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

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ABSTRACT

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.

1. Introduction

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 (Sonter et al., 2020; Luckeneder et al., 2021), soil and water pollution (Rasafi et al., 2021; Bardi, 2014), water consumption (Mudd, 2010; Aitken et al., 2016), and health impacts in workers and neighbouring communities (Stephens et al., 2001; Entwistle et al., 2019). In particular, the mining industry consumes considerable amounts of energy, which results in significant greenhouse gas emissions (Norgate et al., 2007; Norgate et al., 2011; Rankin, 2011). The magnitude of all these impacts has considerably increased over time as the quantities of extracted minerals has surged since the industrial revolution (Krausmann et al., 2009; Krausmann et al., 2018), driven by industrialisation and rapid economic growth (Steinberger et al., 2013; Wiedmann et al., 2015). 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 (Steffen et al., 2015; Steffen et al., 2015; Ceballos et al., 2017), 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 (Rogelj et al., 2016; Schleussner et al., 2016). Achieving such ambitious climate targets requires a steep reduction in

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greenhouse gases until net-zero emissions are reached (Masson-Delmotte et al., 2021), which, in turn, requires a rapid curtailment in fossil fuel consumption (Smith et al., 2019). 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 (Stern and Kander, 2012; Hickel et al., 2019) – and thus resources extraction and mining activities. As the evidence of absolute decoupling between natural resources use and economic growth remains, at a global level, very thin (Bithas et al., 2018; Parrique et al., 2019; Haberl et al., 2020), 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 (Gadgets et al., 2015), is likely to hamper such decoupling. Second is the renewable energy transition. Renewable energy systems are highly dependent on critical raw minerals (Kleijn et al., 2011; Moss et al., 2013; Valero et al., 2018), and their deployment will induce a surge in the demand and extraction of particular materials (Viebahn, 2015; de Koning et al., 2018; Elshkaki et al., 2019; IEA, 2021), potentially leading to bottlenecks in the supply chain and availability issues for specific materials (Valero et al., 2018; Watari et al., 2018; Capellán-Pérez et al., 2019; Moreau et al., 2019). 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 (Cook, 1976; Prior et al., 2012; Bardi, 2014). Such a situation, characteristic of the ongoing process of natural resources depletion (Bardi, 2013; Pigneur, 2019), is likely to happen to numerous minerals as the quality of tapped deposits decreases (Mudd, 2010; Mudd, 2007; Mudd, 2010; Northey et al., 2014; Calvo et al., 2016), and is already limiting the productivity growth of the mining industry (Topp, 2008).

The three drivers of increasing mining activities and associated final energy use can conceptually be summarised by Eq. 1:

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

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 $j_{t,m}$ 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.

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 2 reviews the literature related to energy consumption of mining activities. Section 3 presents the methodology used for the historical and prospective analysis of the mining industry's final energy consumption, and Section 4 presents the results (first and second aims). Section 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 6 discusses our findings and Section 7 presents the conclusions of the study. Appendix A presents a short definition of the energy-related terminology used throughout the paper.

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 Fig. 1, and further described in Appendix B. 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]

2.1. The energy consumption of the mining industry

2.1.1. 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 (Lahiri-Dutt, 2018), 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 A 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

[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 [(Masson-Delmotte et al., 2018) Chap. 2]. (See (Anderson and Peters, 2016; van Vuuren et al., 2017; Vaughan and Gough, 2016; Heck et al., 2018; Smith et al., 2016) for a critical discussion on carbon dioxide removal technologies.)

[2] Categories 07, 08 excluding 0892, and 099 of the United Nations International Standard Industrial Classification (United Nations, 2008).

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

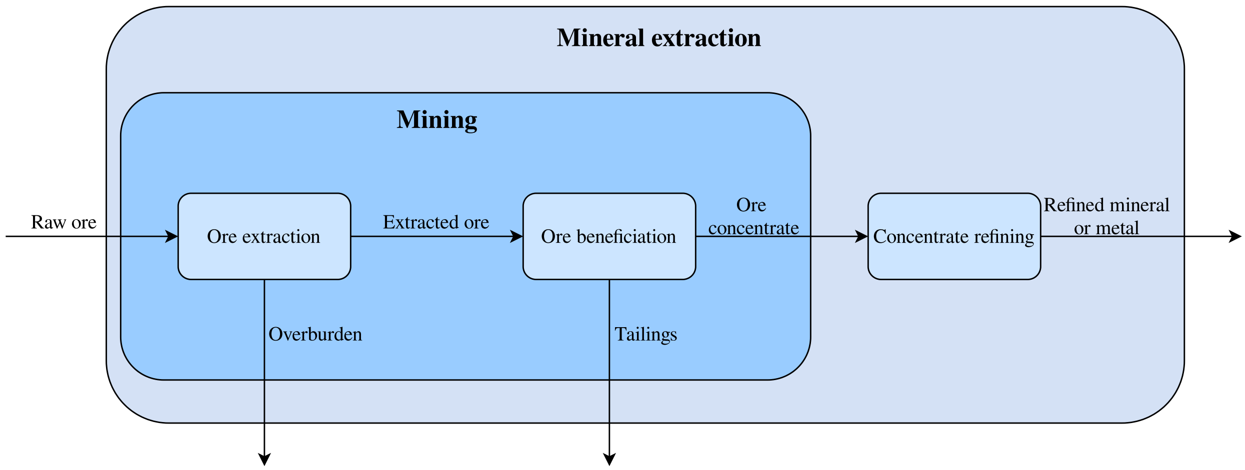

Fig. 1. Graphical representation of the mineral extraction process. The mining activities cover the ore extraction and ore beneficiation steps, while the refining process, mostly relevant for metals, belongs to the metallurgical industry. Energy intensities only refer to the ore extraction and ore beneficiation stages in this paper.

perspective (accounting for both direct and indirect energy requirements). For instance, Bardi (2013) estimates the energy consumption of metal production around 5–10% of Total Primary Energy Supply (TPES), and Bihouix and De Guillebon (2012) around 8–10%. Similar values are obtained by Nuss et al. (2014) 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. (2017) 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.

