrate previously obtained needs to be purified.[3] Different techniques can be used to refine the concentrate and obtain the final product. These techniques can be classified in terms of pyrometallurgical and hydrometallurgical treatments. When using pyrometallurgical treatments, the ore concentrate is smelted at high temperatures (typically in the range 500–2000°C), often in the presence of a reducing agent (for instance coke for iron ore concentrate), to obtain the final metal. When using hydrometallurgical treatments, the metal is extracted either from the extracted ore or from the beneficiated ore using a liquid substance (i.e. the *lixiviant*) — operation known as leaching. Then, the solution may be refined with a set of techniques, including chemical precipitation, solvent extraction, or electrowinning. Finally, the metal needs to be recovered, which can also be done through different techniques, such as electrowinning.

[3]Some minerals that do not need to be purified, for instance some construction and industrial minerals (sand, gravel...), are only likely to undergo the two first steps.

B.2 Glossary of energy terms

Table B.1 introduces a short glossary of the energy-related terminology used throughout the paper.

Table B.1: Glossary of energy-related terminology used throughout the article.

Term	Definition
Direct energy	Final energy used in-situ by an industry, or in general, by any system (e.g. plant, city, country, etc.). May be quantified in terms of primary or final energy.
Energy intensity	When mentioned in relationship to the work conducted in this study, equivalent to final energy intensity.
Final energy	Energy used by the end-user in the form of a final energy carrier (e.g. electricity, gasoline, etc.)
Final energy intensity	Final energy required to mine a unit of a given mineral, including both the direct and indirect energy requirements. It is calculated multiplying the GER by the final-to-primary energy ratio calculated for the mining industry.
Future energy intensity	Final energy required to mine a unit of a given mineral for the future analysis, evolves dynamically following one of the three scenarios defined in Section 3.2.2.
Gross Energy Requirements (GER)	Total of direct and indirect energy requirements associated with a system (in the paper's case, the mining of one unit of a given mineral), quantified in terms of primary energy requirements.
Historical energy intensity	Final energy required to mine unit of a given mineral for the historical analysis, determined using the literature, and kept constant over the timespan of the historical analysis (1971–2015).
Indirect energy	Final energy used ex-situ, i.e. final energy used in the supply chain, of an industry, or in general, of any system (e.g. plant, city, country, etc.). May be quantified in terms of primary or final energy.
Primary energy	Energy flows extracted from the environment (e.g. crude oil, wind power, solar radiation, etc.)
Primary energy intensity	Primary energy required to mine a unit of a given mineral, equivalent to the Gross Energy Requirements of mining a unit of a given mineral.

B.3 Ore grade-tonnage distributions

Figure B.1 shows the unimodal and bimodal ore grade-tonnage distribution curves (tonnage as function of ore grade), as well as their implications in terms of energy intensities of mining as function of ore grades — the grey area represents the tonnage extracted to date.

According to Skinner [4], in the case of the unimodal distribution, common rocks are constituted by different minerals, "one or more of which contains a geochemically

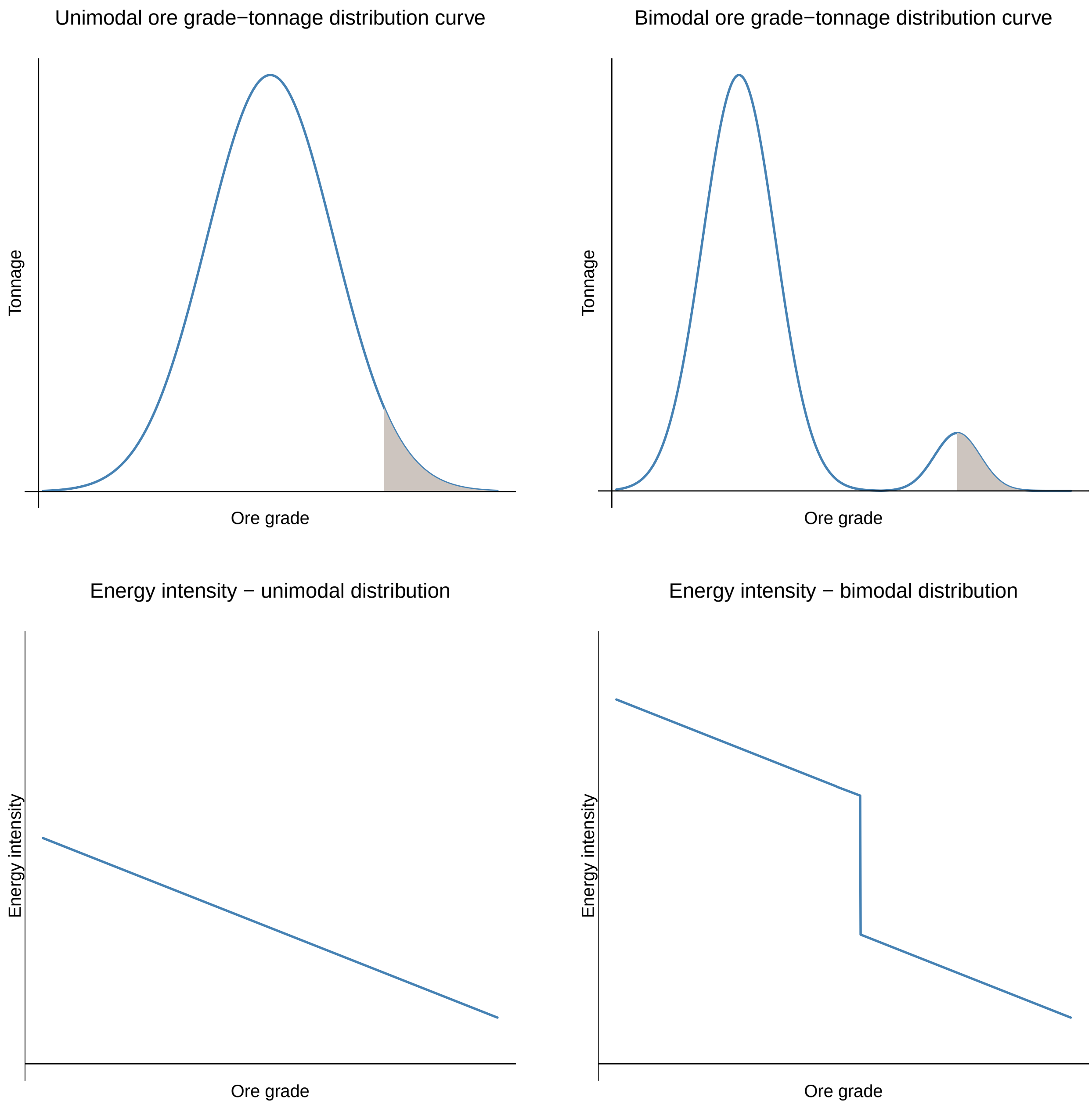

Figure B.1: Unimodal and bimodal ore grade-tonnage distribution curves, as well as implications of each distribution in terms of evolution of energy intensities as function of ore grades. The grey area corresponds to the tonnage extracted to date.

abundant metal as an essential constituent" [4]. The consequence is that producing a mineral concentrate in which a given geochemically abundant element is the main component is possible, without needing to break all minerals to liberate the atoms of interest. Conversely, in the case of the bimodal distribution, only the small distribution peak corresponds to mineralogical deposits where the element of interest is present in mineral compounds of its own, which can be concentrated. Instead, the high peak at low concentrations corresponds to the element being present in minerals "as randomly distributed atoms trapped by isomorphous substitution in minerals of the geochemically abundant elements, an atom of geochemically scarce element replacing an atom of geochemically abundant element" [4]. The consequence is that minerals need to be broken down to liberate and concentrate the elements of interest, which translates into very a high energy consumption — much higher than in the case of elements being available in minerals of their own.

The consequence is that energy intensities increase in a continuous way when ore grade decreases in the case of the unimodal distribution, so that the historical relationship between ore grade and energy intensity is likely to continue over time. Conversely, in the case of the bimodal distribution, the energy intensity increases steeply at a given ore grade resulting from the transition from mineral deposits where the element of interest is present in minerals of its own, to deposits where the element of interest is only available as a randomly distributed element substituting more abundant elements. Hence, when reaching ore grades somewhere between the small and high peaks of the ore grade-tonnage distributions, a mineralogical barrier is reached, at which grade energy intensities steeply increase, which may prevent, or strongly limit, extraction of ores with ore grades lower than the critical mineralogical barrier ore grade. Skinner [4] defends that of industrial metals, only aluminium, iron, magnesium, manganese, and titanium are likely to follow the unimodal distribution curve. However, there are large uncertainties on the exact shape of distribution curves for each element, and Arndt et al. [5] explains for instance that the unimodal distribution currently appears to be more likely in the case of copper — although it is a geochemically scarce metal — because it is found as minerals of its own even at low concentrations.

To conclude, there are large uncertainties regarding the distribution curves that may be followed by each element, which translates in large uncertainties on the future evolution of energy intensities, which are intertwined with ore grade-tonnage distributions.

B.4 Data used

B.4.1 Scenario data

We take final energy consumption and GDP data for the SSP1, SSP2, SSP5, LED and B2DS socio-economic scenarios, used in the Intergovernmental Panel on Climate Change Special Report on 1.5°C [6, Chapter 2], from the 1.5°C Scenario Explorer [7]. For the post-growth socio-economic scenario, we take global GDP declining by 0.2% each year, and we determine the yearly final energy consumption using a linear regression of global final energy consumption as function of global GDP.

B.4.2 Historical production data

Historical data of mineral production (1970–2015) are taken for most minerals from the United States Geological Survey [8]. For uranium production, data are taken from [9, p.89], and for clays, sand and gravel, and limestone, from the work of Krausmann et al. [10], who kindly provided the data on our request. It is worth noting that the data we use from the United States Geological Survey is constructed by combining country and company level data, so that like data from the International Energy Agency (IEA), it is likely to be missing informal mining activities — although it is likely to be more comprehensive than data from the IEA as it also uses company level data (the IEA only uses country level reporting). Next, the data we use from the work of Krausmann et al. [10] is a global estimation of mineral extraction using a wide range of methods depending on the mineral, which does not rely on official primary extraction data, and hence does not suffer from the same drawbacks.

B.4.3 Initial recycling rates

Recycling rates in terms of recycled content are taken from [11, Appendix C] for metals (when more than one value is reported, we use the average of the lowest and highest value), and from [12, Table S1] for other minerals, using the average values reported for industrial minerals and construction minerals.

B.4.4 Historical demand data

The historical demand for each mineral m is determined from its historical production P_m and recycling rate r_m following:

$$D_m = \frac{P_m}{1 - r_m}. \tag{B.1}$$

B.4.5 Historical energy intensities

The initial Gross Energy Requirements (GER) (which represent the primary energy intensities) of mineral extraction are derived from the work of Norgate and Jahanshahi [2], Rankin [1], Nuss and Eckelman [3], Hammond and Jones [13], Mudd [14], Norgate and Haque [15], Calvo et al. [16], and reported in the dataset associated with the chapter (see Data Statement), alongside comments regarding assumptions for their estimation — assumptions were sometimes needed when the literature did not allow to obtain directly the GER associated with mining, for instance when the GER reported included the energy requirements of both the mining and the metallurgical steps without breakdown. Then we multiply the GER by the average final-to-primary energy ratio for the mining and quarrying industry globally, that is determined using data from the IEA and a recently developed Physical Supply Use Table (PSUT) framework for the energy industry [17, 18], which yields the final energy intensity. Section B.8.1 explains briefly the methodology for the calculations using the PSUT framework.

B.4.6 Projections of mineral demand for Energy Transition Technologies

The mineral requirements reported [19] are available as supplemental information of the cited paper. The mineral requirements of the energy transition scenarios conducted by Capellán-Pérez et al. [20] are not publicly available but can be provided under request.

B.5 Linear regression examples

Figure B.2 shows the linear regressions conducted for 8 of the main minerals to assess the mineral requirements of the rest of the economy following Equation 3.3. If we look at the subset of minerals for which future demand for the rest of the economy is determined with a linear regression (conversely to those that do not correlate well with GDP and that are hold constant), the 8 minerals included in Figure B.2 always add up to at least 85% of the final energy consumption of the subset. Hence, the quality of the fits obtained validate the method introduced in Section 3.3.2.

We note that for some minerals (aluminium, iron ore, nickel, zinc), the recent trend is steeper than the long-term trend. Thus, we conduct a sensitivity analysis in which we fit the linear regression for the 1995–2015 period for all minerals. Results for this sensitivity analysis are available in Section B.9.2; conclusions and trends obtained in the main chapter remain unchanged, although the projected mining industry's final energy consumption reaches values somewhat higher (approximatively, by 10–15% higher, depending on the scenario) when conducting the fit in the most recent time period. However, and as discussed in Section 3.3.3, such extrapolation of historical trends does not take into consideration structural changes that may allow material demand to be partly decoupled from economic activity.

Then, Table B.2 gives the values of coefficients a_m, b_m, and r^2, and specifies the fitting time period (1971–2015 or 1990–2015) for each mineral.

B.6 Increasing energy intensities: a comparison

Table B.3 summarises the projections of energy intensities of mining that are used by other studies. The increase factor refers to $\alpha_{m,t}$ in Equation 3.6. To compare, the increase factors we use reach 1.42 in 2050 in the low increase scenario, and reach 2.36 in 2050 in the high increase scenario (it remains constant and equal to unity in the no increase scenario). Hence, the factors we use, particularly in the case of the low increase scenario, are reasonable when compared to factors in Table B.3. The high increase scenario has higher increasing energy intensity factors than most of these studies, but is rather in the lower end of factors reported by Harmsen et al. [21]. We note that the range of increasing energy intensities reported by Harmsen et al.

Table B.2: Values of a_m, b_m, and r^2, and fitting time period. Mt: 10^6 tons. TUS$: 10^9 US$. US$ in constant 2010 values. Dashes refer to non applicable values (minerals for which demand is hold constant and equal to b_m). Dmnl: dimensionless.

Mineral m	Fitting period	a_m Mt/TUS$	b_m Mt	p Dmnl	r^2 %
Aluminium	1971–2015	1.10	-1.06e1	3.70e-27	0.929
Antimony	1971–2015	3.02e-3	-1.94e-3	2.57e-16	0.786
Arsenic	—	—	3.37e-2	—	—
Asbestos	—	—	2.15	—	—
Barite	1995–2015	8.50e-2	2.25	8.97e-06	0.655
Beryllium	—	—	2.69e-4	—	—
Bismuth	1995–2015	2.26e-4	-6.75e-3	7.21e-08	0.790
Boron	1971–2015	1.09e-1	1.15	9.46e-16	0.773
Cadmium	1971–2015	1.86e-4	3.06e-2	3.32e-10	0.602
Chromium	1995–2015	2.18e-1	-5.11	4.88e-11	0.902
Clays	—	—	5.62e+3	—	—
Cobalt	1995–2015	3.18e-3	-1.05e-1	2.90e-14	0.955
Copper	1971–2015	3.16e-1	1.73	6.22e-40	0.982
Diatomite	1971–2015	1.73e-2	1.17	3.58e-13	0.703
Feldspar	1971–2015	4.39e-1	-8.91	2.55e-29	0.945
Fluorspar	1995–2015	1.12	-7.43e-1	4.75e-07	0.745
Gallium	1995–2015	1.65e-5	-7.17e-4	1.02e-05	0.650
Germanium	1995–2015	6.39e-6	-2.06e-4	1.62e-10	0.889
Gold	1971–2015	4.62e-5	9.21e-4	6.79e-19	0.836
Graphite	1971–2015	1.43e-2	1.59e-1	5.66e-18	0.820
Gypsum	1971–2015	3.52	-2.73e+1	2.14e-20	0.860
Indium	1971–2015	1.28e-5	-3.01e-4	1.40e-22	0.888
Iron ore	1971–2015	4.08e+1	1.67e+2	2.61e-17	0.807
Kyanite	—	—	3.98e-1	—	—
Lead	1995–2015	1.57e-1	-1.31	3.19e-09	0.848
Limestone	1971–2015	8.58e+1	-1.33e+3	1.38e-26	.927
Lithium	1995–2015	1.47e-2	-4.99e-1	3.59e-11	0.905
Magnesium	1995–2015	2.89e-2	-7.73e-1	5.88e-13	0.938
Manganese	1995–2015	5.36e-1	-1.35e+1	2.11e-11	0.910
Mercury	—	—	3.26e-3	—	—
Molybdenum	1995–2015	7.15e-3	-1.40e-1	5.96e-10	0.873
Nickel	1971–2015	4.69e-2	-1.97e-1	1.19e-20	0.864
Niobium	1995–2015	2.21e-3	-7.11e-2	1.03e-05	0.650
Perlite	1970–2015	4.69e-2	2.92e-2	1.26e-11	0.651
Phosphate rock	1995–2015	3.22	-2.29e+1	3.32e-08	0.807
Platinum group metals	1970–2015	1.11e-5	4.84e-5	5.25e-23	0.893
Potash	1995–2015	4.22e-1	5.97	6.78e-06	0.664
Pumice and pumicite	—	—	1.79e+1	—	—
Rare Earth Elements	1970–2015	2.17e-3	-2.68e-2	3.80e-24	0.905
Rhenium	1995–2015	8.08e-7	2.24e-6	3.97e-07	0.750
Salt	1970–2015	2.41	9.88e+1	3.10e-31	0.955
Sand and Gravel	1970–2015	4.93e+2	-1.94e+3	5.75e-31	0.954
Selenium	1970–2015	1.99e-5	9.02e-4	2.99e-12	0.673
Silicon	1995–2015	1.78e-1	-4.81	2.93e-15	0.965
Silver	1970–2015	3.75e-4	5.21e-3	9.78e-34	0.965
Soda ash	1995–2015	7.37e-1	1.40e-1	2.92e-17	0.978
Sodium sulfate	1970–2015	4.05e-2	3.56	2.21e-17	0.808
Strontium	—	—	3.93e-1	—	—

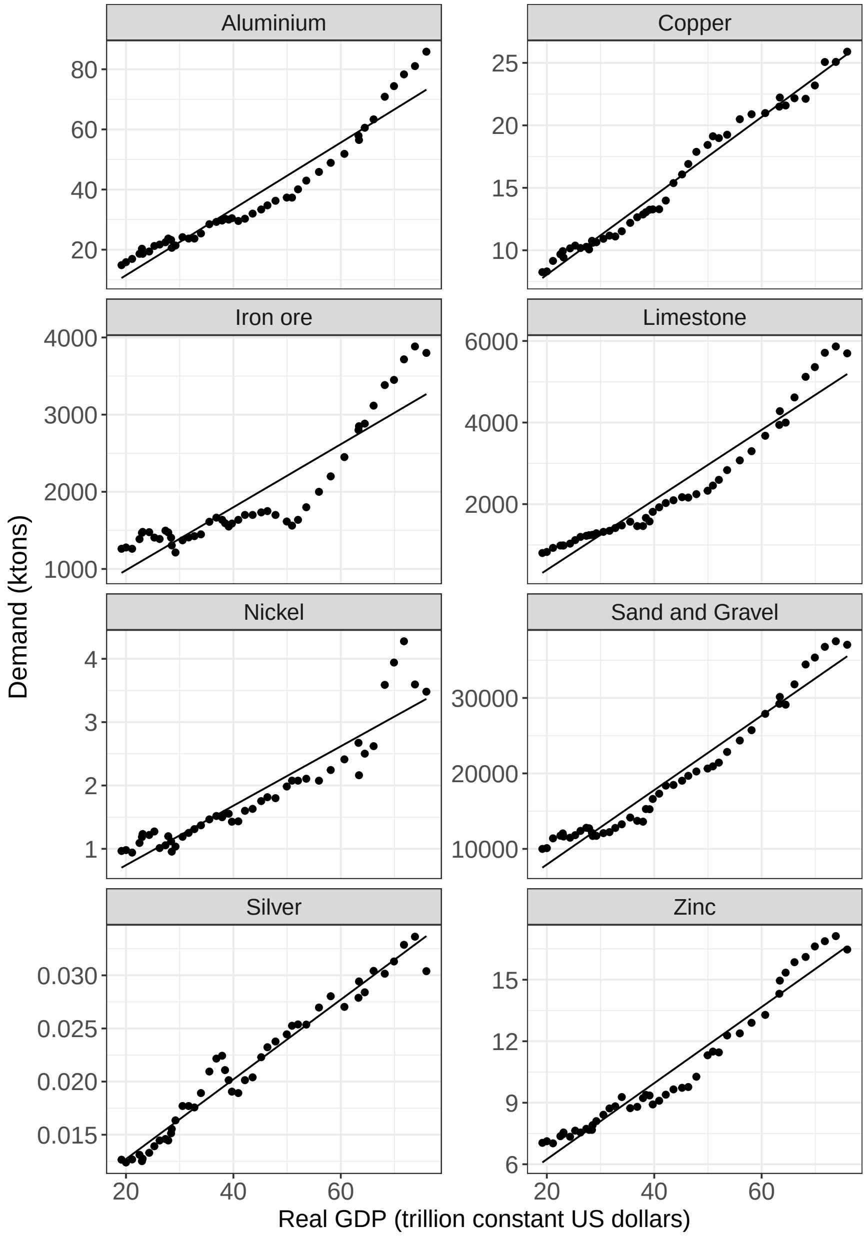

Figure B.2: Examples for 8 main minerals of the linear regressions conducted to determine the mineral requirements of the rest of the economy (Equation 3.3). These 8 minerals always account for 85% of the final energy consumption of extraction, for the subset of minerals which mineral requirements by the rest of the economy are determined with a linear regression.