2.1.2. 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 (Vidal et al., 2021) – see Page et al. (1975) and Cook, 1976 for early studies. Such a relationship has been shown empirically in the case of copper (Norgate et al., 2010; Norgate et al., 2010; Northey, 2013; Calvo et al., 2016; Koppelaar and Koppelaar, 2016), gold (Muller et al., 2010; Norgate et al., 2012; Calvo et al., 2016), nickel (Norgate et al., 2010; Norgate et al., 2011; Norgate et al., 2011), zinc (Norgate et al., 2011; Calvo et al., 2016; Mudd et al., 2017), lead (Norgate et al., 2011; Mudd et al., 2017), rare earth elements (Weng et al., 2016), platinum group metals (Glaister et al., 2010), and uranium (Norgate et al., 2014; Parker et al., 2016). 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 (Norgate et al., 2010; Norgate et al., 2011; Haque et al., 2015). 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 (Morrell, 2004). 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 (2016) 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 et al. (2010) 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 (Norgate et al., 2011; Koppelaar and Koppelaar, 2016). 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 (US-DoE, 2007; Rötzer et al., 2020; Vidal et al., 2021).

2.2. Increase in energy intensities of mining activities

2.2.1. 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. (2016) 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 (2020) reports national copper production and energy use over time; these data show that the energy intensity of copper mining is found to increase by 66% in the period 2001–2019 (average yearly increase of 3.0%; the historical evolution can be found in Appendix C). Third, Rötzer et al. (2020) 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 effects of technological improvements 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 (US-DoE, 2007; Paoli et al., 2020; Vidal et al., 2021).

2.2.2. 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 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. (2019) 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. (2018) and Dong et al. (2020), 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. (2013) explicitly construct a global ore grade-tonnage distribution for copper, and assess how future extraction will increase copper energy intensities. Elshkaki et al. (2016) and Ciacci et al. (2020) both link the average copper ore grade to cumulative copper production in order to estimate environmental impacts of copper production globally and in the EU-28, respectively.

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 (Lasky, 1950) or bimodal (Skinner, 1976) distribution remains a matter of scientific debate (Arndt et al., 2017), and may well have dramatic implications for the future evolution of energy intensities – see Appendix D. Hence, there is large uncertainty associated with the future evolution of ore grades, which depend on unknown geological factors.

3. Methodology

This section introduces the methodology followed in this study. The data used and data sources are described in Appendix E. We cover 59 minerals, the full list can be found in Table F.1.

3.1. Historical final energy consumption of the mining industry

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

$$E_{m,t} = P_{m,t} f_m, \quad (2)$$

where $P_{m,t}$ (kilograms) is the primary extraction of mineral m in the year t, and f_m (Joule/kilogram) 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 [(Rankin, 2011, Chap. 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 Hammond et al. (2011); Norgate et al. (2011); Rankin (2011); Mudd (2012); Norgate et al. (2012); Nuss et al. (2014); Calvo et al. (2018). 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 (Heun et al., 2018; Aramendia et al., 2022) (an explanation of the method and calculations is available in SI-1), 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 SI-2.

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 SI-1 for more information on the standard deviations used.

3.2. Estimating the future final energy consumption of mining activities

Fig. 2 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 Beylot et al. (2019) 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 (hence 108 total pathways).

Socio-economic scenario selection. To explore future pathways, we

[4] We also note the work of Fizaine et al. (2015), 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.

[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 Nuss et al. (2014).

[7] Material requirements are considered for the following technologies according to the review of Watari (2020): solar photovoltaic, concentrated solar power, wind onshore and offshore turbines, electric vehicles, fuel cells, nuclear, geothermal, biomass, 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.

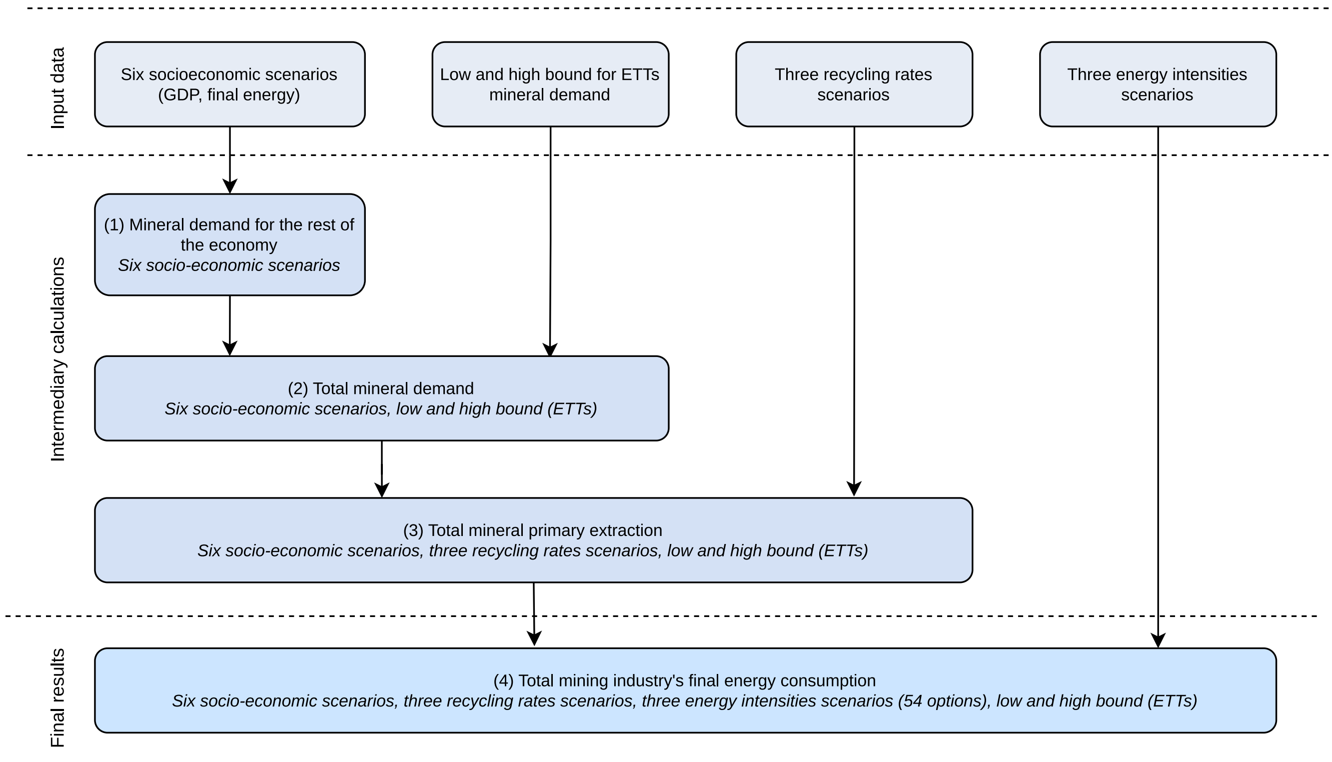

Fig. 2. Workflow for constructing future pathways of the mining industry's global final energy consumption, and possible combinations of socioeconomic scenario, recycling rates scenario, mining energy intensities scenario, and mineral requirements for ETTs. ETTs: Energy Transition Technologies.

select the Beyond 2 Degrees Scenario (B2DS) developed by the IEA (IEA, 2017), as well as the four 1.5°C consistent marker scenarios chosen by the IPCC in the Special Report on 1.5°C [(Masson-Delmotte et al., 2018) Chap. 2], three of which are based on the Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2017); SSP1 (Fujimori et al., 2017), SSP2 (Fricko et al., 2017), SSP5 (Kriegler et al., 2017), and the last being the Low Energy Demand scenario (Grubler et al., 2018). In addition, we recognise the validity of the recent argument in favour of exploring a broader set of socio-economic scenarios and of exploring post-growth scenarios (Keyßer and Lorenz, 2021; Hickel et al., 2021). Hence, we also define and include a post-growth socioeconomic scenario, in which global GDP declines by 0.2% yearly.

3.2.1. Estimation of future mineral demand for the rest of the economy

Considering the strong historical link between economic activity and material consumption (Krausmann et al., 2018), we follow the approach developed in Capellán-Pérez et al. (2019) 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 (in kilograms) for the rest of the economy over time is determined as:

$$D_{m,RoE} = a_m y + b_m, \tag{3}$$

where y stands for GDP (constant 2010 $US), 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 F.

Table 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 in Watari (2020) 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 in Capellán-Pérez et al. (2019) follow the pattern described in column (b).

Mineral demand	(a) Review by Watari (2020)	(b) Study by Capellán-Pérez et al. (2019)
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.

3.2.2. 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 in Watari (2020), 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. (2019), 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 1 – see SI-1 for more information.

3.2.3. Estimation of future primary mineral extraction

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

[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 3.2.2.

Table 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 scenario	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

$$P_{m,t} = D_{m,t}(1 - r_{m,t}), \tag{4}$$

where $D_{m,t}$ (kilograms) represents the total demand for mineral m at t, and $r_{m,t}$ (without unit) 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 rates scenarios presented in Table 2: the constant recycling rate scenario, where no improvements are made, the moderate increase scenario, where recycling rates (modelled as recycled content) increase by 50% in the period 2015–2060, and the high increase scenario, where recycling rates (modelled as recycled content) double in the period 2015–2060 – initial recycling rates are taken from Graedel et al. (2011) and Haas et al. (2005), and can be found in SI-2.[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.

3.2.4. *Estimation of the future mining industry's final energy consumption*

We apply Eq. 5 to determine the future final energy consumption of mining activities (in Joules):

$$E_{m,t} = P_{m,t} e_{m,t}, \tag{5}$$

where $e_{m,t}$ (Joule/kilogram) 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 to mineral m at a given time t is modelled to vary over time as:

$$e_{m,t} = f_m \alpha_{m,t}, \tag{6}$$

where f_m (Joule/kilogram) 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 dimensionless 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 SI-2. To deal with the uncertainty associated with increasing future energy intensities (see Section 2.2.2), 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 in Calvo et al. (2016) 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 (Chilean Copper Commission, 2020). Fig. 3 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 combined effects of mineral depletion and of technological improvements, which are also accounted for. Appendix C shows that our increasing energy intensity scenarios are in line (in terms of magnitude) with other studies.