Mineral m	Fitting period	a_m Mt/TUS$	b_m Mt	p Dmnl	r^2 %
Talc and Pyrophyllite	—	—	8.11	—	—
Tantalum	1970–2015	2.34e-5	-1.94e-4	5.23e-12	0.665
Tin	—	—	3.28e-1	—	—
Titanium mineral concentrates	1970–2015	1.26e-1	1.20	3.14e-30	0.950
Tungsten	1995–2015	2.96e-3	-6.59e-2	1.63e-11	0.913
Uranium	—	—	5.11e-2	—	—
Vanadium	1995–2015	1.46e-3	-2.93e-2	3.12e-14	0.955
Vermiculite	—	—	4.37e-1	—	—
Wollastonite	—	—	6.07e-1	—	—
Zinc	1970–2015	1.86e-1	2.53	8.54e-31	0.953
Zirconium	1970–2015	1.97e-2	7.16e-2	1.91e-19	0.845

[21] places the study as an outlier, and based on our judgment and discussion with external experts (see acknowledgments), the study was not used to inform the energy intensities scenarios presented in Section 3.3.2. The variability in factors reported by Elshkaki et al. [22] and Harmsen et al. [21] is due to (i) the different scenarios considered in each study, which lead to different cumulative primary extraction (because of e.g. differences in demand as well as recycling rates), and hence to different energy intensities in 2050; (ii) to the consideration or not of technological improvements, (iii) to uncertainties in the ore grade-tonnage curves. We note that two studies [23, 24] are based on the work of Van der Voet et al. [25] and have therefore similar results.

B.7 Energy-economy models review: details

Table B.4 introduces each reviewed model alongside the main references, and summarises the findings of our review following for the four following criteria: (i) mineral materials covered, (ii) description of material demand, (iii) description of primary mineral extraction, and (iv) feedback of material flows on energy consumption — note that no model explicitly represented increasing energy intensities of mining activities.

Table B.3: Summary of increasing energy intensities factors in other studies, deduced from the information available (equations, graphs, etc), so values may not be accurate. Increase factors are noted NA for reference [26] because the values are scenario dependent, and are not clearly stated in the article, although the methodology is the same than for reference [22], but with different scenarios.

Study	Mineral	Region	Time period	Increase factor	Methodology
[25]	Copper	World	2010–2050	1.30	Ore grades are extrapolated as a function of time fitting historical data. Then an empirical relationship linking ore grades to energy intensities is applied.
	Zinc			1.35	
	Lead			1.75	
	Nickel sulfides			1.12	
	Nickel laterites			1.14	
[23]	Copper	World	2010–2050	1.30	Same method and values as [25]
[24]	Copper	China	2010–2050	1.42	Same method as [25], different values (specific to China).
[22]	Copper pyro	World	2010–2050	1.33–2.00	Ore grade is determined for each scenario as a function of cumulative extraction, and a energy consumption is determined as function of ore grade.
	Copper hydro			1.36–2.01	
[26]	Copper	EU-28	NA	NA	Same approach and values as [22].
[21]	Copper	World	2010–2050	2.54–6.82	Ore grade is determined for each scenario as a function of cumulative extraction, and a energy consumption is determined as function of ore grade.

Table B.4: Summary of reviewed energy-economy models in relation to the four reviewed criteria. By *energy intensities of production*, we mean a value linking physical production to energy consumption, expressed in a unit such as GJ/tonne. WEPS: World Energy Projection System. ETTs: Energy Transition Technologies. WEM: World Energy Model. REEs: Rare Earth Elements. PGMs: Platinum Group Metals. Note: other materials, such as fossil fuels, plastics, wood, food, are excluded from this review.

Model	Ref	Materials covered in physical units	Determination of material demand	Primary and secondary production	Feedback on energy consumption
IEA's WEM	[27]	Steel, aluminium, copper, nickel, lithium, cobalt, REEs. Only clean technology sector: zinc, PGMs, manganese, graphite, molybdenum.	Demand split by (i) uptake of clean technologies for the energy transition, and (ii) relevant activity drivers (GDP, industry added value, population) for the rest of the economy.	Primary and secondary production differentiated using in-use stocks and end-of-life recycling rates.	Only for steel and aluminium, through the use energy intensities of production, which decrease over time to model increases in efficiency.
AIM/CGE	[28]	Steel, cement	Linear relationship with sectoral output.	No explicit differentiation.	Modelled through the increase in sectoral output.
IMAGE	[29]	Steel, cement	Increasingly through a detailed representation of human activities and services (housing, mobility, infrastructure, etc. requirements translated into material requirements). Use of GDP per capita and population in some cases.	Differentiation for steel, using in-use stocks and end-of-life recycling rates.	Yes, through the use of energy intensities of production, which decrease over time to model increases in efficiency.
Shell's WEM	[30]	Aggregated in four groups: (1) iron and steel, (2) non-ferrous metals, (3) non-metallic minerals, (4) glass.	Using economic data (GDP per capita) and different evolutions depending on scenario narratives.	No explicit differentiation.	Yes, through the use of energy intensities of production, which decrease over time to represent both increases in efficiency and in recycling of metals.

Model	Ref	Materials covered in physical units	Determination of material demand	Primary and secondary production	Feedback on energy consumption
REMIND-MAgPIE	[31]	Steel, cement	Driven by population and GDP, decrease of demand with carbon pricing.	Steel is differentiated using an external steel stock model, with end-of-life recycling rates. Because the model is external, there is no interaction with the scenario and the availability of secondary steel. All cement comes from primary production.	General equilibrium model: steel and cement demand influences final energy demand, and prices of final energy carriers influence back demand for steel and cement, until equilibrium is found.
E3ME	[32]	Aggregated in four groups: (1) construction minerals, (2) industrial minerals, (3) ferrous metals, (4) non-ferrous metals.	Determined through econometric equations, as function of gross economic output by sector, material prices, and innovation.	Materials-related policies can be implemented so that the demand for virgin materials are decreased, and the demand for recycled materials are increased, through exogenous recycled contents.	Demand for materials feedbacks on the gross output of material-producing sectors, which then feedbacks on the final energy demand of those sectors. When more recycled materials are demanded, the gross output of the recycling sector increases while the gross output of virgin material producer sectors decreases.
EIA's WEPS	[33]	Steel	Monetary demand for the iron and steel sector is determined by the economic module, and then converted in physical units (tonnes) following historical trends.	Differentiation of primary and secondary production following historical trends, work ongoing to represent constraints on scrap availability.	Yes, energy consumption by fuel determined as function of primary and secondary steel production and of the manufacturing technologies used.
GCAM	[34]	Cement	Function of GDP.	No explicit differentiation.	Yes, through the use of energy intensities of production, which decrease over time to model increases in efficiency.
IMACLIM – national versions	[35, 36]	Cement and steel on the French version of the model, none in other versions.	Demand for cement and steel is determined within the general equilibrium using prices and elasticities (price and income), with consideration of a minimum level of final demand needed to provide basic needs (set as exogenous parameters).	No differentiation between primary and secondary production	Energy feedback through the general equilibrium, either directly or alternatively, using the total sectoral monetary output determined by the general equilibrium, and exogenous sectoral energy intensities provided by the modeller.

Model	Ref	Materials covered in physical units	Determination of material demand	Primary and secondary production	Feedback on energy consumption
GEM-E3/PRIMES	[37, 38]	Steel, metal products, non-metallic minerals (including bricks, ceramics, glass, sand, cement)	Monetary demand for each sector (provided by GEM-E3) is translated in PRIMES to a physical demand for each mineral material (in tonnes) using material intensities (tonnes per monetary output) for each sector.	Differentiation of primary and secondary production for steel and other relevant minerals. No consideration of in-use stocks and scrap availability.	Yes, a technology mix is determined through an cost optimisation procedure depending on climate policies and prices, which gives an energy intensity of production for each mineral material.
MEDEAS	[20, 39]	Numerous materials at least partially covered, some only for energy transition technologies (most abundant ones), and some also for the rest of the economy (scarcest ones).	Demand split by (i) uptake of energy transition technologies, and (ii) the rest of economic activities, with mineral demand as a linear function of GDP.	Materials-related policies can be implemented so that the demand for virgin materials are decreased, and the demand for recycled materials are increased, through exogenous recycled contents. Consideration of in-use stocks and scrap availability only for ETTs.	Only partially and indirectly, through the energy requirements of energy transition technologies, which modify the Energy Return On Investment of the energy system, and then feedback on global final energy demand.
POLES	[40]	Only steel, although previous studies looked at cement, copper, aluminium, and glass.	Current version: demand for steel is mostly determined from economic activity data, i.e. using a material intensity in tons/GDP for each country. Version under development: demand for specific end-uses (automotive, building, power sectors) is calculated using bottom-up activity data (i.e. number of vehicles produced multiplied by steel required for a vehicle).	Differentiation of primary and secondary steel using the availability of steel scrap at a given time, which is function of the in-use stocks of steel in each type of equipment, of the lifetime of each equipment, and of the end-of-life recycling rates of scrap steel. Primary production covers remaining demand.	Yes, through the use of energy intensities of production, which vary as function of energy prices. Version under development: production processes broken down in different processes, each with own intensity of production, with the share of each production process determined through a cost optimisation procedure.
MESSAGE	[41]	Steel, Cement, Aluminium	Demand determined bottom-up for major end-uses (buildings and transports). Rest of demand is determined using an econometric formulation, as function of GDP and population.	A share of production becomes scrap at each time. Consideration of in-use stocks, end-of-life materials and scrap availability only for electricity generation technologies. Secondary production driven by scrap availability and costs compared to primary production.	Material demand is satisfied by particular production technologies (mix determined following a cost minimisation procedure), which each have a specific energy intensity.

B.8 Additional information regarding the methodology

B.8.1 Determination of the final-to-primary energy ratio for the mining industry

In this section, we shortly introduce the method used to calculate the final-to-primary energy ratio for the mining industry (obtained to be 0.58). For more detailed information, we advice to read the original papers documenting the PSUT framework that we use [17, 18]. The extended PSUT framework [18] is composed by:

- the **U** matrix: a product-by-industry matrix describing energy products inputs to each industry;
- the **V** matrix: a industry-by-product matrix describing energy products outputs of each industry;
- the **Y** matrix: a product-by-sector matrix describing energy products final demand for each economic sector;
- the **R** matrix: a resource-stock-by-product matrix describing the energy products extracted from each resource stock.

We populate these matrices using data from the IEA's World Energy Extended Balances [42]. From these matrices, we define the new vectors and matrices introduced in Table B.5 — note that the $^{\mathrm{T}}$ symbol stands for the transposee of a matrix or vector, that the hat stands for a diagonalised vector (populated with vector coefficients in the diagonal, and zeros elsewhere), and that the $^{-1}$ symbol stands for the inverse of a matrix. Note that post-multiplying a matrix by the unity vector **i** (vector filled with ones) returns a vector in which the coefficient of each row contains the sum of the coefficients in the given row of the matrix.

Then, we define a new $\mathbf{Y}'$ matrix standing for the final energy demand of the mining industry, i.e. the **Y** matrix with only the column corresponding to the mining industry having non zero values. From there, the new set of vectors and matrices associated with $\mathbf{Y}'$ can be determined according to Table B.6.

Table B.5: Matrices and vectors definitions, and coefficients meaning. Adapted from [17] and [18].

Definition	Name
$\mathbf{y} = \mathbf{Y}\mathbf{i}$	Final demand by product
$\mathbf{q} = \mathbf{U}\mathbf{i} + \mathbf{y}$	Total output by product
$\mathbf{g} = \mathbf{V}\mathbf{i}$	Total output by industry
$\mathbf{r} = \mathbf{R}\mathbf{i}$	Total resources output, by resource stock type
$\mathbf{h} = \mathbf{R}^{\mathrm{T}}\mathbf{i}$	Total resources output, by resource product type
$\mathbf{W} = \mathbf{V}^{\mathrm{T}} - \mathbf{U}$	Value added matrix, by industry
$\mathbf{D} = \mathbf{V}\widehat{\mathbf{q}}^{-1}$	Market shares matrix
$\mathbf{Z} = \mathbf{U}\widehat{\mathbf{g}}^{-1}$	Direct requirements matrix (product-by-industry)
$\mathbf{A} = \mathbf{Z}\mathbf{D}$	Direct requirements matrix (product-by-product)
$\underset{\mathrm{p\times p}}{\mathbf{L}} = (\mathbf{I} - \mathbf{A})^{-1}$	Total requirements matrix (product-by-product)
$\underset{\mathrm{i\times p}}{\mathbf{L}} = \mathbf{D}(\mathbf{I} - \mathbf{A})^{-1}$	Total requirements matrix (industry-by-product)
$\mathbf{O} = \mathbf{R}\widehat{\mathbf{h}}^{-1}$	Resource shares matrix

Table B.6: New set of vectors and matrices associated with the new final demand matrix $\mathbf{Y}'$. Adapted from [17] and [18].

Definition	Name
$\mathbf{y}' = \mathbf{Y}'\mathbf{i}$	New final demand by product
$\mathbf{q}' = \underset{\mathrm{p\times p}}{\mathbf{L}}\mathbf{y}'$	New total output by product
$\mathbf{g}' = \underset{\mathrm{i\times p}}{\mathbf{L}}\mathbf{y}'$	New total output by industry
$\mathbf{U}' = \mathbf{Z}\widehat{\mathbf{g}'}$	New use matrix
$\mathbf{V}' = \mathbf{D}\widehat{\mathbf{q}'}$	New supply matrix
$\mathbf{W}' = \mathbf{V}'^{\mathrm{T}} - \mathbf{U}'$	New added value matrix
$\mathbf{h}' = \mathbf{y}' - \mathbf{W}'\mathbf{i}$	New total resources output, by resource product
$\mathbf{R}' = \mathbf{O}(\widehat{\mathbf{h}'})^{\mathrm{T}}$	New resource matrix

Adding up all coefficients of the $\mathbf{Y}'$ matrix gives the mining industry's final energy consumption, and adding all coefficients of the $\mathbf{R}'$ matrix gives the associated primary energy supply. The final-to-primary ratio can then directly be calculated from these numbers, for each year. We then use the average ratio over the time period 2000–2015 — note that the ratio almost does not change in that time period.

B.8.2 Sensitivity analysis: Monte Carlo simulation

For the sensitivity analysis, we specify a normal probability distribution function for each historical (final) energy intensity f_m, and we then perform 1000 runs of the historical analysis (for each run, the historical energy intensity of each mineral m is sampled independently — i.e. the intensity may be higher than the average value for clays while lower for copper). In the few cases where the sampled energy intensity is negative for a mineral m, we set it back to its average value – the average value here stands for historical energy intensity used by default in the study — see the GER values provided for each mineral in the dataset associated with the chapter (see Data Statement).

To specify the normal distribution function, we use either 15% or 30% of the mineral's average historical energy intensity as standard deviation, depending on the confidence we have on the average historical energy intensity. When different studies backed up similar values, we used 15% of the average historical energy intensity as standard deviation, while if we only had one study available or if different studies pointed to values considerably different, we used 30%. We summarise below the approach used for each mineral:

- Standard deviation equal to 15% of f_m: aluminium, germanium, gold, iron ore, lead, platinum group metals, uranium, zinc.
- Standard deviation equal to 30% of f_m: antimony, arsenic, asbestos, barite, beryllium, bismuth, boron, cadmium, chromium, clays, cobalt, copper, diatomite, feldspar, fluorspar, gallium, graphite, gypsum, indium, kyanite, limestone, lithium, magnesium, manganese, mercury, molybdenum, nickel, niobium, perlite, phosphate rock, potash, pumice and pumicite, rare earth elements, rhenium, salt, sand and gravel, selenium, silicon, silver, soda ash, sodium sulfate, strontium, talc and pyrophyllite, tantalum, tin, titanium mineral concentrates, tungsten, vanadium, vermiculite, wollastonite, zirconium.

B.8.3 Future mineral demand by Energy Transition Technologies

As mentioned in the main chapter, we combine two studies for assessing the future mineral demand by Energy Transition Technologies (ETTs) [19, 20]. We use either study depending on whether the mineral is covered in the literature review conducted by Watari et al. [19].

Using the literature review by Watari

The following minerals are covered in Watari et al.'s study: indium, silver, platinum, selenium, lead, cadmium, chromium, tellurium, tin, zinc, molybdenum, dysprosium, manganese, cobalt, germanium, gallium, copper, tantalum, nickel, lithium, silicon, and neodymium and dysprosium (that we gather as rare earth elements). Technologies considered for the energy transition in the literature review are solar photovoltaic, concentrated solar power, wind onshore, wind offshore, electric vehicles, fuel cells, nuclear plants, geothermal energy, biomass, Carbon Capture and Storage (CCS), and additional grids and storage batteries required for the deployment of renewable energy. For those minerals, we select the highest value of demand to 2050 found in the reviewed studies to be the high bound for mineral demand by ETTs, and the lowest value of demand to 2050 found in the reviewed studies to be low bound for mineral demand by ETTs. Then, we use data kindly provided by I. Capellán-Pérez (and extracted from study [20]) as starting point of the mineral demand by ETTs in 2015, and we use a linear interpolation to project over the period 2015–2060. After 2050, we keep the demand constant and equal to its value in 2050.

Using the dynamic modelling by Capellán-Pérez and co-authors

We use the underlying data of the paper [20] kindly provided by I. Capellán-Pérez to estimate the mineral demand by ETTs for other minerals: aluminium, sand and gravel, silicon, potash, iron ore, limestone, magnesium, soda ash, titanium mineral concentrates, and vanadium (for the rest of minerals, we consider that the mineral requirements by ETTs is marginal). This study estimates material requirements for solar photovoltaic, concentrated solar power, wind onshore and offshore, and additional grids required for the deployment of renewable energy. We use as a high bound of mineral demand by ETTs the mineral demand projections in the scenario reaching a 100% renewable energy system by 2060 in [20] and as a low bound of mineral demand by ETTs the scenario reaching a 50% renewable energy system by 2060 in [20]. There is no need to interpolate data points as the data provided include projections for all years.

B.8.4 Mineral classification

Mineral group

We define the following mineral groups (see Figure B.4) : construction minerals, industrial minerals, ferro-alloy metals, non-ferrous metals, and precious metals. The groups are mostly based on the work of Reichl and Schatz [43] and are constituted as follow:

- *construction minerals*: clays, limestone, sand and gravel.
- *industrial minerals*: asbestos, barite, boron, diatomite, feldspar, fluorspar, graphite, gypsum, kyanite, perlite, phosphate rock, potash, pumice and pumicite, salt, silicon, soda ash, sodium sulfate, talc and pyrophyllite, vermiculite, wollastonite.
- *ferro-alloy metals*: chromium, cobalt, manganese, molybdenum, nickel, niobium, tantalum, titanium mineral concentrates, tungsten, vanadium.
- *non-ferrous metals*: aluminium, antimony, arsenic, beryllium, bismuth, cadmium, copper, gallium, germanium, indium, iron ore, lead, lithium, magnesium, mercury, rare earth elements, rhenium, selenium, strontium, tin, uranium, zinc, zirconium.
- *precious metals*: gold, platinum group metals, silver.

Assumption on minerals affected by depletion

We assume that industrial and construction minerals, aluminium, chromium, iron ore, manganese, magnesium, and titanium are abundant enough to be only marginally affected by depletion, and hence we apply constant energy intensities of mining to those minerals. We also assume that gallium is not affected by mineral depletion as it is mostly a by-product of aluminium mining. We assume that all other minerals are subject to mineral depletion and hence model increasing energy intensities.

B.9 Additional results

B.9.1 Historical period

Breakdown of final energy consumption by mineral over time

Figure B.3 shows the shares of historical mining final energy consumption by mineral over time. The breakdown needs to be taken carefully as there are significant uncertainties associated with the historical energy intensities of mining that we use for each mineral, but remains nonetheless indicative.

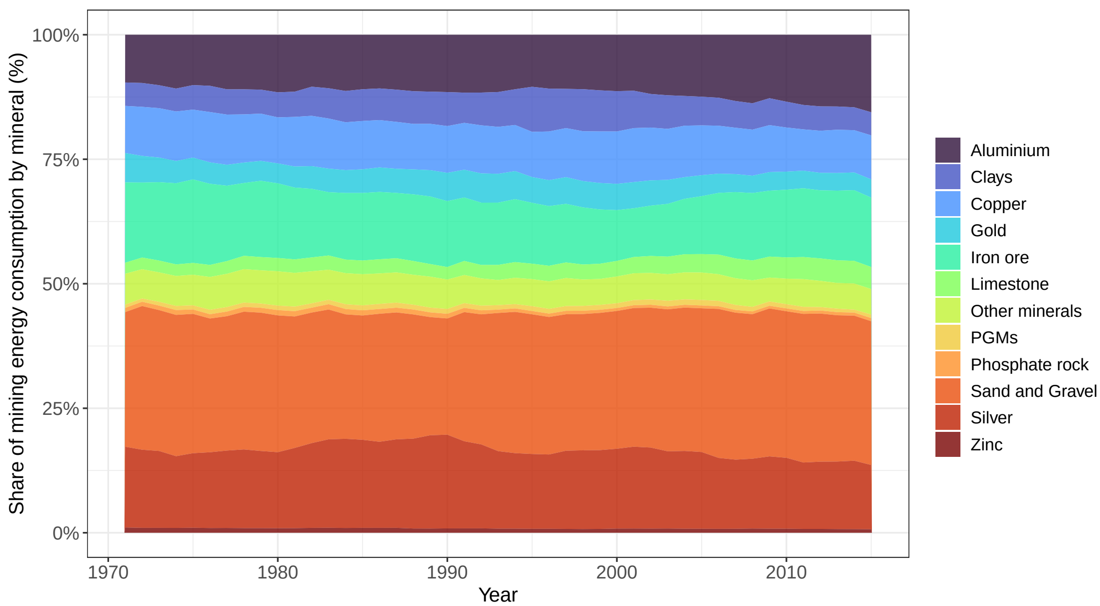

Figure B.3: Breakdown of mining industry final energy consumption by mineral. PGMs: Platinum Group Metals.

Breakdown of final energy consumption by mineral group over time

Figure B.4 shows the shares of historical mining final energy consumption by mineral group over time. Construction minerals account for the largest share of final energy consumption, while precious, non-ferrous, and ferro-alloy metals also account for a large share of the breakdown. Conversely, industrial minerals only account for a minor share.