3.3. *Methodology limitations*

3.3.1. *Exogenous inputs*

Our methodology uses several exogenous parameters (recycling rates, future energy intensities, mineral demand for ETTs), while these parameters are endogenous parameters and dependent on the socio-economic scenario. 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 such assumptions are appropriate. However the following points should be noted:

- *Exogenous 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 mineral 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.

3.3.2. *Mineral demand modelling*

The approach we follow to determine mineral demand for the rest of the economy (Eq. 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 (Pauliuk et al., 2013; Bleischwitz et al., 2018), material demand saturation (Ruijven et al., 2016), structural economic

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

[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.

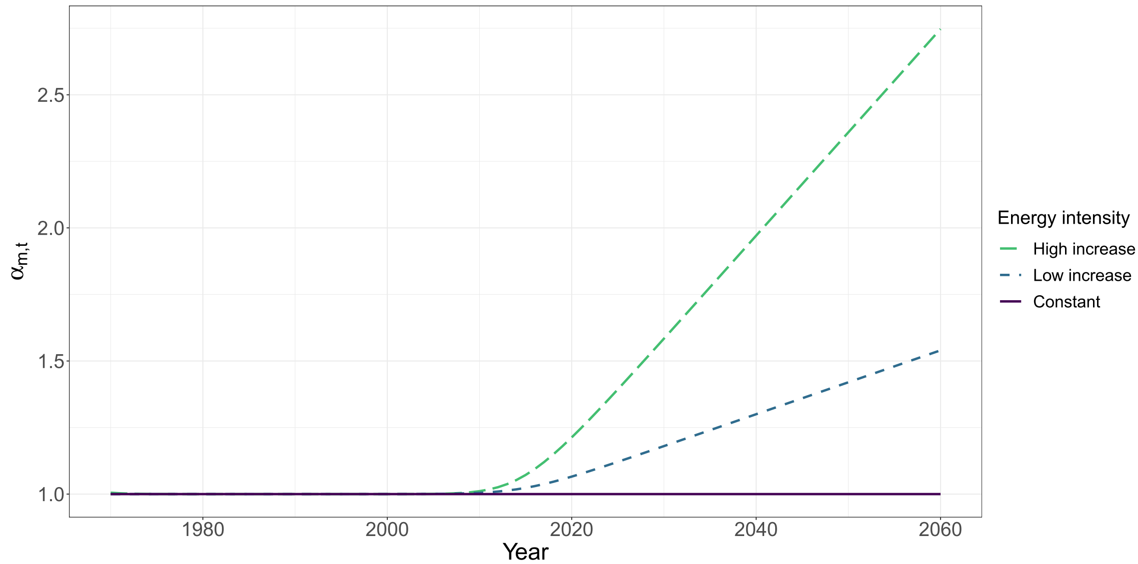

Fig. 3. Values of $\alpha_{m,t}$ for minerals affected by the decrease in mineral deposit qualities for the three increasing energy intensities scenarios. Constant scenario: energy intensities are kept constant for all minerals. Low increase: energy intensities start increasing around the year 2000 and are extrapolated following the trend reported in Calvo et al. (2016). High increase: energy intensities start increasing around 2000 and are extrapolated following the trend calculated from the Chilean Copper Commission (2020) data.

changes towards less material intensive sectors (Pothen, 2017), or increases in the material efficiency with which services are delivered (Allwood et al., 2013; Carmona et al., 2017). 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.

4. Results

4.1. Historical final energy consumption of the mining industry

Fig. 4.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, Fig. 4.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 2.1.1 for the limitations of IEA data), as shown in Table 3. As explained in Section 2.1.1, 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.

Fig. 5 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 f_m 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 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.

4.2. Future pathways for the mining industry's final energy consumption

Fig. 6 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, so 108 total pathways). 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.

Fig. 7 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

[11] See SI-1 for the evolution of the breakdown over time and for the breakdown by mineral group.