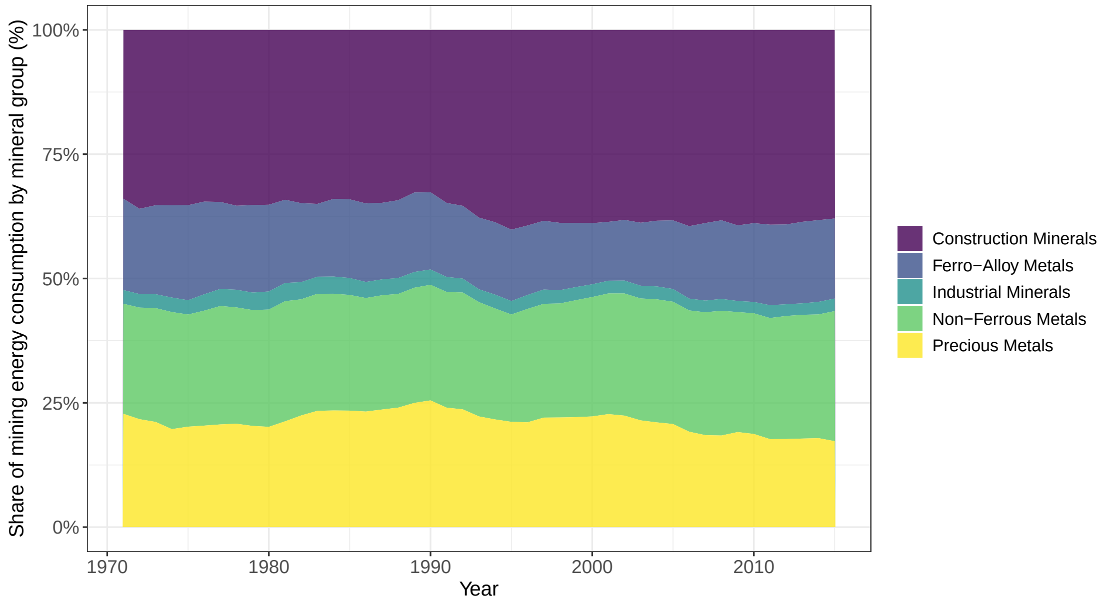

Figure B.4: Breakdown of mining industry final energy consumption by mineral group.

B.9.2 Future pathways

Ratio of mining industry final energy consumption for forecasted total final energy consumption

Figure B.5 shows the share of global final energy consumption devoted to the mining industry, using the global final energy consumption forecasted in each socioeconomic scenario and our estimate of the mining industry final energy consumption. The share increases very significantly over time, and reaches a value in the range 4–12% of forecasted global final energy consumption in most cases, or even higher in some scenarios with high increases in energy intensities. Only in the post-growth socioeconomic scenarios do the share remain at levels lower than 4% of global final energy consumption.

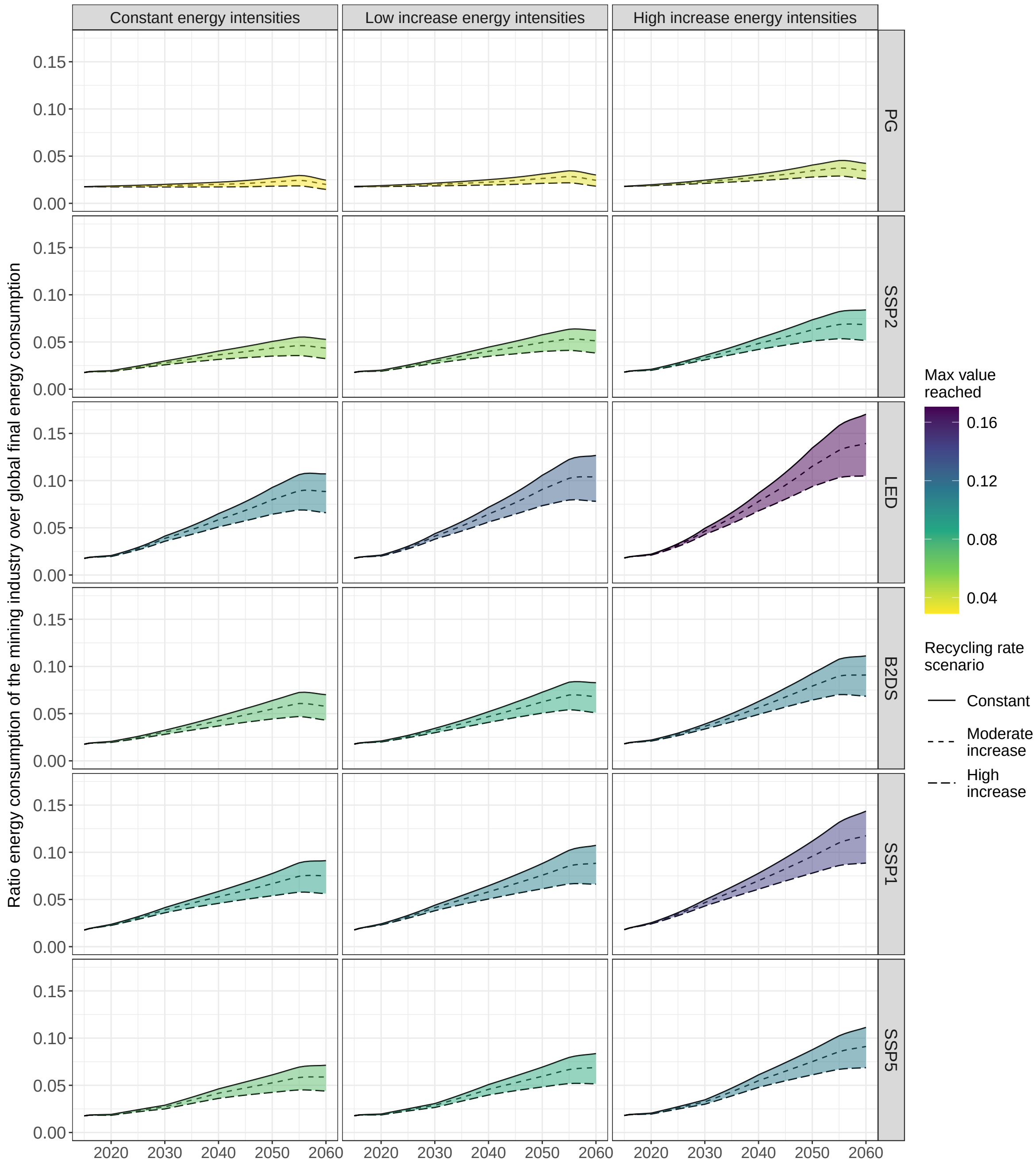

Figure B.5: Fraction of global final energy devoted to the mining industry, by socio-economic scenario, energy intensity, and recycling rates scenarios.

Figure 3.8: additional results

Low bound value of mineral demand by ETTs Figure B.6 shows the figure equivalent to Figure 3.8 when considering the low bound of mineral demand by ETTs. As expected, the ETTs sector is then responsible for a lower amount of final energy consumption than in Figure 3.8. The conclusion according to which mineral demand by the rest of the economy is the main determinant of the future mining industry's final energy consumption remains unchanged.

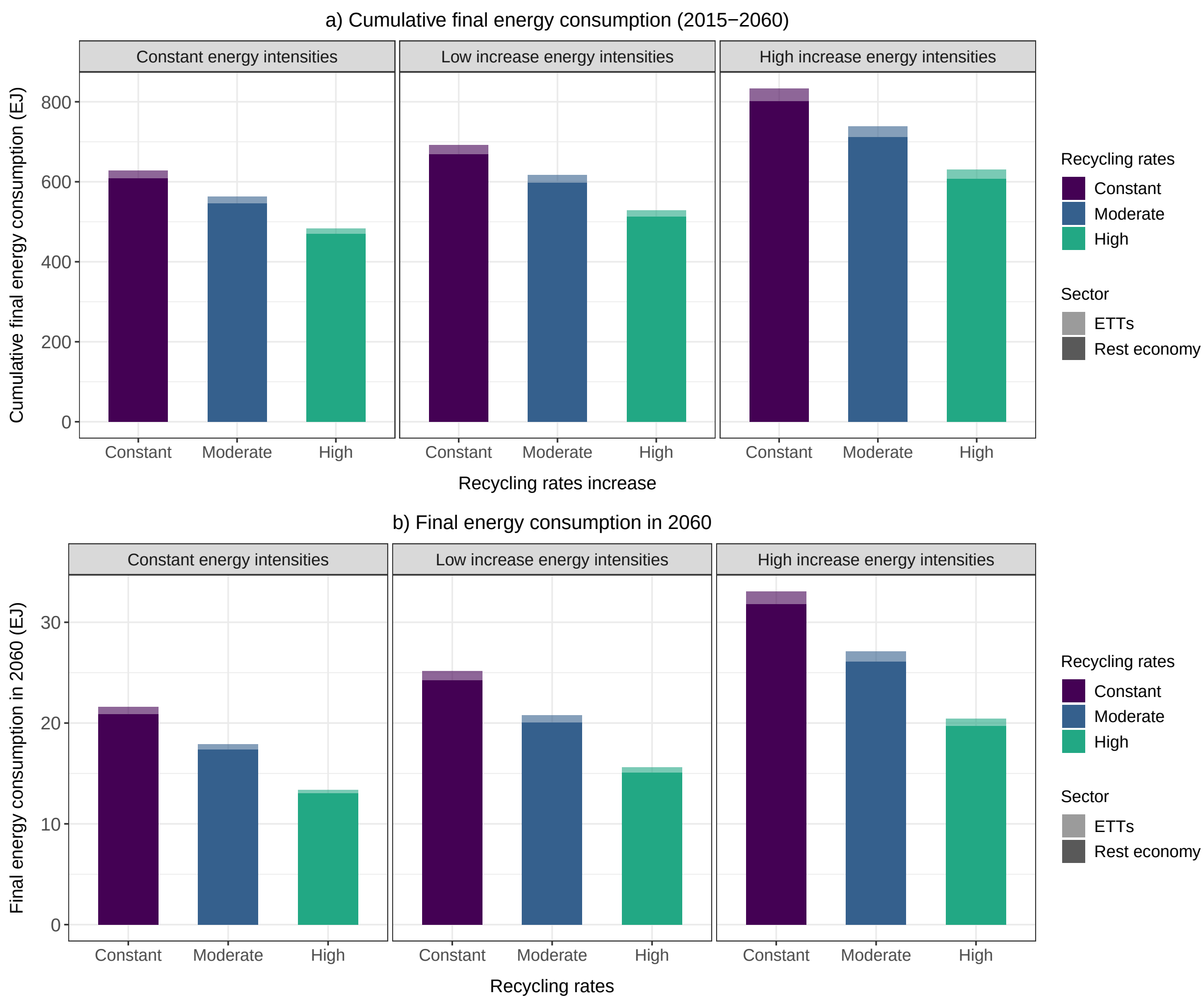

Figure B.6: (a) Cumulative final energy consumption (2015–2060) and (b) Final energy consumption in 2060 for the Beyond 2 Degrees Scenario, as function of the recycling rates scenario, of the energy intensities scenario. Results for the low bound value of mineral demand by Energy Transition Technologies (ETTs).

Post-growth socio-economic scenario Figure B.7 shows the figure equivalent to Figure 3.8 when considering the post-growth socio-economic scenario (instead of the B2DS), and the high bound of mineral demand by ETTs.

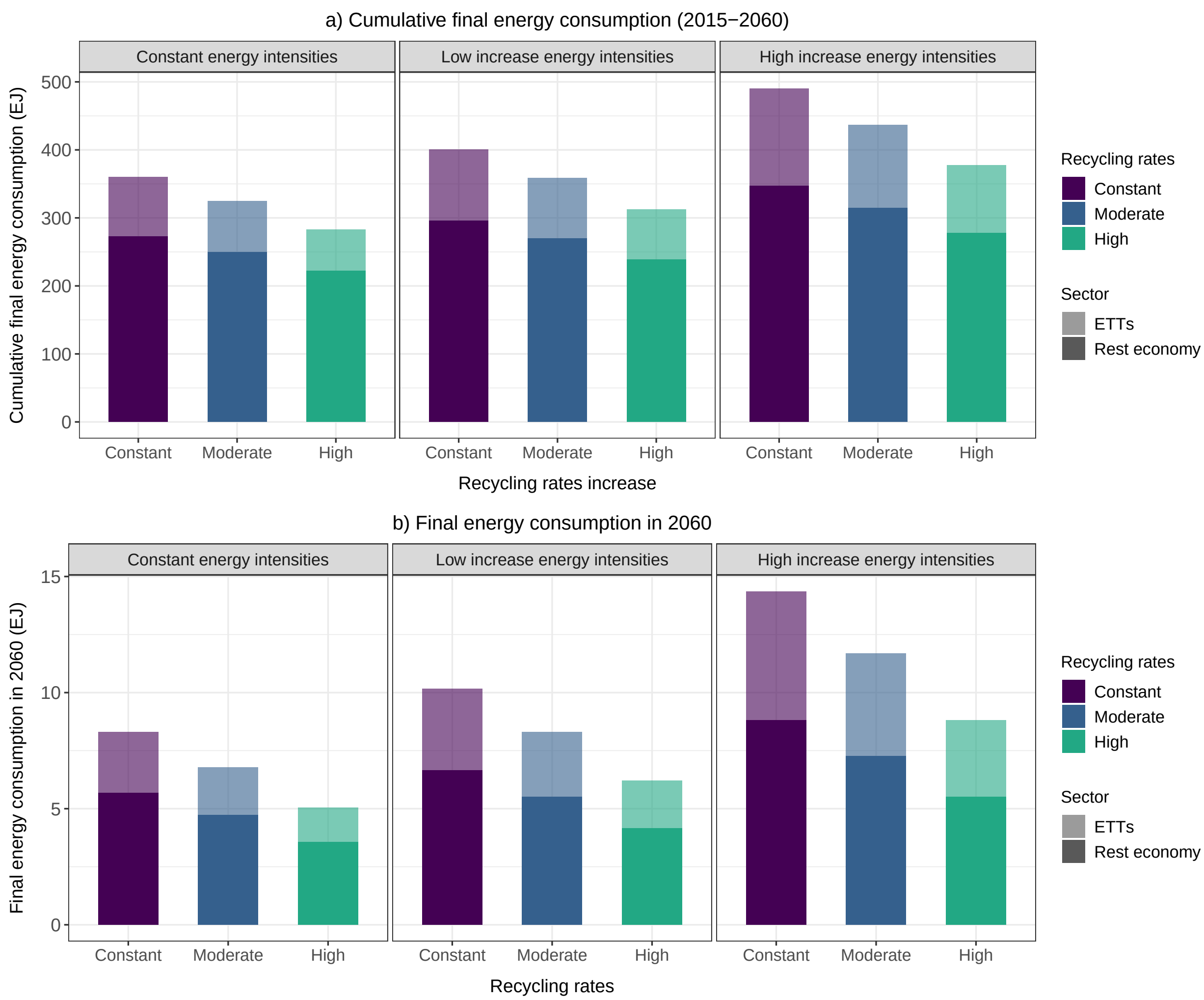

Figure B.7: (a) Cumulative final energy consumption (2015–2060) and (b) Final energy consumption in 2060 for the Post-Growth scenario, as function of the recycling rates scenario, of the energy intensities scenario. Results for the high bound value of mineral demand by Energy Transition Technologies (ETTs).

In this situation, the ETTs sector becomes a significant driver of the mining industry's final energy consumption, although the rest of the economy remains dominant. We note that the high bound of mineral demand by ETTs is probably an overestimation of the mineral demand in the case of a PG socio-economic scenario, where less energy may be required as the economic activity slightly decreases. Considering that the current mining industry's final energy consumption is around 6.6 EJ, the figure shows that the ETTs sector may become a significant driver of the mining industry's final energy consumption, but that the evolution of such energy consumption will be first and foremost determined by future mineral demand by the rest of the economy — pathways of high mineral demand (as for B2DS) and of low mineral demand (as for post-growth scenario) make a considerable difference in the future final energy consumption. The figures obtained for the rest of socio-economic scenarios are very similar to Figure 3.8.

Figure 3.9: additional results

Low bound value of mineral demand by ETTs Figure B.8 shows the figure equivalent to the main chapter Figure 3.9 when using the low bound for mineral demand by ETTs. The difference with Figure 3.9 is not so much on the levels of final energy consumption reached but on the shape of the evolution of final energy consumption. While in Figure 3.9, the increase in final energy consumption slows down in 2055, or even decreases for the post-growth socio-economic scenario, the increase continues steadily in Figure B.8. This is due to the underlying mineral demand for ETTs data [20], according to which the energy transition is completed in 2055 for the high bound of mineral demand by ETTs, and is still ongoing for the low bound of mineral demand by ETTs.

Sensitivity analysis: fitting mineral demand in the 1995–2015 period

Figure B.9 shows future pathways obtained for the mining industry's final energy consumption when fitting the material demand-GDP relationship over the recent period 1995–2015. Trends and conclusions obtained in the main chapter remain unchanged, but the mining industry's final energy consumption reaches values somewhat higher when conducting the fit in this more recent time period.

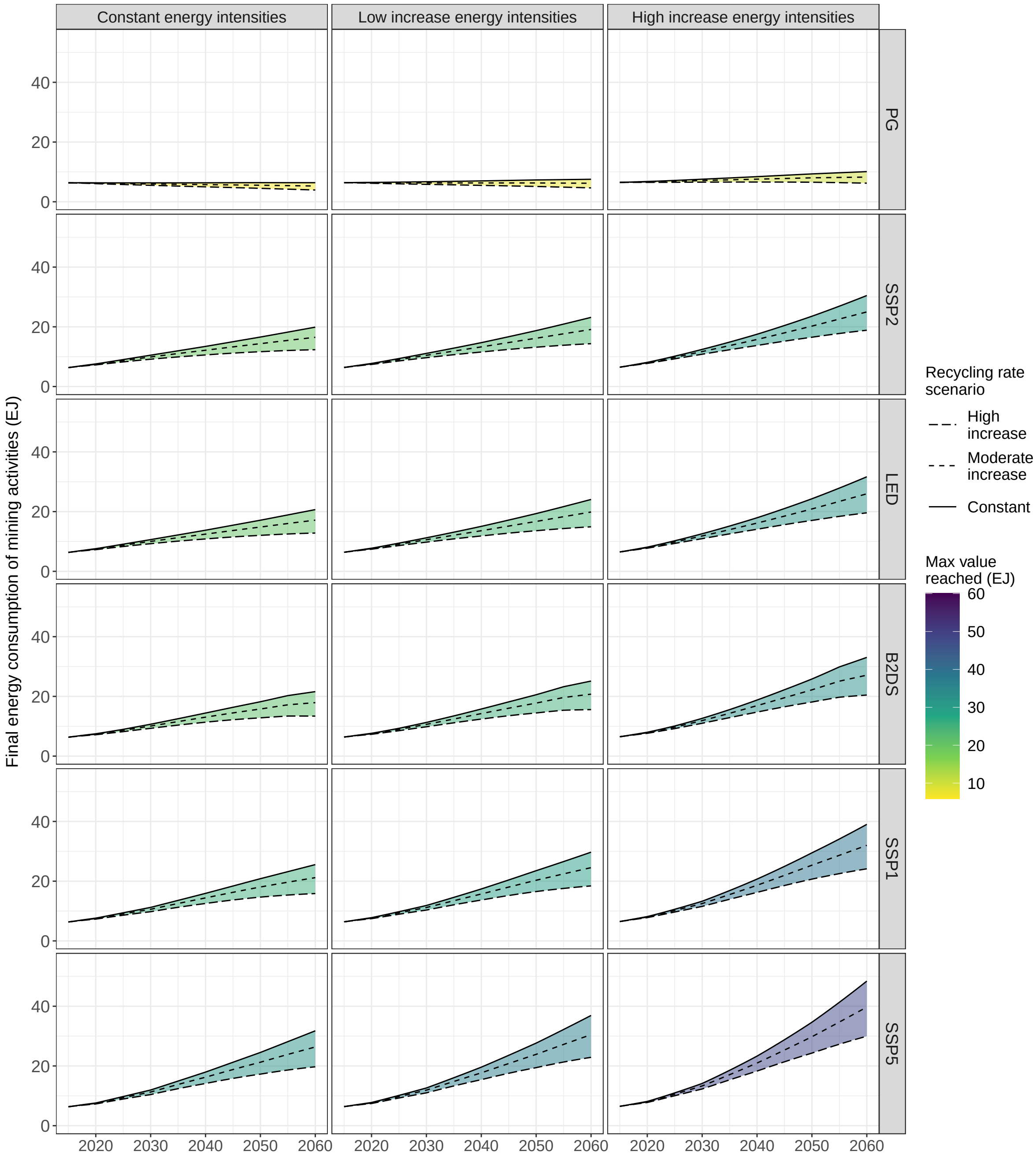

Figure B.8: Future mining industry's final energy consumption pathways by socio-economic scenario, energy intensity scenario, and recycling rate scenario, when considering the low range for mineral demand by the Energy Transition Technologies.