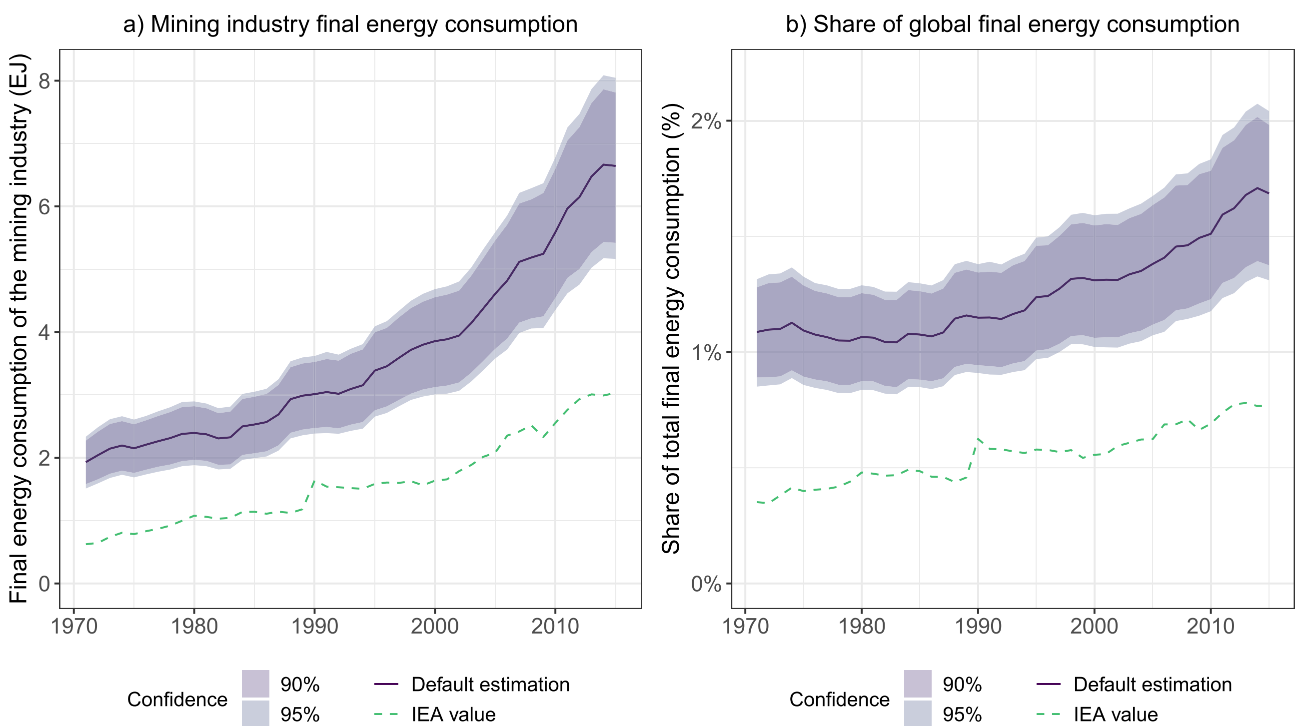

Fig. 4. Final energy consumption of the mining industry (left), and share of global final energy consumption consumed by the mining industry (right). Note that calculated values account for both direct and indirect energy, while the IEA's accounting method only includes direct energy.

Table 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	0.625	1.08	1.64	1.64	2.55	3.03

(results for other socio-economic scenarios are available in SI-1), 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 a 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%.

Fig. 8 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 SI-1 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 slower from 2055 onwards (and even decreases in the post-growth scenario) due to the underlying ETTs development data (see Table 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 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 SI-1 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

[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.

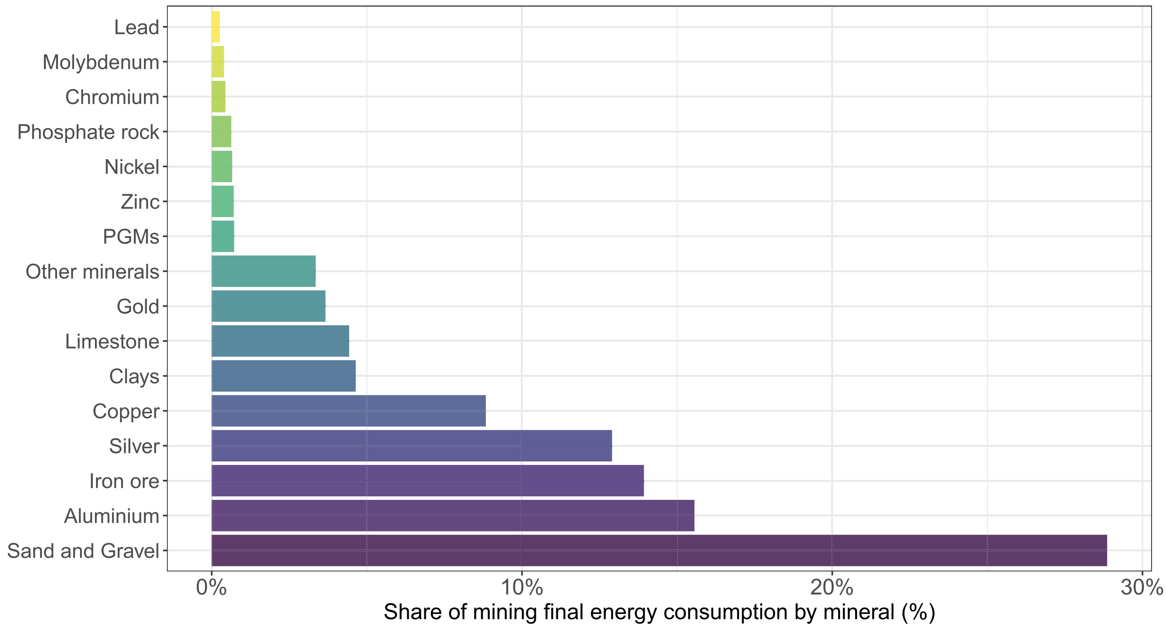

Fig. 5. Breakdown of historical final energy consumption of the mining industry by mineral for the year 2015. PGMs: Platinum Group Metals.

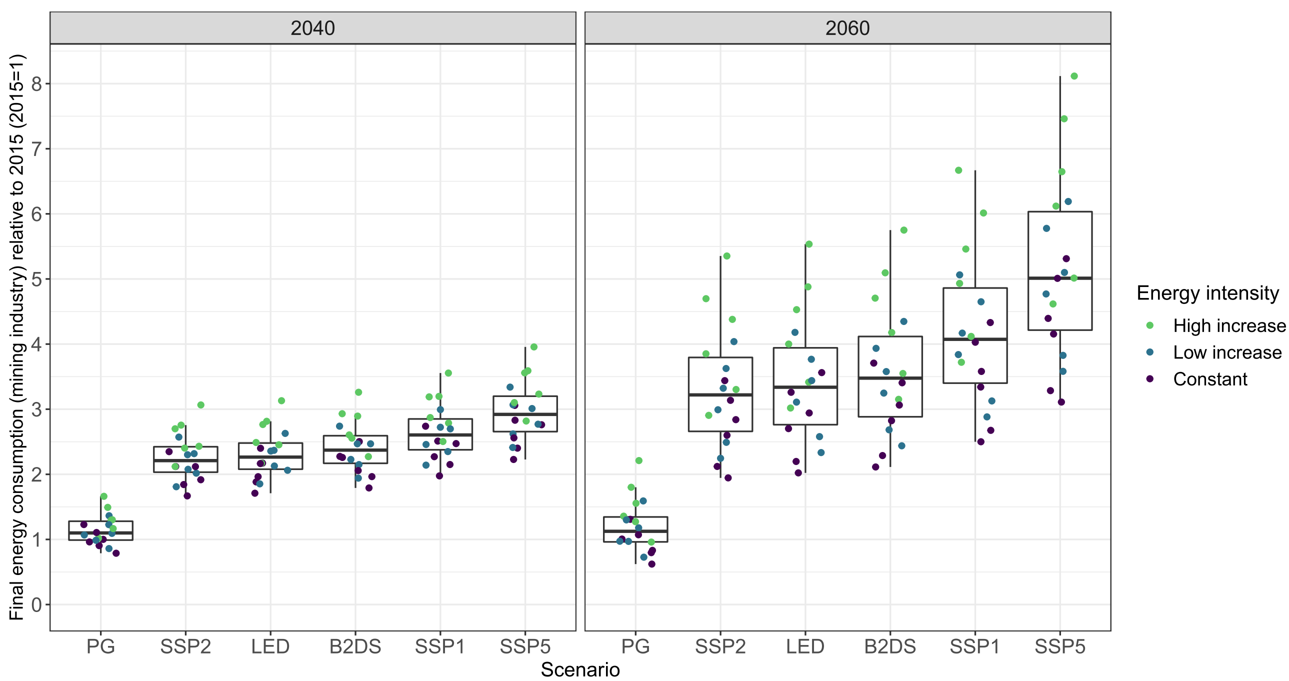

Fig. 6. Final energy consumption of the mining industry in 2060 relative to 2015, for each different socio-economic, recycling rate, energy intensity, and renewable energy scenario. (2015=1.) Points with the same colour and shape correspond to the high and low range of mineral demand for the Energy Transition Technologies, with the same recycling rate and energy intensity scenarios. Energy intensity refers to the α variable.

whether climate targets would be reached – or whether global final energy 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.