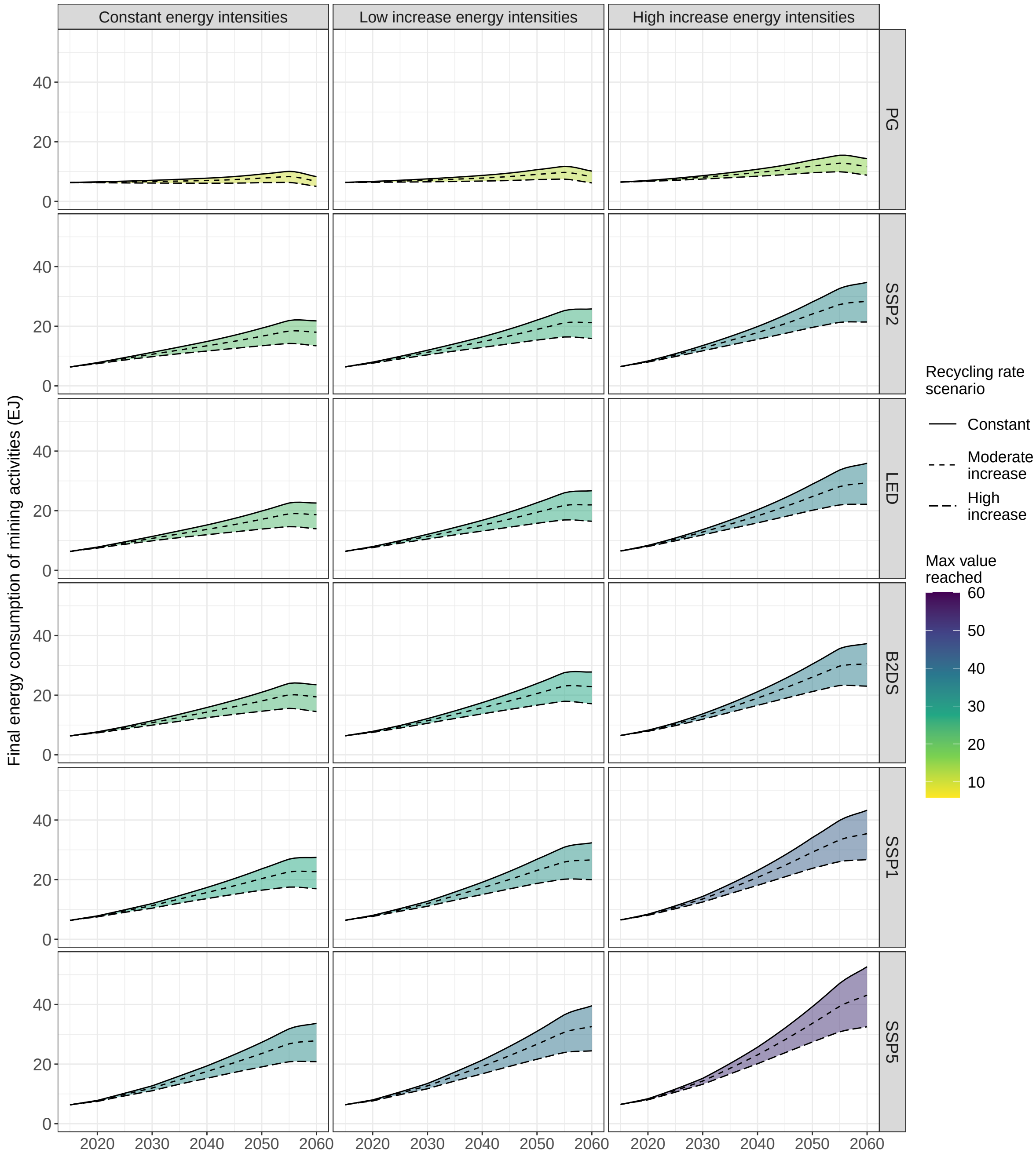

Figure B.9: Sensitivity analysis: future mining industry's final energy consumption socio-economic scenario, energy intensity scenario, and recycling rate scenario, when considering the high range for mineral demand by the Energy Transition Technologies. Material demand-GDP relationship fitted over the 1995–2015 period.

Breakdown of final energy consumption by mineral Figure B.10 shows the breakdown of the future mining industry's final energy consumption by mineral, in the case of a moderate increase in recycling rates and of a low increase in energy intensities (results with other recycling rates, energy intensities scenarios, and socio-economic scenarios are similar).

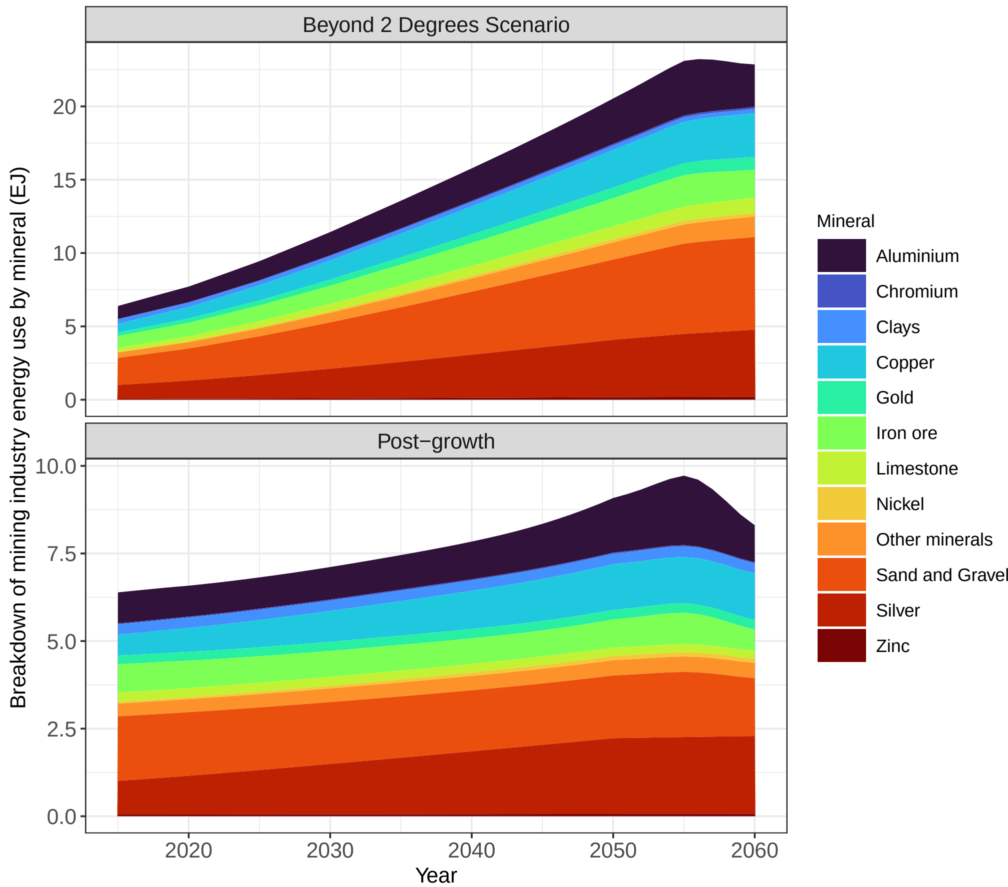

Figure B.10: Breakdown of the future mining industry's final energy consumption by mineral, for the low increase in energy intensities scenario and the moderate increase in recycling rates scenario. Results for the high bound of mineral demand by ETTs.

Caution note: the breakdown needs to be taken carefully as there are significant uncertainties associated with the historical energy intensities of mining used for each mineral.

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Appendix C

Supporting Information to Chapter 4: Estimation of fossil fuels useful stage Energy Return On Investment and implications for renewable energy systems

Emmanuel Aramendia, Paul E. Brockway, Peter G. Taylor, Jonathan Norman, Matthew K. Heun, Zeke Marshall

C.1 Methods

C.1.1 Calculation of final and useful stage Energy Return On Investment, excluding indirect energy requirements

Calculation of final stage Energy Return On Investment

From the International Energy Agency's (IEA) World Energy Extended Balances (WEEB), we construct a Physical Supply Use Table (PSUT) framework [1] (for calculations at the global level) and a Multi-Regional Physical Supply Use Table (MR-PSUT) framework [2] covering all the regions covered in the IEA's WEEB (for calculations at the regional level). Such frameworks represent the Energy Conversion Chain in terms of physical energy flows, from the primary extraction of energy resources to the delivery of final energy carriers to end-use sectors. The set of basic matrices that constitute these frameworks are the resource matrix **R**, which represents the primary extraction of energy, the use matrix **U**, which represents the use of energy products by each energy industry, the supply matrix **V**, which represents the supply of energy products by each energy industry, and the final demand matrix **Y**, which represents the final demand of energy carriers by end-use sector (e.g. road, iron and steel, etc.). The vectors of total output by industry **g** and of total output by product **q** stem directly from this set of matrices, and are defined respectively as the sum across industries of the **V** matrix, and of the sum across energy products of the **R** and **V** matrices. For further clarification on the PSUT structure and on subsequent calculations, see previous work by Heun et al. [1] and Aramendia et al. [2].

Then, input-output matrices are specified following the industry technology assumption, which is the most appropriate for describing the energy industry, due to numerous cases of joint and by-production [3]. Particularly, we define the set of matrices shown in Table C.1.

Table C.1: Input-Output matrices definition and coefficients meaning. Adapted from Aramendia et al. [2].

Matrix definition	Matrix name	Matrix coefficients meaning
$\mathbf{Z} = \mathbf{U}\widehat{\mathbf{g}}^{-1}$	Direct requirement matrix (product-by-industry)	Coefficient (k, l) represents the needed input of product k to produce one unit of output of industry l.
$\mathbf{D} = \mathbf{V}\widehat{\mathbf{q}}^{-1}$	Market shares matrix	Coefficient (k, l) represents the share of product l by industry k in total supply of product l.
$\mathbf{A} = \mathbf{Z}\mathbf{D}$	Direct requirement matrix (product-by-product)	Coefficient (k, l) represents the directly (excluding supply chain) needed input of product k to produce one unit of product l.

The next step is to determine the vector of final energy intensities by energy industry, i.e. the consumption of final energy required for each energy industry to deliver one unit of energy output. To do so, we split the use matrix **U** in its feedstock component $\mathbf{U}_{\text{feed}}$ (representing energy products used for transformation processes by industry) and its energy self-consumption component $\mathbf{U}_{\text{eiou}}$ (representing energy products used for energy purposes by the energy industry).

Then, we determine the required final energy production of the energy industry for the manufacture of one unit of each energy product as:

$$\mathbf{e}_{\text{eiou}} = \widehat{\mathbf{g}}^{-1}(\mathbf{U}_{\text{eiou}}^{\text{T}}\mathbf{i}), \tag{C.1}$$

where the hat notation refers to vector diagonalised, e.g. a matrix with coefficients in the diagonal equal to the vector's coefficients, and coefficients outside the diagonal equal to zero, and where **i** refers to a column vector filled with ones. Next, we determine the vector of final energy requirements for the production of one unit of each energy product as:

$$\mathbf{m}^{\mathrm{T}} = \mathbf{e}_{\mathrm{eiou}}^{\mathrm{T}} \mathbf{D}(\mathbf{I} - \mathbf{A})^{-1}, \tag{C.2}$$

where $^{\mathrm{T}}$ stands for the transpose of a vector, or matrix. Then, the Energy Return On Investment for each energy product is simply calculated as the inverse of the coefficient corresponding to the given product in vector $\mathbf{m}$.

These calculations are conducted alike both when using the global PSUT framework (single world region) and the MR-PSUT framework, yielding in the first case global final stage EROIs by energy product, and in the second case the final stage EROIs for the manufacture of a given product in a given country (in the multi-regional framework, the names of energy products are specified according to the region of production). Next, we aggregate these EROIs to determine average values by fossil fuel group using the shares of use of each energy product within each fossil fuel group, which we calculate directly from the IEA's WEEB for both the global and national levels.

In practical terms, the PSUT framework is constructed using the **IEATools** [4] and **ECCTools** [5] `R` packages, input-output calculations (including product-level EROI calculations) are conducted using the **Recca** [6] `R` package, and the aggregation of EROIs by fossil fuel group is conducted using the **EROITools** [7] `R` package.

Calculation of useful stage Energy Return On Investment

To obtain the useful stage EROI values, we determine both the economy-wide and end-use specific average final-to-useful efficiencies of each energy product, globally and by country. The global primary-final-useful database is structured as a list of national PSUT matrices in which end-use conversion devices (cars, heaters, etc) are considered industries (alongside conventional primary energy extraction and energy processing industries), and final demand sectors demand useful energy products (like high temperature heating, mechanical drive, etc) instead of final energy products (like gasoline, electricity, etc). This section describes the determination of average final-to-useful efficiencies for each energy product in each country and of their global average, both economy-wide and end-use specific — the method for conducting final demand sector-specific calculations are described in Section C.3.3, alongside an example.

Economy-wide. To determine the average final-to-useful efficiencies for each energy product in each country, it is first needed to introduce the amended national $\tilde{\mathbf{U}}$, $\tilde{\mathbf{V}}$, and $\tilde{\mathbf{Y}}$ matrices, which correspond respectively to the $\mathbf{U}$ and $\mathbf{V}$ matrices from which only the final-to-useful end-use conversion devices have been kept as industries (excluding flows of energy products for non-energy purposes), and to the $\mathbf{Y}$ matrix from which only final demand for useful energy products are kept (so, this excludes e.g. exports of final energy products). The $\mathbf{q}'$ vector stands for the amended $\mathbf{q}$ vector calculated from the $\tilde{\mathbf{U}}$ and $\tilde{\mathbf{Y}}$ matrices, and the $\mathbf{g}'$ vector for the amended $\mathbf{g}$ vector calculated from the $\tilde{\mathbf{V}}$ matrix. We also introduce the vector of total input by industry $\mathbf{f}'$ calculated from the $\tilde{\mathbf{U}}$ matrix by summing inputs across industries. Then, we define the use shares matrix $\tilde{\mathbf{D}}^*$ as:

$$\tilde{\mathbf{D}}^* = \tilde{\mathbf{U}}^{\mathrm{T}} \widehat{\mathbf{q}'}^{-1}, \tag{C.3}$$

where each coefficient $\tilde{d}^*_{k,l}$ stands for the share of product l used as input to industry k. We also introduce the vector containing the final-to-useful efficiencies of each end-use conversion device $\mathbf{n}$:

$$\mathbf{n} = \widehat{\mathbf{g}'}^{-1} \mathbf{f}'. \tag{C.4}$$

Next, the average final-to-useful efficiency for each energy product p can be determined, in each country, as:

$$\eta_p = \frac{\sum\limits_{i \in \mathcal{I}} \tilde{d}^*_{i,p} n_i}{\sum\limits_{i \in \mathcal{I}} \tilde{d}^*_{i,p}}, \tag{C.5}$$

where $\mathcal{I}$ stands for the subset of industries corresponding to end-use conversion devices. To determine the global average final-to-useful efficiency for each product, we compute the shares of use of each energy product by country using the IEA's WEEB, and use these shares to calculate the weighted average final-to-useful efficiency at the global level. Then, applying Equation 4.3 using the final stage EROIs previously calculated (inverse of Equation C.2) and the average final-to-useful efficiencies yields the useful stage EROI for each product, in each country, as well as at the global level.

End-use specific. The end-use specific average final-to-useful efficiency for each energy product p in each end-use c is similarly determined from the matrix $\tilde{\mathbf{D}}^*$ and the vector $\mathbf{n}$:

$$\eta_{p,c} = \frac{\sum\limits_{i \in \mathcal{C}} \tilde{d}^*_{i,p} n_i}{\sum\limits_{i \in \mathcal{C}} \tilde{d}^*_{i,p}}, \tag{C.6}$$

where $\mathcal{C}$ stands for the subset of end-use conversion devices that deliver the specific end-use c. To determine the end-use specific global average final-to-useful efficiency, we determine the share of use of each product by country within a given end-use c, using the $\tilde{\mathbf{U}}$ matrices. Applying Equation 4.3 using the end-use specific final-to-useful efficiency then yields the end-use specific useful stage EROI for a given energy product, in each country, as well as at the global level.

Like for the final stage, the calculated useful stage EROIs are then aggregated by fossil fuel group using the shares of use of each energy product within each fossil fuel group and within each end-use for end-use specific calculations (these are calculated from the global primary-final-useful database).

C.1.2 Calculation and addition of indirect final energy requirements to final and useful stage EROIs

General approach

In this section, we describe how the indirect final energy e_{iE} required for the production (including primary extraction, and downstream transformation and refining) of fossil fuels can be determined from the Exiobase Multi-Regional Input Output model [8]. Equations 4.1 and 4.2 can then be adapted adding such indirect final energy requirements to the denominator. Calculations are conducted at the global level only, for each of the following fossil fuel group: all fossil fuels, coal products, fossil gas, oil products, and oil and gas products. However, one important note is that the indirect final energy requirements associated with fossil fuel industries' capital investments have not been quantified — the reason is that the capital investment vector (part of the final demand matrix) in the Exiobase model is not disaggregated by industry doing the investment, which hinders the quantification of indirect energy associated with capital investments.

Importantly, this section describes the calculations conducted with the Exiobase MRIO model set of input-output matrices. Hence, *the matrices we refer to in this section are different* from those mentioned in the rest of this SI, even when they may bear the same names, for consistency with the IO framework [3]. The algebra described thereafter thus stands independently of the algebra described in the rest of the SI.

Input-Output calculations: zeroing method

The method we use is inspired by previous work by Brand-Correa et al. [9] and Brockway et al. [10], who also used the Exiobase MRIO database to determine indirect energy use by the energy industry, although there are some methodological differences with these previous studies, which we discuss in Section C.3.6.

Adapted final energy extension vector From the Exiobase dataset, one can construct the vector of final energy consumption directly consumed by each industry using the net energy extension vectors — let us call $\mathbf{f}$ such vector.[1] Then, we can calculate a final energy extension vector $\mathbf{e}$ by dividing the final energy consumption of each industry by its gross output, which in matrix terms gives:

$$\mathbf{e} = \widehat{\mathbf{x}}^{-1}\mathbf{f}, \tag{C.7}$$

where $\mathbf{x}$ stands for the vector of gross output for each industry, and is equally provided in the Exiobase dataset, or alternatively, simply calculated as:

$$\mathbf{x} = \mathbf{Zi} + \mathbf{Yi}. \tag{C.8}$$

Then, we define the $\mathbf{e_0}$ vector as the final energy extension vector for which all values corresponding to a fossil fuel energy industry have been set to zero — the reason is that direct energy inputs of the energy industry have already been quantified in the main chapter using the PSUT approach.

[1] To do so, we take the total net energy vector "TOTAL", and subtract the losses vector "LOSS" as well as the non-energy uses "NENE" vector.

Final energy consumption footprints The database also contains the transaction matrix $\mathbf{Z}$ and the direct requirements matrix $\mathbf{A}$, which is calculated as

$$\mathbf{A} = \mathbf{Z}\widehat{\mathbf{x}}^{-1}. \tag{C.9}$$

From these matrices, the final energy consumption footprint matrix $\mathbf{F}$ can be determined as:

$$\mathbf{F} = \widehat{\mathbf{e_0}}(\mathbf{I} - \mathbf{A})^{-1}\widehat{\mathbf{y}}, \tag{C.10}$$

where $\mathbf{y}$ stands for the final demand vector (final demand matrix summed across final demand sectors, $\mathbf{y} = \mathbf{Yi}$). Each coefficient $f_{k,l}$ represents the final energy consumption by industry k to satisfy final demand for the output of industry l. (Note that Exiobase is a multi-regional dataset, so that industries k and l are location specific).

Next, we introduce the $\mathbf{F_0}$ matrix, which represents the final energy consumption footprint excluding final energy flows that are part of the supply chain of any fossil fuel energy industry, and which is calculated as:

$$\mathbf{F_0} = \widehat{\mathbf{e_0}}(\mathbf{I} - \mathbf{A_0})^{-1}\widehat{\mathbf{y}}, \tag{C.11}$$

where $\mathbf{A_0}$ is the direct requirements matrix for which the requirements of all fossil fuel energy industries are set to zero. In other words, each coefficient $a_{k,l}$ is set to zero when l stands for a fossil fuel energy industry, disregarding the region of location. We also define for each fossil fuel energy industry j the matrix $\mathbf{F_j}$, which represents the final energy consumption excluding final energy flows which are part of the supply chain of the fossil fuel energy industry j, and which is defined as:

$$\mathbf{F_j} = \widehat{\mathbf{e_0}}(\mathbf{I} - \mathbf{A_j})^{-1}\widehat{\mathbf{y}}, \tag{C.12}$$

where $\mathbf{A_j}$ is the direct requirements matrix for which the requirements of the energy industry j are set to zero. In other words, each coefficient $a_{k,l}$ is set to zero when l stands for the energy industry j, disregarding the region of location. Last, we define the $\mathbf{F'_j}$ matrix, which represents the final energy consumption excluding final energy flows that are part of the supply chain of a fossil fuel energy industry different than j, and which is calculated as:

$$\mathbf{F'_j} = \widehat{\mathbf{e_0}}(\mathbf{I} - \mathbf{A'_j})^{-1}\widehat{\mathbf{y}}, \tag{C.13}$$

where $\mathbf{A'_j}$ is the direct requirements matrix for which the requirements of fossil fuel energy industries different from j are set to zero. In other words, each coefficient $a_{k,l}$ is set to zero when l stands for a fossil fuel energy industry different from j, disregarding the region of location.

Determination of indirect final energy consumed by each fossil fuel energy industry From the set of matrices defined, we can define the indirect final energy consumed by each fossil fuel energy industry j in two ways. First, we can define the matrix $\mathbf{E_j}$, which stands for the matrix of final energy flows that are part of the supply chain of industry j, as:

$$\mathbf{E_j} = \mathbf{F} - \mathbf{F_j}. \tag{C.14}$$

then, summing all coefficients of the $\mathbf{E_j}$ matrix will yield the total final energy consumption that is part of industry j supply chain, i.e. the indirect final energy consumption of industry j, independently of the region of location of industry j. Such value would slightly overestimate the indirect final energy of fossil fuel energy industries when aggregating by group (see Table C.2) as $\mathbf{E_j}$ also accounts for final energy flows that are part of other fossil fuel industries' supply chains, so that some final energy flows may be accounted for in different $\mathbf{E_j}$ matrices.

The second option, which removes double accounting issues, is to define the matrix $\mathbf{E'_j}$, which stands for the matrix of final energy flows which are part of the supply chain of the fossil fuel energy industry j, and of no other fossil fuel energy industry, as:

$$\mathbf{E'_j} = \mathbf{F'_j} - \mathbf{F_0}. \tag{C.15}$$

then, summing all coefficients of the $\mathbf{E'_j}$ matrix will yield the total final energy consumption that is only part of the supply chain of the fossil fuel industry j, independently of the region of location of industry j, and of no other fossil fuel industry. Conversely to the first approach, such value would slightly underestimate the indirect final energy of fossil fuel energy industries as flows that are part of more than a single fossil fuel energy industry's supply chain would not be accounted for in any $\mathbf{E}_\mathbf{j}'$ matrix. Our approach is therefore to conduct calculations with both the first and second method, which will provide a range with a low and high estimate of the fossil fuel industries indirect final energy requirements, and then to report the average of these values as indirect energy requirements. Section C.3.1 shows the sensibility of indirect energy requirements to the method used.

Aggregation of indirect final energy requirements by fossil fuel group Next, we aggregate the indirect final energy requirements by fossil fuel group, following the information given in Table C.2, which provides the fossil fuel groups that each fossil fuel industry contributes to manufacture.