5. Mineral materials in energy-economy models: a review

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

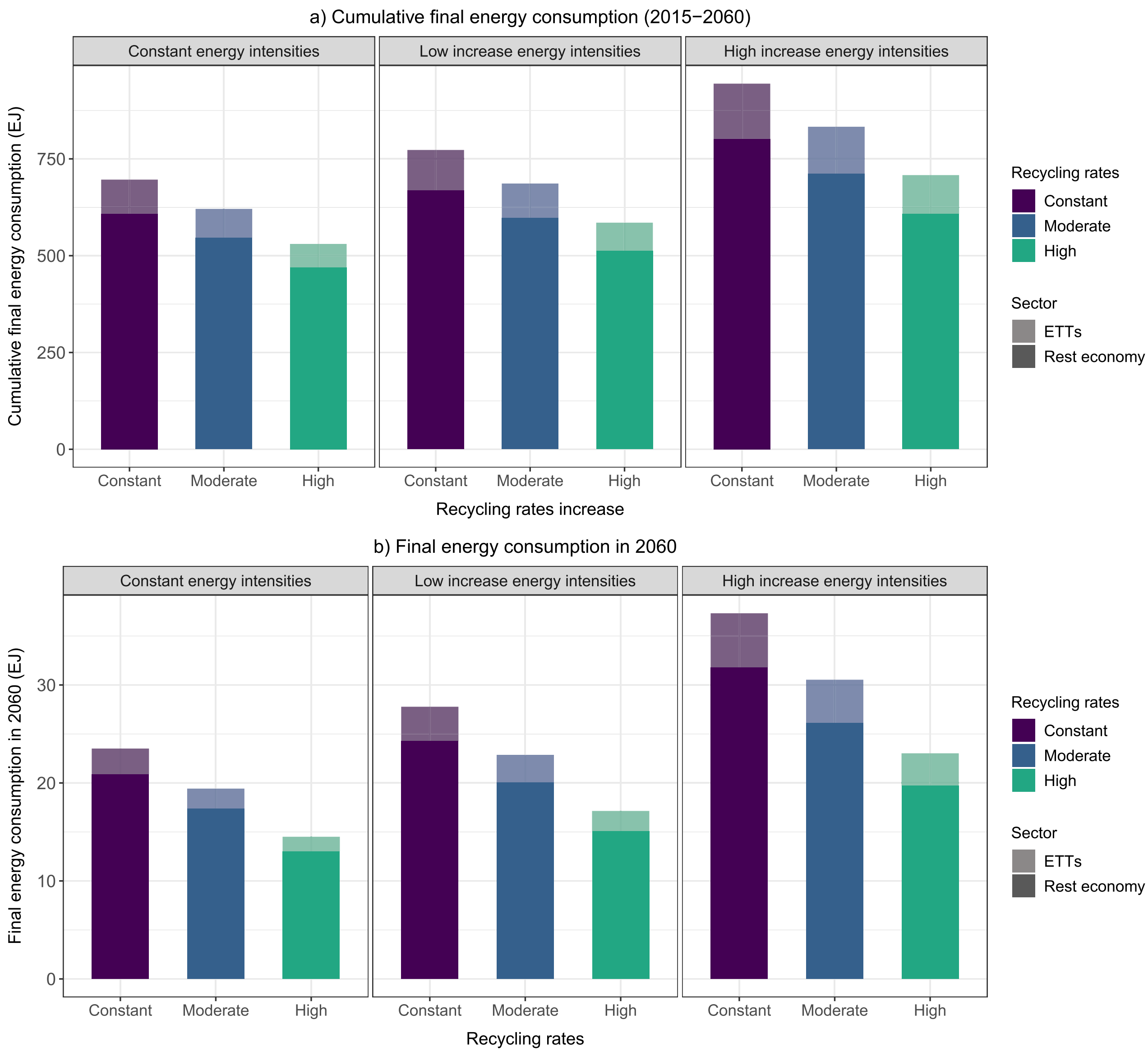

Fig. 7. (a) Cumulative final energy consumption (2015–2060) and (b) Final energy consumption in 2060 for the Beyond 2 Degrees Scenario, as function of the recycling rates scenario, of the energy intensities scenario. Results for the high bound value of mineral demand for Energy Transition Technologies (ETTs). Energy intensity refers to the α variable.

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 G summarises the approach of each reviewed model in respect of each criterion.

5.2. Review findings

We summarise here the findings of the review – implications for the modelling community are further discussed in Section 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 (Capellán-Pérez et al., 2019).

Consideration of mineral material 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 (Deetman et al., 2018; Deetman et al., 2020; Deetman et al., 2021)). Conversely, most models do not