Table C.2: Ascription of each fossil fuel industry to a fossil fuel group, at the final energy stage. Note that sector 23 is not ascribed to either oil or gas as it is hard to disentangle, but only to the aggregated "oil and gas" and "all fossil fuels" groups.

Sector	Coal	Oil	Natural gas	Oil and gas	All fossil fuels
Sector 20: Mining of coal and lignite, extraction of peat	✓				✓
Sector 21: Extraction of crude petroleum and services related		✓		✓	✓
Sector 22: Extraction of natural gas and services related			✓	✓	✓
Sector 23: Extraction, liquefaction, and regasification of other petroleum and gaseous materials				✓	✓
Sector 56: Manufacture of coke oven products	✓				✓
Sector 57: Petroleum refinery		✓		✓	✓
Sector 96: Production of electricity by coal	✓				✓
Sector 97: Production of electricity by gas			✓	✓	✓
Sector 101: Production of electricity by petroleum and other oil derivatives		✓		✓	✓
Sector 110: Manufacture of gas, distribution of gaseous fuels through mains			✓	✓	✓

Including indirect final energy requirements in the EROI calculation Next, we normalise the indirect final energy requirements for each fossil fuel group by unit of fossil fuel being produced. We determine the total output of each fossil fuel group using the IEA's WEEB, processed with the **IEATools** [4] and **ECC-Tools** [5] `R` packages, by adding all fossil fuel energy consumption flows, including electricity and heat from fossil fuel origin — calculation done with the **EROITools** package [7] (`calc_fec_from_ff_by_group` function). The ratio of indirect final energy requirements by final energy output $e_{\text{f,iE}}$ is then simply calculated, and the final stage EROI including indirect final energy requirements $\text{EROI}_{\text{f,iE}}$ for each fossil fuel group is determined as:

$$\text{EROI}_{\text{f,iE}} = (\text{EROI}_{\text{f,dE}}^{-1} + e_{\text{f,iE}})^{-1}, \tag{C.16}$$

where $\text{EROI}_{\text{f,dE}}$ refers to the final stage EROI including only direct energy requirements. To determine the indirect final energy requirements for delivering one unit of useful energy of each fossil fuel category $e_{\text{u,iE}}$, we use the average final-to-useful efficiency of each fossil fuel group as follows:

$$e_{\text{u,iE}} = \frac{e_{\text{f,iE}}}{\eta}, \tag{C.17}$$

and the useful stage EROI including indirect final energy requirements $\text{EROI}_{\text{u,iE}}$ is calculated as:

$$\text{EROI}_{\text{u,iE}} = (\text{EROI}_{\text{u,dE}}^{-1} + e_{\text{u,iE}})^{-1}, \tag{C.18}$$

where $\text{EROI}_{\text{u,dE}}$ stands for the useful stage EROI including only direct energy requirements. To include indirect final energy requirements at the useful stage by end-use category c (or final demand sector s), we proceed in the same way, but use the end-use c (or final demand sector s) specific final-to-useful efficiency η_c (or η_s) in Equation C.17.

Including indirect final energy requirements in the national EROI calculations We use the global indirect final energy requirements per unit of fossil fuel output, both at the final stage ($e_{\text{f,iE}}$) and at the useful stage ($e_{\text{u,iE}}$) as proxy for the indirect final energy requirements per fossil fuel output in each country. Hence, we calculate the national EROIs including indirect final energy requirements by replacing the global EROI with the national specific final and useful stage EROIs in Equations C.17 and C.18, while using the same value of respectively $e_{\text{f,iE}}$ and $e_{\text{u,iE}}$.

C.1.3 Determination of the final stage EROI equivalent of renewable energy systems

Manufacture of renewable energy systems using renewable energy

Using Equation 4.2, one can express the net useful energy output for one unit of final energy input, for any energy system, as:

$$\begin{aligned} e_{\mathrm{u}} &= \mathrm{EROI}_{\mathrm{u}} - \frac{\mathrm{E}_{\mathrm{u,input}}}{\mathrm{E}_{\mathrm{f,input}}} \\ &= \mathrm{EROI}_{\mathrm{u}} - \eta_{\mathrm{m}}, \end{aligned} \tag{C.19}$$

where η_{m} stands for the final-to-useful efficiency of the manufacturing process, which we take equal to the average final-to-useful efficiency of the energy carriers delivered by the considered energy system (i.e. electricity for renewable energy technologies, and average fossil fuel efficiencies — calculated using the weighted shares of use of each energy product in each fossil fuel group). Such approach for the definition of η_{m} allows us to estimate the fraction of useful energy output that ought to be redirected to the energy sector, should the considered energy system be self-sufficient. Then, Equation C.19 yields directly Equations 4.6 and 4.7.

Equation C.19 can be adapted to determine the net useful energy output obtained for one unit of final energy input, for any energy system, when the energy output is used in a particular end-use c as:

$$e_{\mathrm{u}} = \mathrm{EROI}_{\mathrm{u},c} - \eta_{\mathrm{m}}, \tag{C.20}$$

which directly yields Equation 4.9.

Alternative assumption: manufacture of renewable energy systems dependent on fossil fuel energy

Alternatively, one can assume that renewable energy technologies currently need to be manufactured dominantly with fossil fuel energy, so that the net useful energy $e_{\mathrm{u,ret}}$ delivered by investing one unit of energy in a renewable energy technology becomes:

$$\begin{aligned} e_{\mathrm{u,ret}} &= \mathrm{EROI}_{\mathrm{u,ret}} - \eta_{\mathrm{ff}} \\ &= \mathrm{EROI}_{\mathrm{f,ret}}.\eta_{\mathrm{elec}} - \eta_{\mathrm{ff}}, \end{aligned} \tag{C.21}$$

which replaces Equation 4.6. Then, finding the value of $\text{EROI}_{\text{f,ret}}$ for which the variation in net useful energy Δe_{u} resulting from investing one unit of energy in a renewable energy technology instead of in fossil fuel energy is null leads to the following expression of EROI equivalent:

$$\text{EROI}_{\text{f,eq}} = \frac{\text{EROI}_{\text{u,ff}}}{\eta_{\text{elec}}}, \tag{C.22}$$

which can be adapted for each end-use category as:

$$\text{EROI}_{\text{f},c,\text{eq}} = \frac{\text{EROI}_{\text{u},c,\text{ff}}}{\eta_{c,\text{elec}}}. \tag{C.23}$$

Determining the average final-to-useful efficiencies of substituting fossil fuels

In the global primary-final-useful database [11], end-use machines (e.g., car engines, light bulbs, etc.) convert final energy carriers into a end-use energy product (for instance, propulsion, low temperature heat, etc.). For each machine, we assume an alternative substituting machine, which corresponds to the machine that would currently be used for substituting fossil fuels. For instance, a Internal Combustion Engine would be replaced by an electric car, a gas boiler by an electric heater, etc. We avoid making scenarios of future uptake of technologies, and use instead the "current natural" replacement of each machine — so for instance, we do not include heat pumps as replacement machine, because their deployment is currently marginal at the global level. (See the repository associated with the chapter in Data Statement for a table of machines alongside the assumed substituting machine.)

Then, we determine the proportion of each energy product used by each machine, in each country (and in each end-use for end-use specific calculations). We then apply the efficiency of the alternative, substituting machine in each country to determine the average final-to-useful efficiency with which each fossil fuel-based product would currently be substituted, in each country (and in each end-use for end-use specific calculations). Then, we determine the weighted average final-to-useful efficiencies of substitution by fossil fuel group using the use shares of each product in each product group (either within each country or at the global level). Table C.3 shows the average final-to-useful efficiencies of substituting each fossil fuel at the global level in 2019, both at the economy-wide level (η_{elec}) and by end-use category ($\eta_{\text{c,elec}}$).

Table C.3: Final-to-useful efficiencies of substituting each fossil fuel determined at the global level, for each end-use category, in 2019. Values for fossil fuels include fossil fuel-based electricity and heat. LTH: Low Temperature Heating. MTH: Medium Temperature Heating. HTH: High Temperature Heating. RaP: Rail Propulsion. RoP: Road Propulsion. MW: Mechanical Work.

Product group	Economy-wide	LTH	MTH	HTH	RaP	RoP	MW
All fossil fuel products	0.78	1	0.82	0.47	0.79	0.74	0.82
Oil products	0.69	1	0.78	0.59	0.79	0.74	0.70
Gas	0.90	1	0.84	0.56	0.79	0.74	0.56
Coal products	0.80	1	0.80	0.40	0.79	0.74	0.45
Oil and gas products	0.77	1	0.83	0.57	0.79	0.74	0.66

Average fossil fuels final-to-useful efficiencies

Table C.4 shows the average final-to-useful efficiencies determined at the global level in 2019 for each fossil fuel group, at the economy-wide level and by end-use category. To represent the fact that all fossil fuels are used in the energy sector, we use the economy-wide value of η_{ff} determined for fossil fuels on average (so, "All fossil fuel products" row in Table C.4) in the EROI equivalent calculations (Equations 4.8 and 4.9 in main chapter).

Table C.4: Final-to-useful efficiencies determined at the global level, for each fossil fuel, for each end-use category, in 2019. Values for fossil fuels include fossil fuel-based electricity and heat. LTH: Low Temperature Heating. MTH: Medium Temperature Heating. HTH: High Temperature Heating. RaP: Rail Propulsion. RoP: Road Propulsion. MW: Mechanical Work.

Product group	Economy-wide	LTH	MTH	HTH	RaP	RoP	MW
All fossil fuel products	0.59	0.88	0.76	0.47	0.50	0.23	0.42
Oil products	0.35	0.71	0.64	0.59	0.38	0.23	0.37
Gas	0.82	0.95	0.77	0.56	0.79	0.24	0.49
Coal products	0.79	0.78	0.80	0.40	0.72	0.74	0.49
Oil and gas products	0.53	0.90	0.74	0.57	0.43	0.23	0.40

A few caveats on Table C.4 are worth noting. First, values include the use of fossil fuels used as electricity and heat. For instance the 0.79 average efficiency for coal products in the road transportation sector stands for the average final-to-useful efficiency of electricity in road transportation, because the only use of coal for road transportation is indirect, coal-based electricity.

Second, the ratio of useful to final stage EROIs reported in the main chapter will not yield the average final-to-useful efficiencies reported in Table C.4. The reason is that the useful stage (as well as final stage) EROIs are determined at the product level, and then aggregated by fossil fuel group using the use shares of each product within each fossil fuel group, and not by applying the fossil group specific final-to-useful efficiency to the aggregated fossil fuel group specific final stage EROI. Working at the product level and aggregating afterwards is more precise and is the correct approach.

Third, these values are the result of a weighted average across countries, and across products, depending on the use share of each product within each fossil fuel group and end-use, on the use share of each product by country. As a result, the values reported in the table are not particularly straightforward to interpret and may hide significant variability across countries and energy carriers.

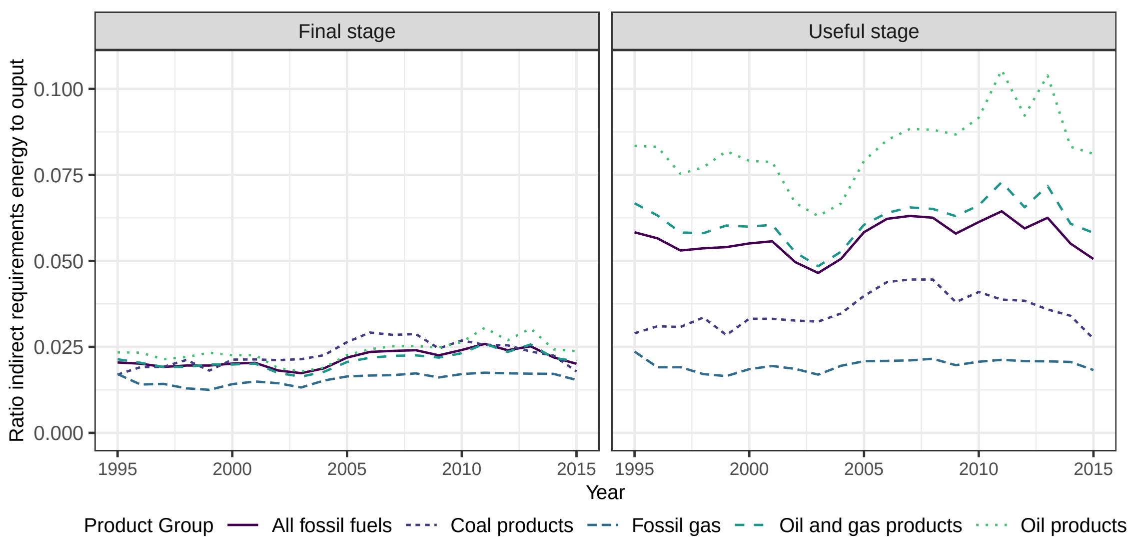
C.1.4 Adjustment of renewable energy EROIs reported in the literature

Values from Murphy et al. 2022 The EROI values reported in Murphy et al. [12] are measured in terms of primary energy equivalent output divided by primary energy inputs. To compare such values with the EROI equivalent values we determine and to use them in Equations C.33 and C.34, we need to transform the EROIs in terms of final energy output over final energy inputs. To do so, we use the values reported by Murphy et al. [12] when using $\eta_{\text{grid}} = 0.3$, so we multiply the numerator by 0.3, and the denominator by the average final-to-primary energy ratio obtained by the IEA, i.e. 0.68. Summarising, the EROI values reported with $\eta_{\text{grid}} = 0.3$ are multiplied by the ratio 0.3/0.68.

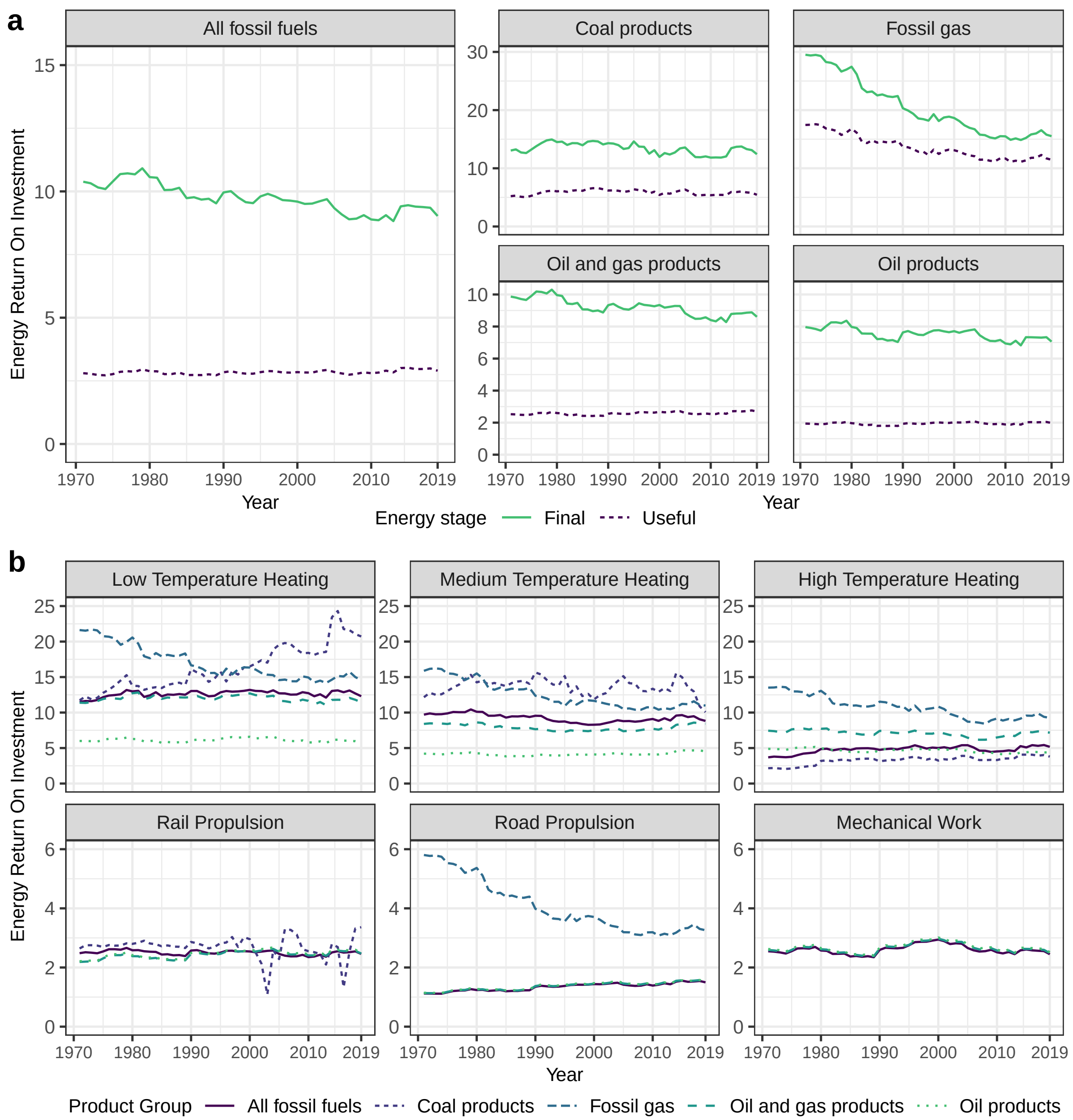
Last, we need to downscale the numerator to account for losses in grid (losses are modelled in the rest of our calculations, so for consistency losses should be added here too). We determine losses to be approximately 7.6% of electricity output based on the IEA's WEEB, so we multiply the EROI value by 0.924 to account for electricity losses in the grid.

Values from de Castro and Capellán-Pérez 2020 We add to the EROI values of renewable energy technologies the values reported by de Castro and Capellán-Pérez [13] (at the point-of-use) as these are rather on the lower end of EROI values. We adjust the values reported to (i) subtract the energy requirements for grids from the denominator, and (ii) account for electricity self-consumption of plants as a decrease in the energy output rather as an increase in the energy inputs — such adjustments could be done as the authors agreed to share their detailed calculations. Last, we use the same losses factor as the one used for the values reported by Murphy et al. [12].

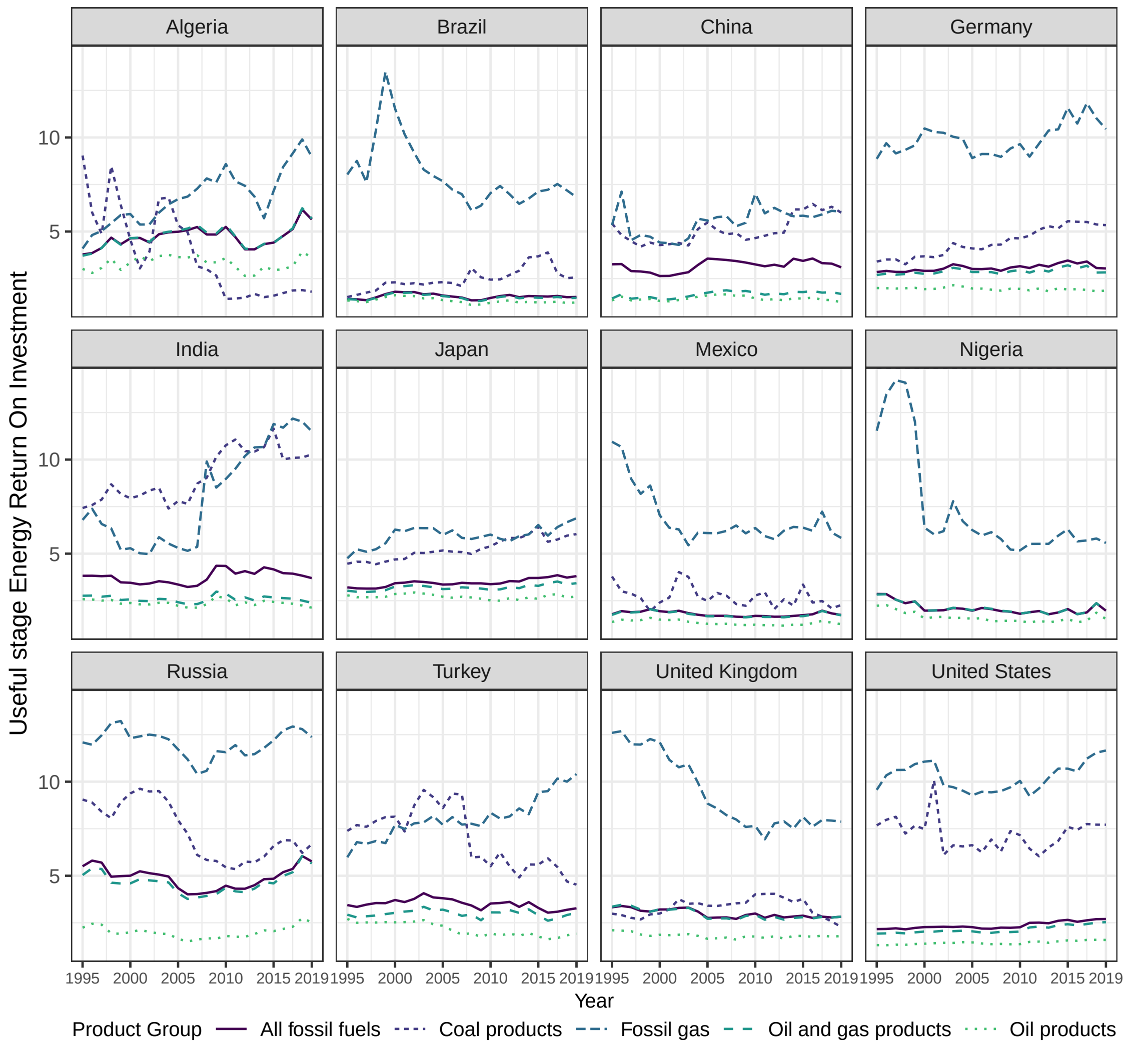
C.2 Extended Data Displays



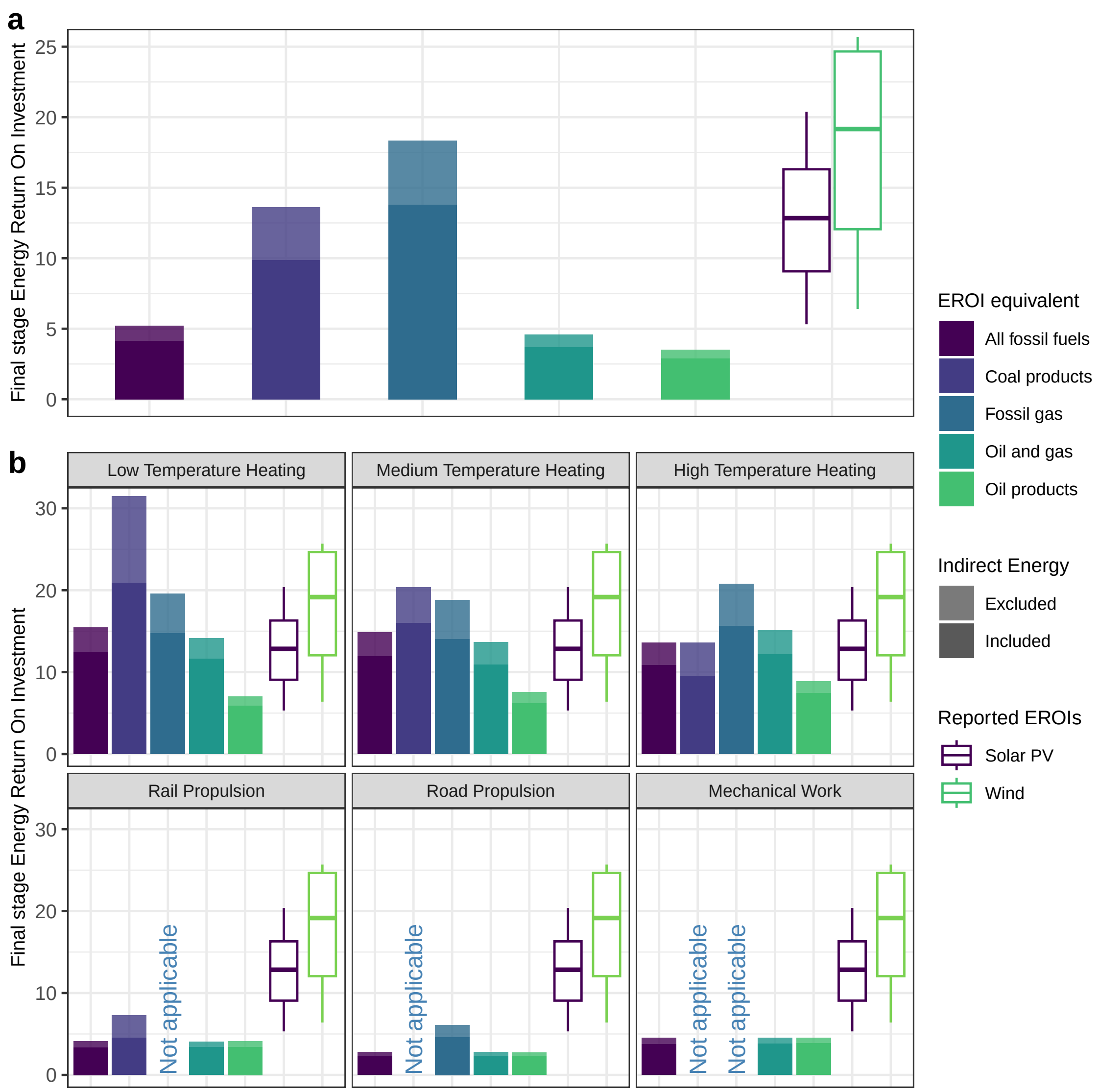
Extended Data Figure C.1: Ratio of indirect energy requirements to energy output at the global level, both at the final and useful energy stages, for each product group.



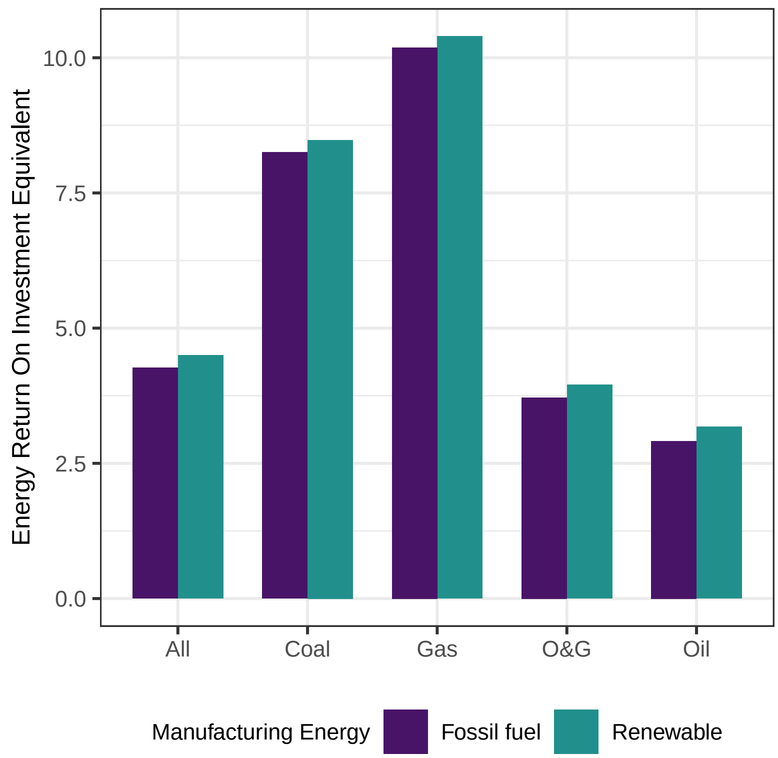
Extended Data Figure C.2: **a**, Final and useful stage average Energy Return On Investment (EROI) for the five fossil fuel groups, at the global level. **b**, Useful stage EROIs by end-use category for the five fossil fuel groups, at the global level. Calculations considering only fossil fuels used as fuels.



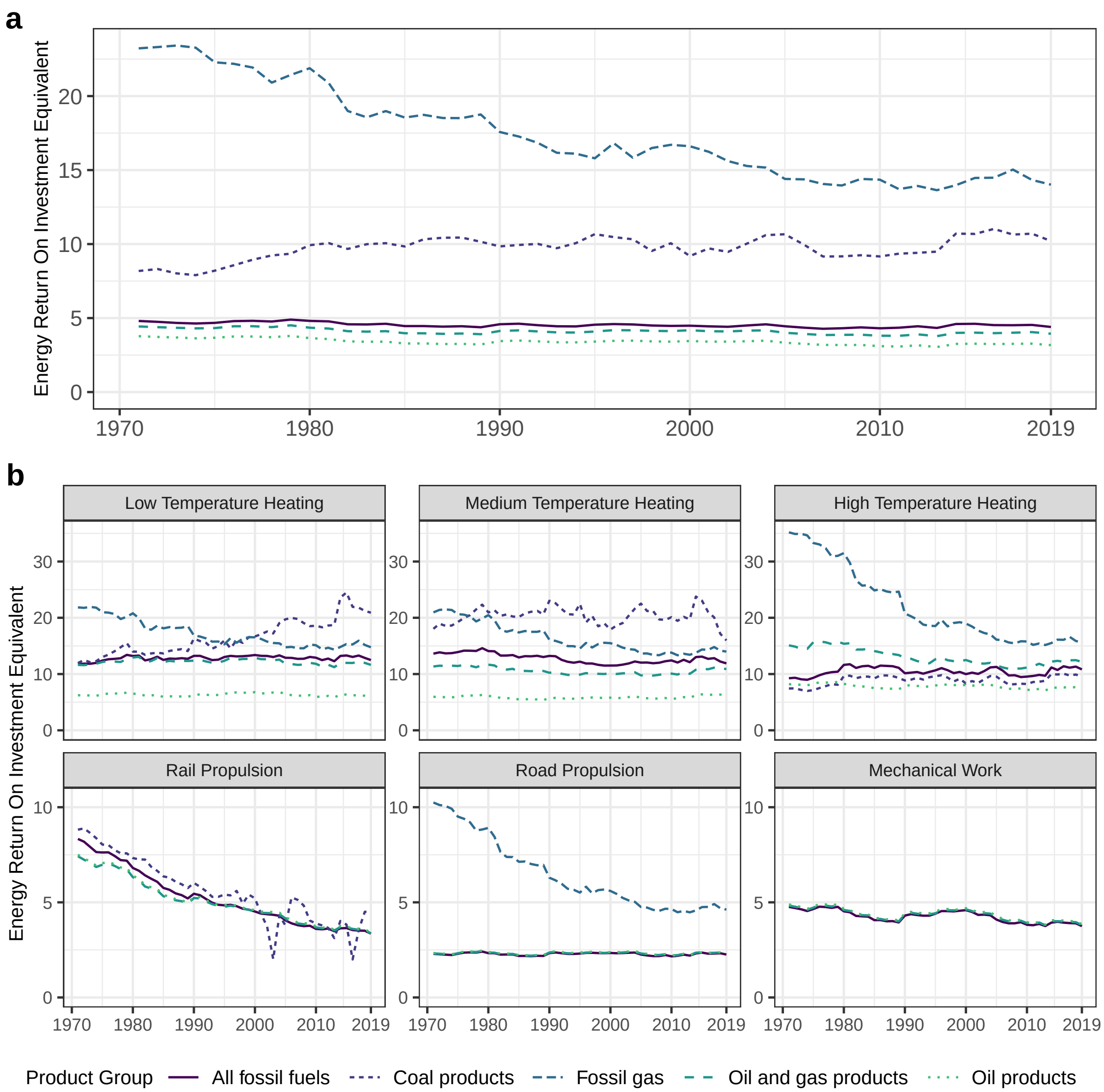
Extended Data Figure C.3: Useful stage average Energy Return On Investment (EROI) for a selection of countries, for the five fossil fuel groups over time. Calculations considering fossil fuels used as fuels, electricity, and heat.



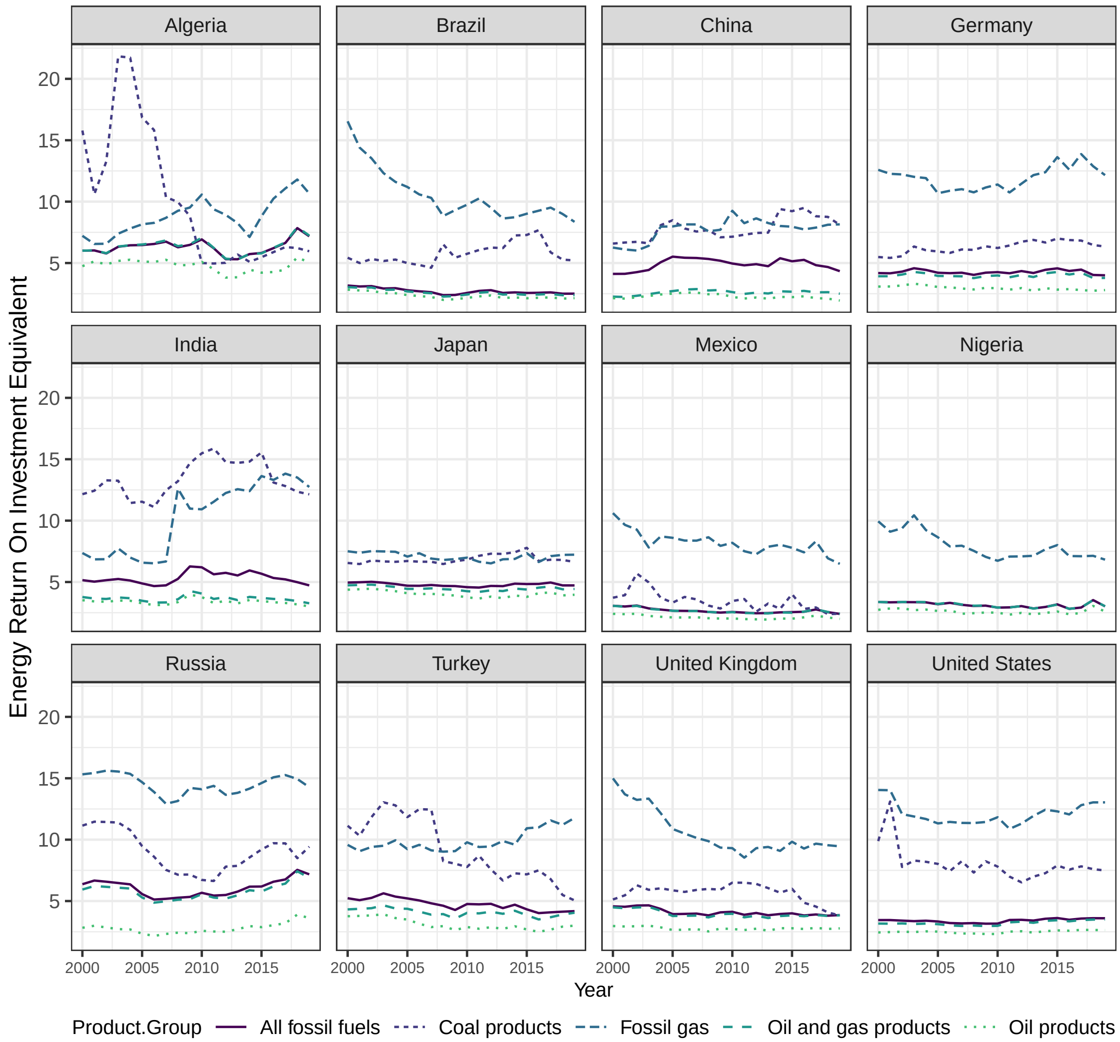
Extended Data Figure C.4: Final stage Energy Return On Investment (EROI) equivalent calculated for 2019 at the global level alongside actual EROIs of renewable energy systems reported in the literature, **a,** economy-wide, and **b,** by end-use category. Values calculated for fossil fuels used as fuels only.



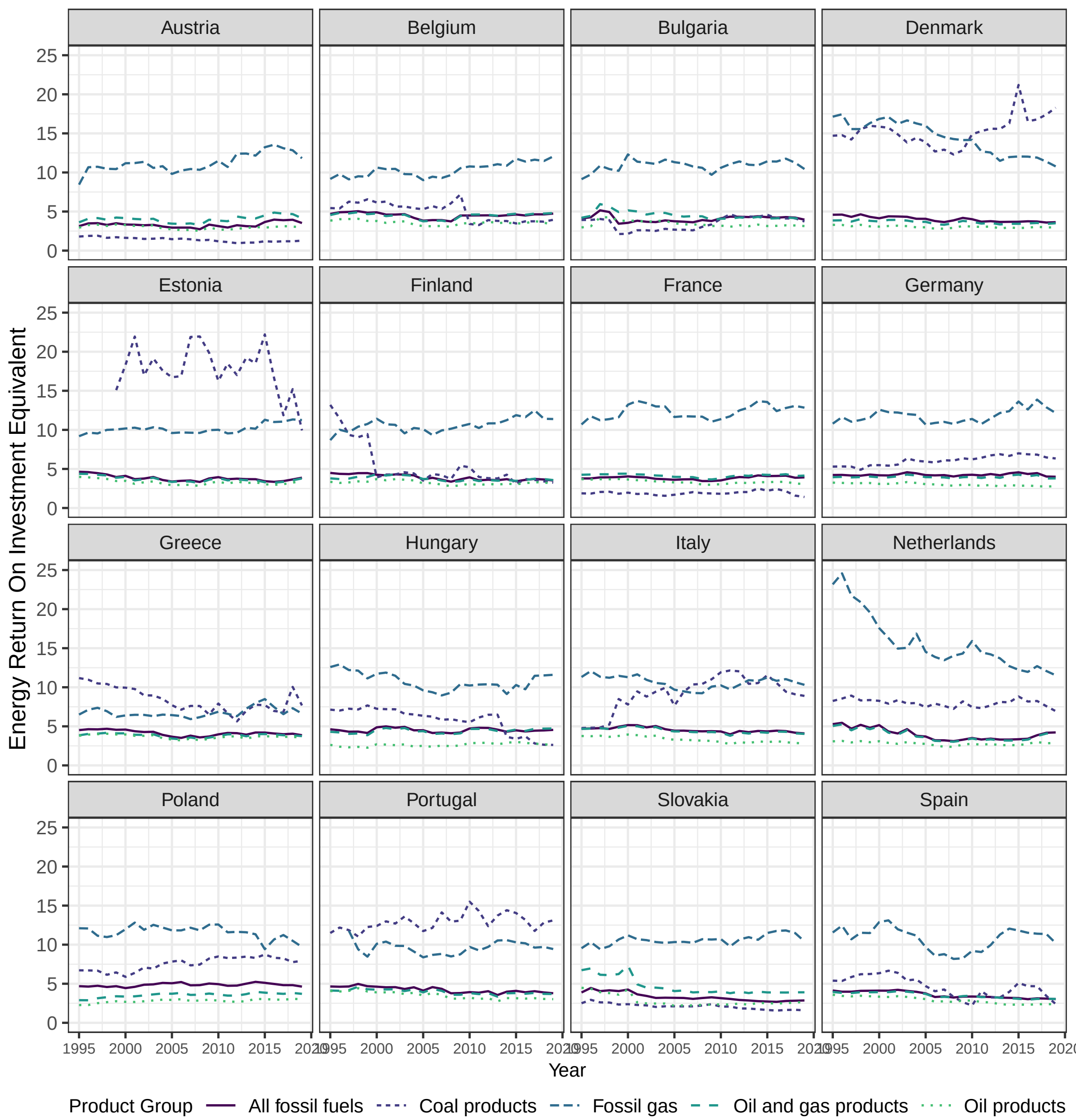
Extended Data Figure C.5: Variation in the final stage EROI equivalent when using the renewable-based manufacturing — Equation 4.6 — versus the fossil fuel-based manufacturing — Equation C.22. Values calculated for 2019 at the global level, for fossil fuels used as fuels, electricity, and heat.



Extended Data Figure C.6: Final stage Energy Return On Investment equivalent of renewable energy systems over time at the global level, **a,** economy-wide, and **b,** by end-use. Values calculated for fossil fuels used as fuels only.



Extended Data Figure C.7: Final stage Energy Return On Investment equivalent of renewable energy systems for a selection of countries over time. Values calculated for fossil fuels used as fuels, electricity, and heat.



Extended Data Figure C.8: Final stage Energy Return On Investment equivalent of renewable energy systems for a selection of EU countries over time. Values calculated for fossil fuels used as fuels, electricity, and heat.

C.3 Additional results and discussion

C.3.1 Sensitivity of indirect energy requirements quantification method

Figure C.9 shows the change in breakdown of energy requirements in terms of direct and indirect energy requirements when using either the underestimation or overestimation method for quantifying indirect energy requirements (results in the main chapter are calculated as the average as the two methods).

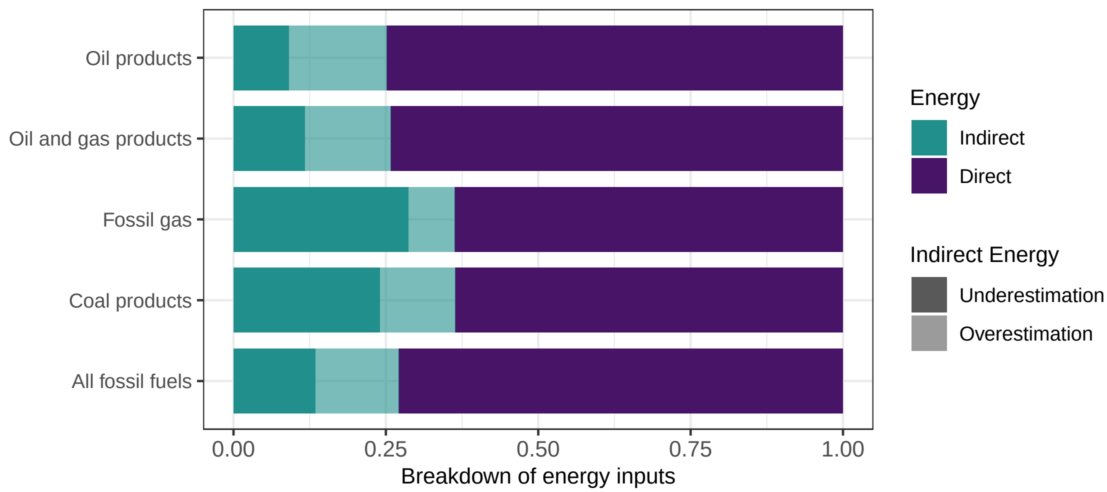


Figure C.9: Breakdown of energy requirements in terms of direct and indirect energy requirements (average 2000–2015) at the global level, with both the underestimation and overestimation of indirect energy requirements. With the underestimation method, the portion referred to as *overestimation* should be regarded as direct energy requirements.

There are significant differences in terms of indirect energy requirements between the two methods, but as shown as Figure 4.4, the quantifying of indirect energy requirements does not change findings as the EROI equivalent of renewable energy systems remains low even when indirect energy requirements are excluded from calculations.

C.3.2 Heat pump scenario

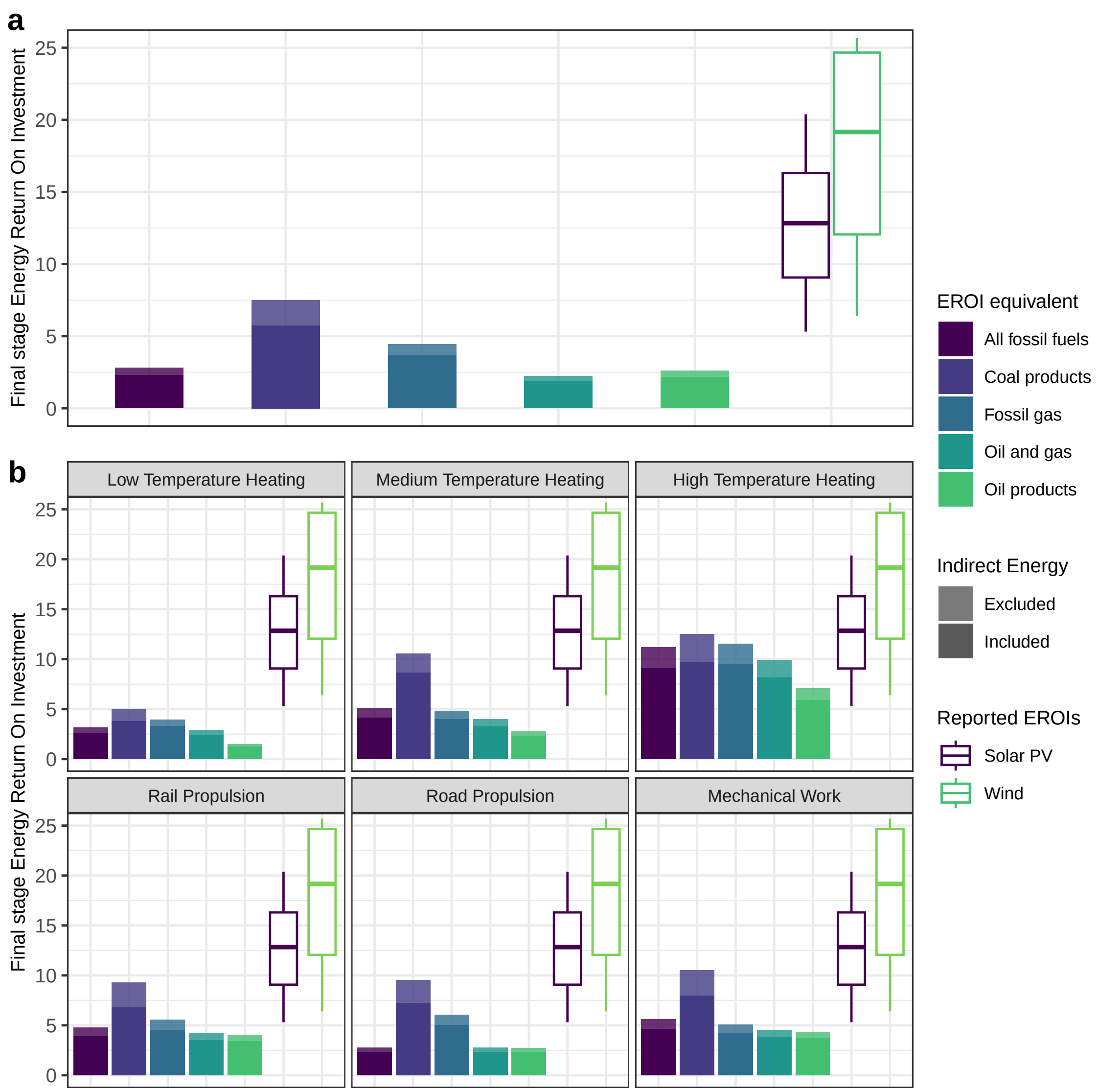


Figure C.10: Final stage Energy Return On Investment (EROI) equivalent calculated for 2019 at the global level under the assumption that heat pumps will substitute low and medium (up to 100°C) heating processes, except cooking. Renewable energy EROIs reported in the literature are displayed alongside. **a,** Economy-wide, and **b,** by end-use category. Values calculated for fossil fuels used as fuels, electricity, and heat.

Figure C.10 shows the EROI equivalent for renewable energy systems under the alternative assumption that heat pumps will replace low and medium temperature (up to 100°C) heating processes, except cooking. (See Data Statement for more details on the assumption.) Under such an assumption, the EROI equivalent values drop to 2.3 for fossil fuels on average, to 5.7 for coal products, 3.7 for fossil gas, 2.2 for oil products, and 1.8 for oil and gas products. So, to substitute on average fossil fuels without decline in the net useful energy delivered, renewable energy systems would only need a final stage EROI of 2.3, provided that the low and medium temperature heating processes from which fossil fuels are phased out are delivered by heat pumps.

C.3.3 Quantification of useful stage and EROI equivalent by final demand sector

Methodology

Similarly to end-use specific calculations, final demand sector specific useful stage EROIs are determined for each energy product p, and for each final demand sector s, as:

$$\mathrm{EROI}_{u,p,s} = \eta_{p,s}.\mathrm{EROI}_f, \tag{C.24}$$

both at the national and global levels. To determine the average sectoral final-to-useful efficiencies, for each product, in each country, we need to introduce the inputs shares matrix $\tilde{\mathbf{C}}^*$ and the market shares matrix $\tilde{\mathbf{D}}$ (see [2]), defined following Equations C.25 and C.26:

$$\tilde{\mathbf{C}}^* = \tilde{\mathbf{U}}\widehat{\mathbf{f}'}^{-1}, \tag{C.25}$$

$$\tilde{\mathbf{D}} = \tilde{\mathbf{V}}\widehat{\mathbf{q}'}^{-1}, \tag{C.26}$$

so that $\tilde{c}^*_{k,l}$ stands for the fraction of product k in industry l inputs, and $\tilde{d}_{k,l}$ stands for the share of product l supplied by industry k. From these matrices, we define the three dimensions tensor $\mathbf{T}$ as:

$$\mathbf{T} = \tilde{\mathbf{C}}^* \otimes (\widehat{\mathbf{n}}^{-1}\tilde{\mathbf{D}}\tilde{\mathbf{Y}}), \tag{C.27}$$

where $\otimes$ defines the outer product of two matrices, and $\mathbf{n}$ refers to the vector of end-use conversion devices final-to-primary energy efficiencies. In other words, if we define the matrix $\mathbf{M}$ as:

$$\mathbf{M} = \widehat{\mathbf{n}}^{-1}\tilde{\mathbf{D}}\tilde{\mathbf{Y}}, \tag{C.28}$$

then the coefficient $t_{p,i,s}$ of the tensor $\mathbf{T}$ is calculated as:

$$t_{p,i,s} = \tilde{c}^{*}_{p,i} m_{i,s}, \tag{C.29}$$

and stands for the inputs of product p to industry i required to fulfil the final demand of sector s. From the tensor $\mathbf{T}$, we can then determine the share of product p used in each industry i to fulfil a given final demand sector s as:

$$s_{p,i,s} = \frac{t_{p,i,s}}{\sum\limits_{i \in \mathcal{I}} t_{p,i,s}}, \tag{C.30}$$

where $\mathcal{I}$ refers to the set of end-use conversion devices. Then, the average final-to-useful efficiency of a product p used in a given final demand sector s can be determined, for each country, as:

$$\eta_{p,s} = \sum_{i \in \mathcal{I}} s_{p,i,s} n_i. \tag{C.31}$$

We determine the global average final-to-useful efficiency by weighting the country-level sectoral efficiencies according to each country's share of global product use within each final demand sector, which we determine using the IEA's WEEB.

Last, we can adapt Equation 4.9 to obtain the final stage EROI equivalent of renewable energy systems to allow for the substitution of fossil fuel to happen without decrease in the net useful energy available in each final demand sector s:

$$\text{EROI}_{\text{f},s,\text{ret}} = \frac{\text{EROI}_{\text{u},s,\text{ff}} - \eta_{\text{ff}} + \eta_{\text{elec}}}{\eta_{s,\text{elec}}}. \tag{C.32}$$

Example: iron and steel and road transportation sectors

Figure C.11 shows the useful stage EROIs (**a**) and the EROI equivalent of renewable energy systems (**b**) for the iron and steel and road transportation sectors as examples.

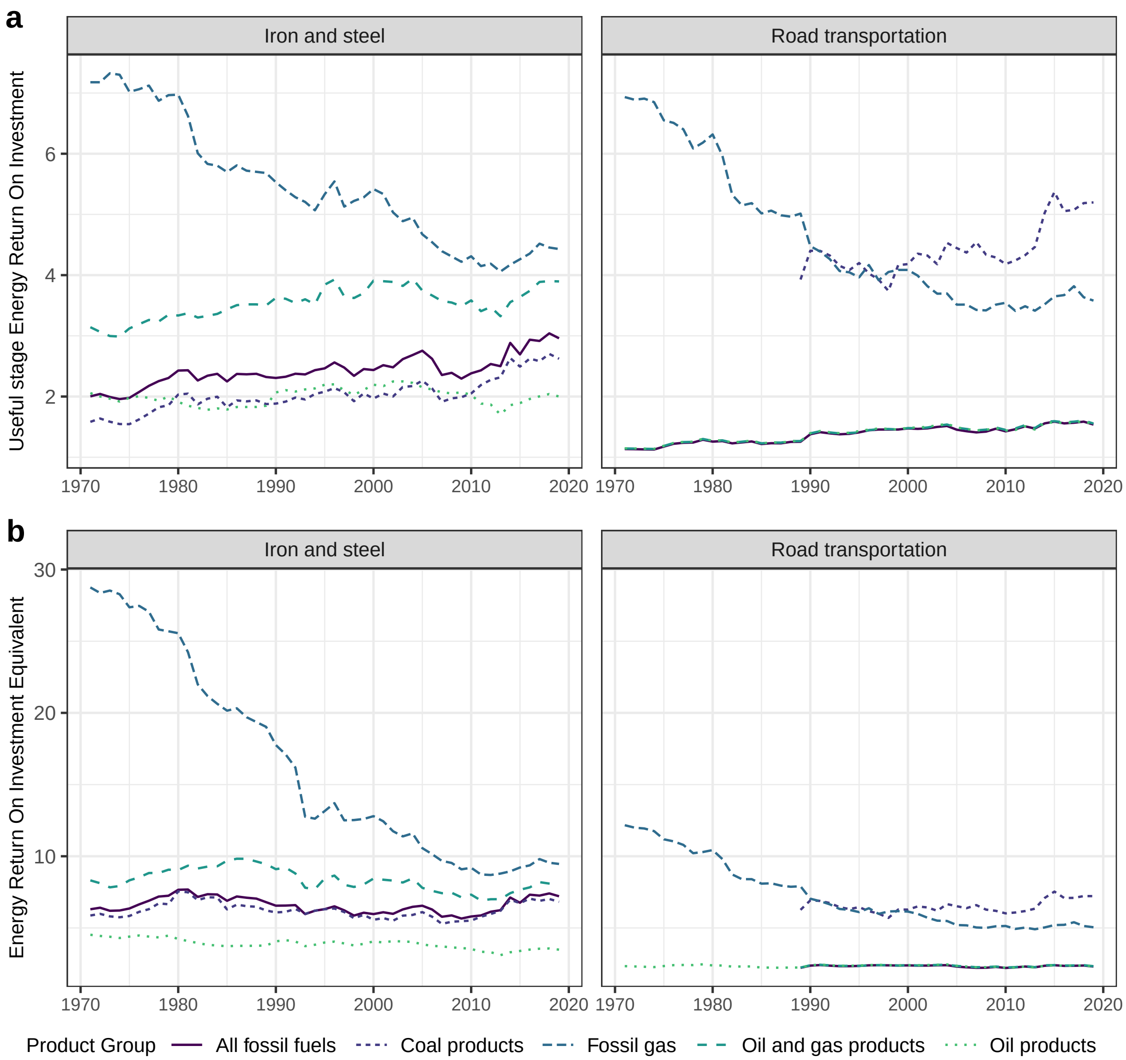


Figure C.11: **a,** Useful stage Energy Return On Investment (EROI), and **b,** EROI equivalent of renewable energy systems Energy Return On Investment, for the iron and steel and road transportation final demand sector, at the global level.

Values are calculated for fossil fuels used as either fuels, electricity, or heat, so that "Coal products" in the road transportation sector refer to coal-based electricity used in electric vehicles.

C.3.4 Quantification of the variation in net useful energy delivered as result of the energy transition

In addition, the EROI values of renewable energy technologies reported in the literature allow us to estimate, for each reported value, the net useful energy implications of substituting fossil fuels by renewable energy technologies. Indeed, using Equations 4.6 and 4.7, one obtains Δe_{u}:

$$\Delta e_{\mathrm{u}} = (\mathrm{EROI}_{\mathrm{f,ret}}.\eta_{\mathrm{elec}} - \eta_{\mathrm{elec}}) - (\mathrm{EROI}_{\mathrm{u,ff}} - \eta_{\mathrm{ff}}), \tag{C.33}$$

where the $\mathrm{EROI}_{\mathrm{f,ret}}$ is taken from the literature. Likewise, the analysis can be conducted at the end-use specific level, with the new expression of the end-use specific $\Delta e_{\mathrm{u},c}$ becoming:

$$\Delta e_{\mathrm{u},c} = (\mathrm{EROI}_{\mathrm{f,ret}}.\eta_{c,\mathrm{elec}} - \eta_{\mathrm{elec}}) - (\mathrm{EROI}_{\mathrm{u},c,\mathrm{ff}} - \eta_{\mathrm{ff}}). \tag{C.34}$$

Figure C.12 shows a boxplot of the variation in the net useful energy delivered to society that can be expected when investing one unit of energy in renewable energy technologies instead of fossil fuel energy according to the EROIs of renewable energy technologies found in the literature, without breakdown (**a**) and with breakdown by end-use (**b**).

Figure C.12.**a** shows most reported EROIs for renewable energy technologies would lead to an increase in the net useful energy delivered to society, and in quite some cases to very significant increases. Particularly, in the case of oil products, results show that even the lowest EROI values obtained from the literature would lead to almost a fivefold increase in the net useful energy delivered to society. The results are however highly dependent on the end-use of substitution as shown by Figure C.12.**b**. The net useful energy impacts of substituting fossil fuels in heating end-uses seems highly uncertain given the range of EROIs reported in the literature for renewable energy technologies, but it seems that a decrease in the net useful energy can be expected, particularly when substituting fossil gas. Conversely, when substituting fossil fuels used for mechanical work or propulsion, significant net useful energy gains can be expected.

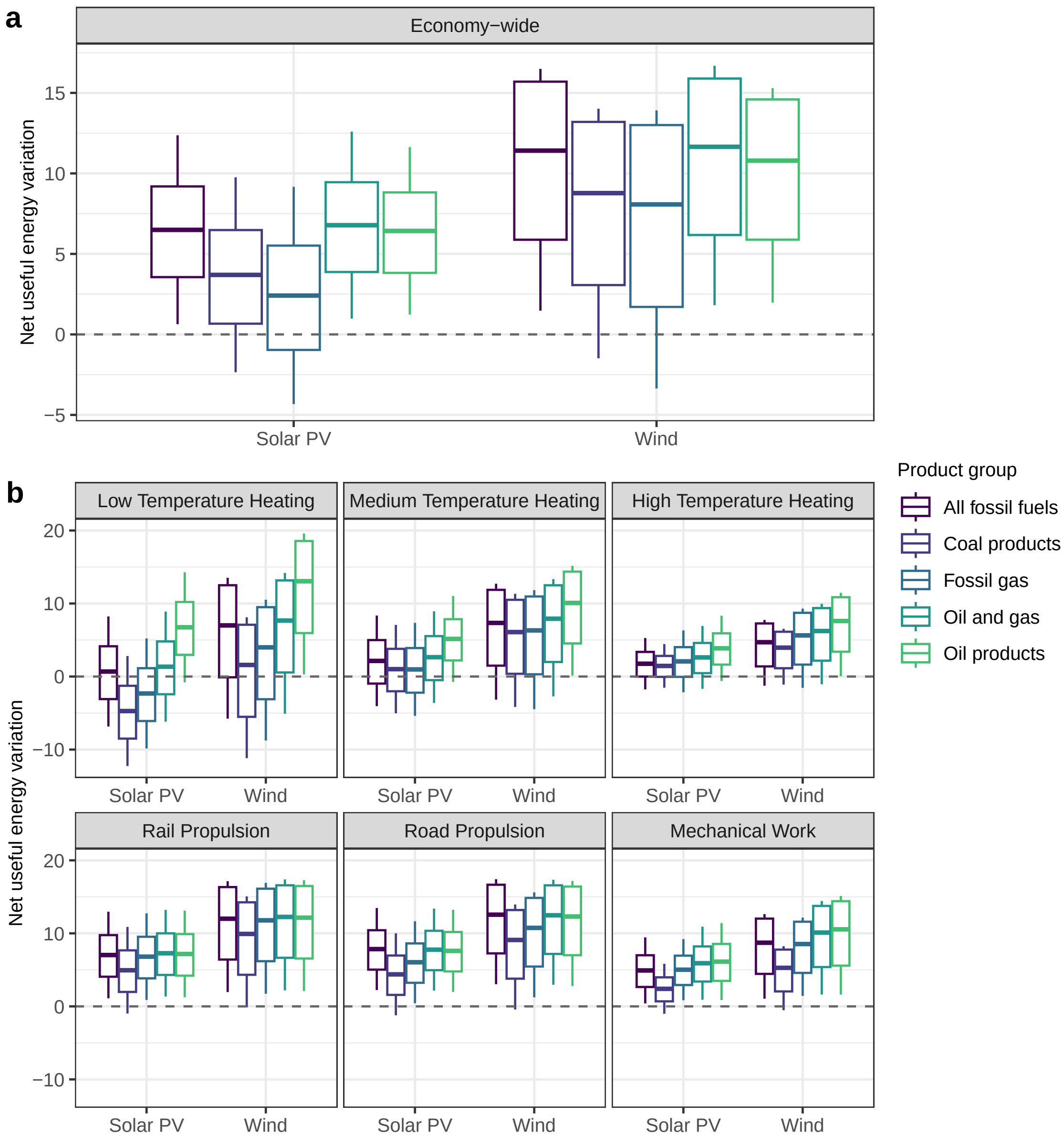


Figure C.12: Boxplot of the net useful energy variation that can be expected when investing one unit of energy in renewable energy systems instead of fossil fuels at the global level, **a,** economy-wide, and **b,** by end-use.

C.3.5 Quantification of the potential final energy savings as result of the energy transition

By noting that $e_{\text{u,ret}}$ (Equation 4.6) and $e_{\text{u,ff}}$ (Equation 4.7) stand for the net useful energy made available when investing one unit of final energy in respectively renewable energy systems and fossil fuels, one can determine the multiple of final energy α that would be required to deliver the same level of net useful energy when investing in renewable energy systems instead of fossil fuels by solving Equation C.35:

$$\alpha . e_{\text{u,ret}} = e_{\text{u,ff}}. \tag{C.35}$$

The corresponding value of α can then be determined at the economy-wide level as:

$$\alpha = \frac{\text{EROI}_{\text{u,ff}} - \eta_{\text{ff}}}{\text{EROI}_{\text{f,ret}} \eta_{\text{elec}} - \eta_{\text{elec}}}, \tag{C.36}$$

or alternatively, by end-use, as:

$$\alpha_c = \frac{\text{EROI}_{\text{u},c,\text{ff}} - \eta_{\text{ff}}}{\text{EROI}_{\text{f,ret}} \eta_{c,\text{elec}} - \eta_{\text{elec}}}. \tag{C.37}$$

The share of potential final energy savings, which can be interpreted as the share of final energy that can be saved while still delivering the same quantity of net useful energy, can then be determined as $1 - \alpha$. Figure C.13 shows the potential final energy savings obtained from the useful stage EROIs and final-to-useful efficiencies quantified in Chapter 4 and from the final stage EROI values of renewable energy systems obtained from the literature.

The figure shows that significant final energy savings may be achieved, although values are highly dependent on the fossil fuel and end-use considered. A value between 0 and 1 indicated the share of final energy that can be saved, a value of 0 indicates that the same amount of final energy would be required, and a negative value indicates that an increase in final energy would be required to deliver the same amount of net useful energy. At the economy-wide level, the potential final energy savings are quantified above 50% of final energy consumption for most of the renewable energy EROIs reported in the literature.

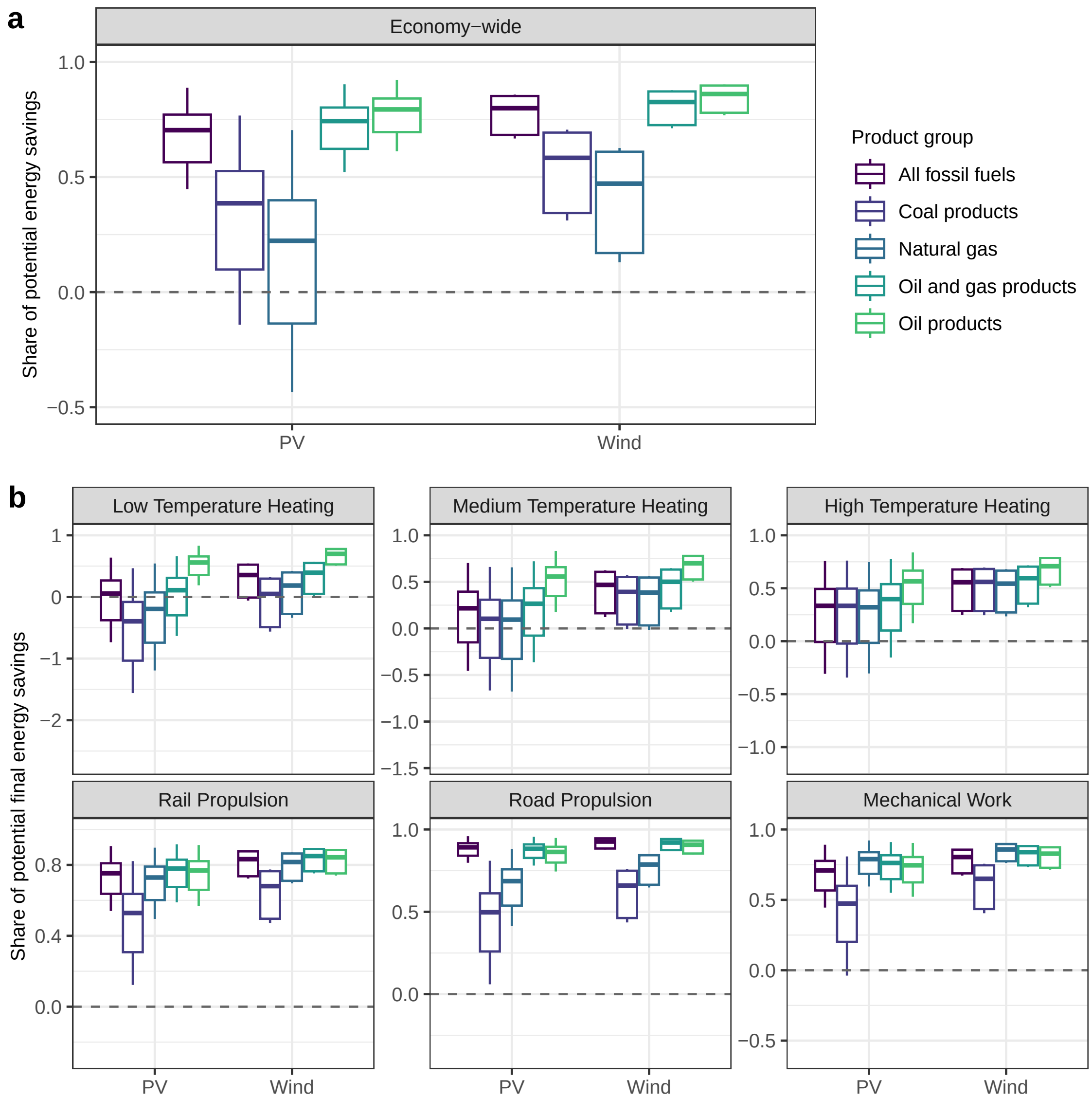


Figure C.13: Boxplot of the potential final energy savings that can be expected when investing one unit of energy in renewable energy systems instead of fossil fuels at the global level, **a,** economy-wide, and **b,** by end-use.

C.3.6 Comparison of final stage EROIs with Brockway et al. 2019

There are several methodological differences with the estimation of EROIs and energy requirements conducted by Brockway et al. [10]. First , regarding the EROI values, the final stage EROI values reported by Brockway et al. are net EROI values, so that they are one unit lower than the final stage EROI values we report (gross values) — however this is only a difference in the way results are reported. Next, we discuss differences in the way direct and indirect energy requirements are defined and calculated — note that most of these contribute to the fact that EROIs found by Brockway et al. are lower than the ones we estimate.

Direct energy requirements. Despite the obvious methodological difference of this study using the MR-PSUT framework while the work by Brockway et al. directly computed flows summing across IEA data, additional differences can be highlighted on how direct energy use flows were defined. The first difference is related to the definition of final energy flows that are included as final energy inputs to the fossil fuel industry. "Losses" flows were included in the calculation of direct energy requirements by Brockway et al., while they were modelled as decreasing the final energy output in our study. Next, the "Own use in electricity, combined heat and power plants, and heat plants" was ascribed to the fossil fuel industry in the study by Brockway et al., while in our study, it is ascribed to different fuels according to the input shares of each fuel type (although this should only make a minor difference as most inputs are fossil fuels).

Last, final energy flows used by the fossil fuel industry were fully considered as final energy requirements to produce fossil fuels in the work by Brockway et al., disregarding the fact that the output of these industries are also somewhat used as non-energy products, the implicit assumption being that fossil fuels production should bear the burden of energy use for non-energy products. Conversely, our approach, by quantifying the energy requirements by unit of energy output, ascribes (proportionally to the output) some of the energy inputs to the manufacture of non-energy products.

Indirect energy requirements. Regarding indirect energy requirements, the algebra used in Brockway et al. [10] is slightly different from the one we use, as they estimated indirect energy requirements for fossil fuels as a whole, while our study estimated indirect energy requirements for each fossil fuel industry represented in Exiobase, so that such requirements can be added up by fossil fuel group. The difference in the algebra used should however not be responsible for a major difference in the quantification of indirect energy requirements.

However important differences should be expected from differences in the energy extension vector used in both studies. Brockway et al. use a primary energy extraction vector, and hence quantify the primary energy extraction associated with the fossil fuel industry. This leads to two issues; first, the indirect energy requirements they determine is expressed in terms of primary energy instead of final energy, which leads to slightly overestimated value, as some primary energy extracted does not end up being used as final energy (indeed, some — approximately 10% — is used as non-energy products, and some is lost as transformed in the energy conversion chain). Second, by using a primary extraction vector that includes all fossil fuel extraction extracted, all energy requirements are implicitly ascribed to industries, and none to final demand. However, a significant share of fossil fuels are directly consumed as final consumption, for instance for heating, transportation, or cooking, by e.g. households, or the public sector. For instance, data from the IEA's WEEB point to approximately 36% of fossil fuels being used directly in road transportation (some of which is commercial transportation), and 13% in residential uses in 2019. Hence indirect energy requirements are overestimated in Brockway et al. [10] by overlooking the fact that some primary energy extracted is not eventually consumed by industries, but instead, as final consumption. Conversely, our approach uses Exiobase's [8] final energy extension vector, which was constructed accounting for the fact that some final energy flows are directly used as final demand [14].

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Appendix D

Supporting Information to Chapter 5: Exploring the effects of mineral depletion on renewable energy technologies net energy returns

Emmanuel Aramendia, Paul E. Brockway, Peter G. Taylor, Jonathan Norman

D.1 Nomenclature

Table D.1: Nomenclature.

Symbol	Description
Letters	
e	Future final energy intensity of mining, specific to a mineral m.
f	Current final energy intensity of mining, specific to a mineral m.
i	Material intensity of a renewable energy technology, specific to a mineral m.
r	Recycling rate of a given mineral m.
s	Final energy intensity of mineral recycling (static), specific to a mineral m.
Greek letters	
α	Coefficient modelling the increase in energy intensities of mining.
β	Coefficient modelling the increases in energy efficiency of metallurgical processes.
δ	Variation in a given coefficient, used specifically for recycling rates.
η	Share of net energy returns of a given renewable energy technology.
λ	Coefficient modelling the increases in material efficiencies of manufacturing.
φ	Final energy intensity of mineral refining, specific to a mineral m.
Others	
CF	Capacity factor.
L	Average lifetime.
e_{input}	Energy input required to manufacture and operate a renewable energy technology.
e_{output}	Energy output delivered over the lifetime of a renewable energy technology.
Δe	Total variation of energy inputs.
$\Delta e_{\text{manufacture}}$	Variation of energy inputs due to changes in material intensities of manufacturing.
Δe_{mining}	Variation of energy inputs due to mineral mining.
$\Delta e_{\text{refining}}$	Variation of energy inputs due to mineral refining.
$\Delta e_{\text{recycling}}$	Variation of energy inputs due to mineral recycling.
Acronyms/abbreviations	
EROI	Energy Return On Investment
PV	Photovoltaic
CSP	Concentrated Solar Power
Subscripts	
m	Refers to a given mineral.
t	Refers to time.
offset	Refers to the value of the parameter that offsets mineral depletion effects.

D.2 Uncertainty on material intensities

Figure D.1 shows the variation in the shares of net energy returns $\Delta\eta$ that can be expected by 2060 when increasing and decreasing material intensities by 50% compared to the material intensities used in the rest of the study (see Figure 5.3). As expected, the figure shows that the variation in the shares of net energy returns is highly dependent on the material intensities chosen, but the main results and conclusions of this article (i.e. the relatively low impacts of increasing energy intensities of mining on the net energy returns of renewable energy technologies) are not likely to be affected by the uncertainty on material intensities.

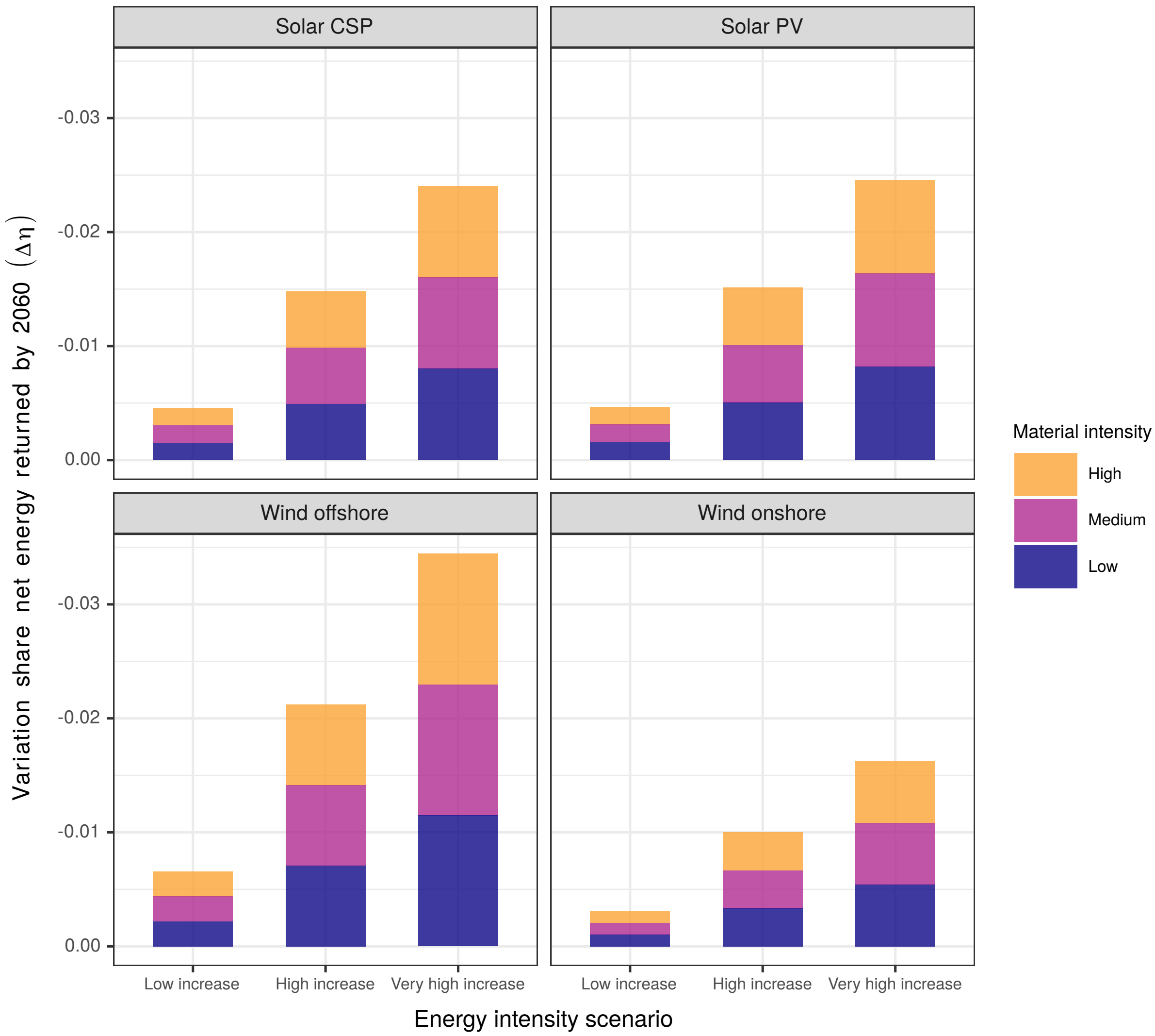

Figure D.1: Variation in the shares of net energy returns $\Delta\eta$ for each renewable energy technology, each energy intensity scenario, and a low, medium, and high value for material intensities. The medium material intensities stands for the material intensities used in the rest of this article, and the low and high material intensities stand for material intensities respectively 50% lower and higher than those used in the rest of the article.

D.3 Change in net energy returns as function of alpha

Figure D.2 shows the evolution of the Energy Return On Investment (EROI) of each renewable energy technology as function of the increasing energy intensities of mining (represented by α), when adopting a low, medium, and high value as initial EROI. Similarly to Figure 5.6, the variation in the EROI values is highly dependent on the value used as initial EROI. The values of EROIs decline significantly when α reaches very high values.

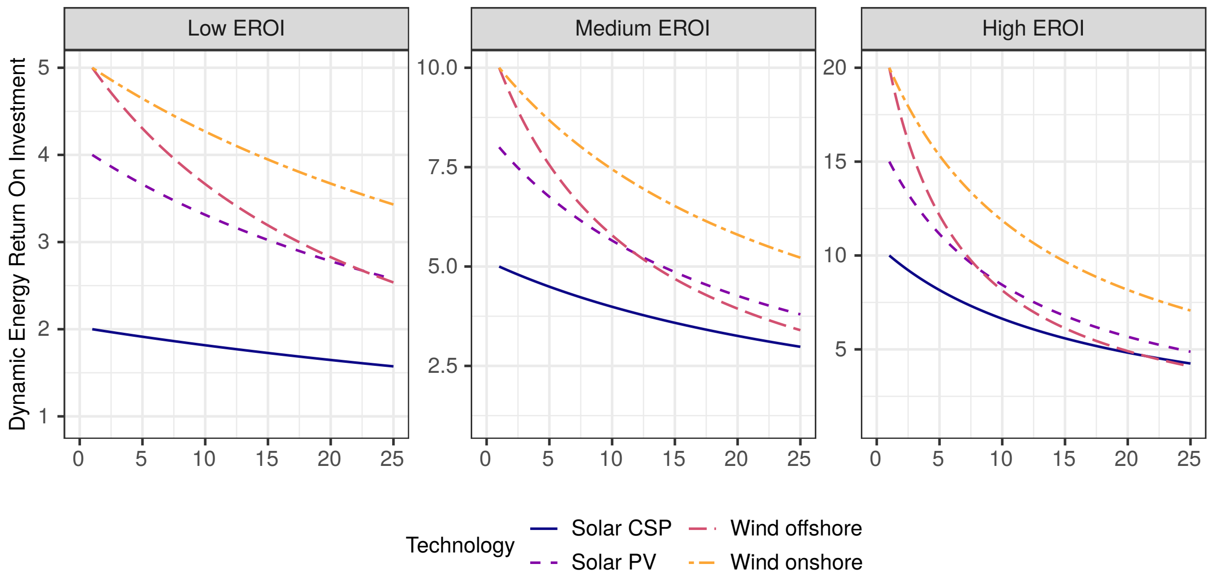

Figure D.2: Dynamic Energy Return On Investment (EROI) for each renewable energy technology as function of increasing energy intensities of mining (α), and for each of the low, medium, and high initial EROI values introduced in Table 5.1.

Figure D.3 shows the evolution of the share of net energy returns as function of the increasing energy intensities of mining (represented by α), when adopting a low, medium, and high value as initial EROI — note again that the variation of η as function of α is independent from the initial EROI value, although the absolute value of η is not. For high values of α, the impacts on the share of net energy returns are significant. For instance, with $\alpha = 25$, the share of net energy returns declines by 9.1%, 13.5%, 13.8%, and 19.4% for respectively wind onshore, concentrated solar power, solar photovoltaic, and wind offshore. However, α reaching a value of 25 means energy intensities of mining increasing by 2400%, which will pose another set of challenges prior to affecting considerably the net energy returns of renewable energy technologies.

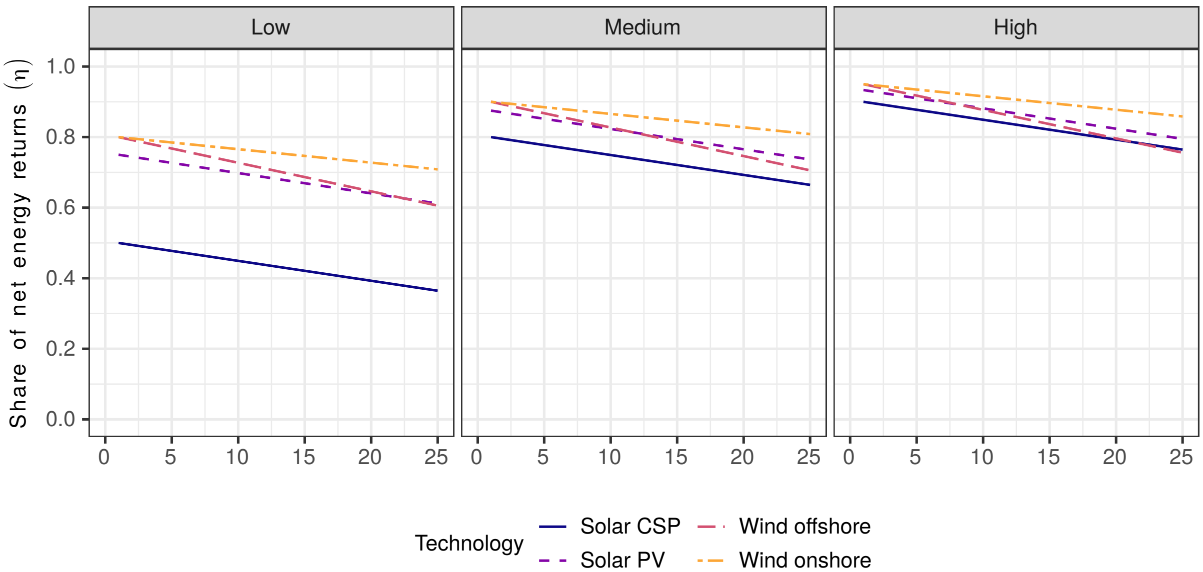

Figure D.3: Dynamic share of net energy returns η for each renewable energy technology as function of increasing energy intensities of mining (α), and for each of the low, medium, and high initial Energy Return On Investment values introduced in Table 5.1.

D.4 Non-linearity of the Energy Return On Investment metric

For 1 unit of energy produced, one can express the dynamic EROI as:

$$\text{EROI} = \frac{1}{e_{\text{input}} + \Delta e_{\text{input}}}, \tag{D.1}$$

while the shares of net energy returns can be expressed as:

$$\eta_t = 1 - \frac{(e_{\text{input}} + \Delta e_{\text{input}})}{e_{\text{output}}}. \tag{D.2}$$

Figure D.4 shows the graphical evolution of both variables as function of Δe_{input}. At high EROI values, a minor increase in Δe_{input} may cause a substantial decrease in the EROI value, while representing a negligible loss in terms of net energy returns.

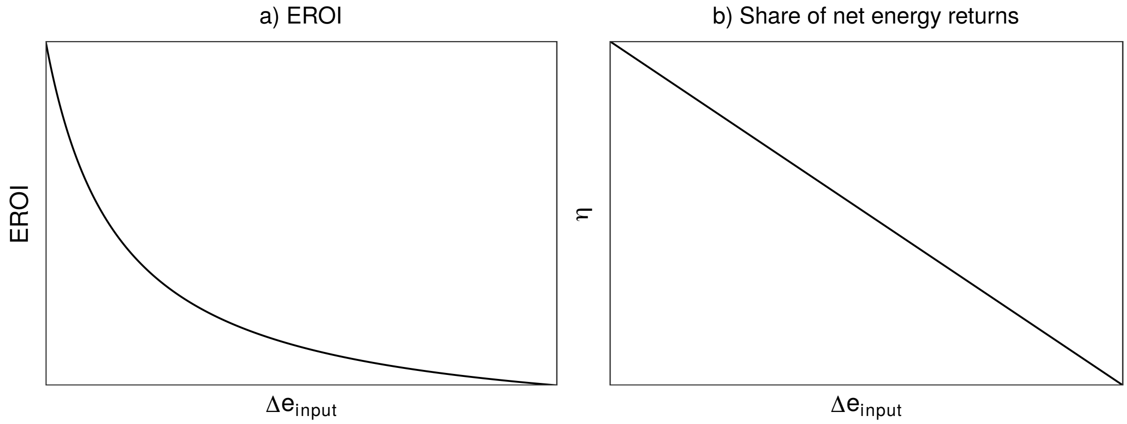

Figure D.4: Evolution of the Energy Return On Investment and the share of net energy returns η as function of increasing energy inputs Δe_{input}.

Additionally, this section on the non-linearity of the EROI metric allows us to point to further caveats for net energy analysts and modellers. A usual attempt in the literature has been to extrapolate the EROI values of fossil fuels based on historical data, and thereby to construct a curve linking the EROI of a given fossil fuel type (coal, gas, oil) to time (alternatively, to cumulative production) [1–5]. Often, these attempts have lead to a curve whereby the EROI decreases quickly from its maximum value (reached after an initial period of technological progress increasing the EROI) until stabilising at a very low value, as sketched in Figure D.5.

However, an evolution of EROI as described in Figure D.5 implies a very steep increase in energy inputs when EROI values drop to low levels, as shown in Figure D.4.a. Such an evolution of the energy inputs may be overlooked when directly extrapolating the EROI, and may neither be consistent with historical values nor be realistic. In addition, Figure D.4.a shows that the early EROI decline can be modelled as a linear function of e_{input}, although such a linear approximation does not hold at low EROI values. Therefore, the risk when deriving EROI values based on historical trends *directly* is to obtain a good fit due to the initial linear relation with e_{input}, which however does not hold at lowering values of EROI. Hence, the trend *should first be established at the level of the energy inputs* e_{input}, and only thereafter translated into the corresponding EROI, to avoid misleading extrapolations.[1] Re-

[1]Such a careful process will moreover ensure to apply increasing energy requirements only to the relevant processes, for instance, only to oil extraction, and not to its refining, in the case of the oil supply chain.

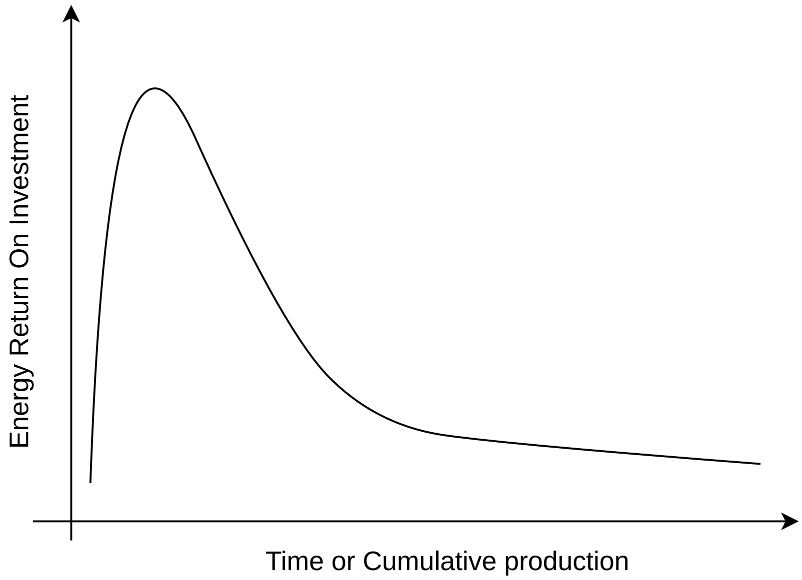

Figure D.5: Example of typical curve linking the Energy Return On Investment to time or to cumulative production.

cent work attempting to forecast future EROI values for fossil fuels may have been overly pessimistic by missing the modelling of increasing energy requirements, from which future EROI should be derived.

D.5 References

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