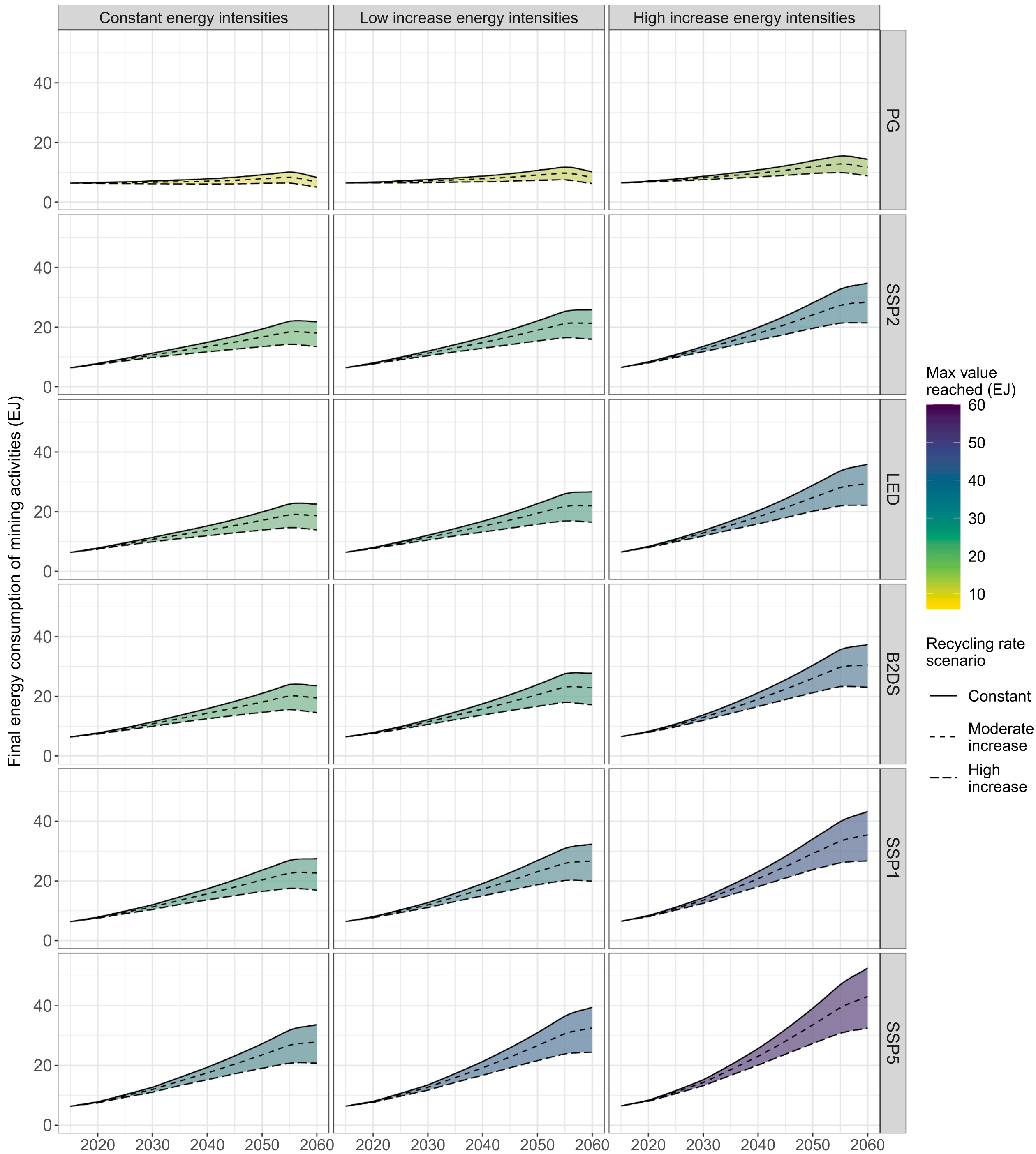

Fig. 8. Future mining industry's final energy consumption pathways by socio-economic scenario, energy intensity scenario, and recycling rate scenario, when considering the high range for mineral demand for Energy Transition Technologies. Energy intensity refers to the α variable.

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 are 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 are 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 are 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.

Table 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 refers to the α variable.

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

6. Discussion

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 (US-DoE, 2007). 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 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 (US-DoE, 2007; Paoli et al., 2020; Vidal et al., 2021).

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 (Vidal et al., 2021), for which recycling is either altogether impossible, or is currently not achievable, and are hence "lost by design" (Ciacci et al., 2015).[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 (Schäfer et al., 2020). 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 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 (Keyßer and Lorenz, 2021; Hickel et al., 2021).

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 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 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 (Busch et al., 2014). Recent work by Elshkaki et al. (2018) and Deetman et al. (2021) explicitly models in-use stocks and shows that the availability of materials acts as an important limiting

[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 Ciacci et al. (2015).

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 the 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 (Valero et al., 2018).

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.

CRediT authorship contribution statement

Emmanuel Aramendia: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Paul E. Brockway:** Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. **Peter G. Taylor:** Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing, Supervision. **Jonathan Norman:** Conceptualization, Methodology, Validation, Supervision.

Declaration of Competing Interest

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

Data availability

The R code that was used for this analysis can be found in the online repository associated with this article at the University of Leeds Data Repository: https://doi.org/10.5518/1420. Input data, including recycling rates and energy intensities of mining, can be found in the Supplemental Information 2. Future recycling rates and α values can also be found in Supplemental Information 2. Input data in the format used by the R code can be found in the online repository, except mineral extraction data and International Energy Agency data, which are proprietary. Further data may be available upon reasonable request to the authors.

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Appendix A. Glossary of energy terms

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

Table A.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. (See SI-1.)
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 3.2.4.
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 (see SI-2), 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.

Appendix B. The mineral extraction process

The subsequent summary of the mineral extraction process is based on [Rankin, 2011, Chap. 7 and 8], which provides an excellent overview of the different extraction processes.[14]

Ore extraction. The ore of interest is extracted from the ground, lifted and hauled until the processing facility, where it is further processed.[15] 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 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.[16] 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.

Appendix C. Increasing energy intensities: a comparison

Fig. C.1 shows the historical evolution of copper mining energy intensities in Chile (2001–2019), which has increased by 66% over the covered time period, or by a yearly rate of 3%. The rest of this appendix compares the energy intensity scenarios developed in this study with those obtained in the literature.

[14] 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. Norgate et al. (2011) and Nuss et al. (2014) for a breakdown for different minerals.

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

[16] 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.

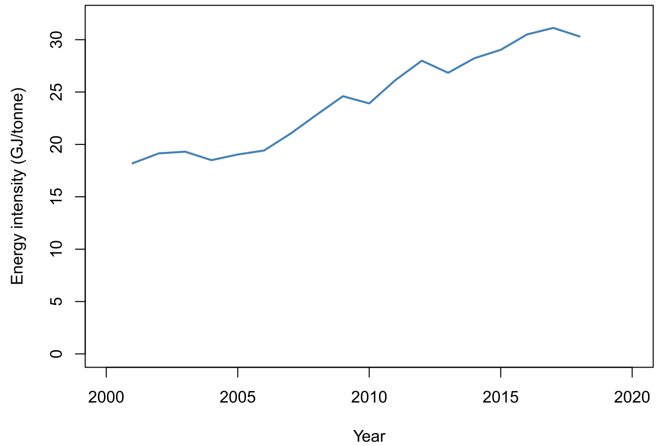

Fig. C.1. Energy intensity of copper mining over time in Chile. Time series deduced from the data provided by the Chilean Copper Commission. (See e.g. (Chilean Copper Commission, 2020)).

Table C.1 summarises the projections of energy intensities of mining that are used by other studies. The increase factor refers to $\alpha_{m,t}$ in Eq. 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 C.1. 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 in Harmsen et al. (2013). We note that the range of increasing energy intensities reported by Harmsen et al. (2013) 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 3.2.4. The variability in factors reported in Elshkaki et al. (2016) and Harmsen et al. (2013) 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 (Kuipers et al., 2018; Dong et al., 2020) are based on van der Voet et al. (2019) and have therefore similar results.

Table C.1
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 Ciacci et al. (2020) because the values are scenario dependent, and are not clearly stated in the article, although the methodology is the same than for Elshkaki et al. (2016), but with different scenarios.

Study	Mineral	Region	Time period	Increase factor	Methodology
Ester Van der Voet et al. (2019)	Copper Zinc Lead Nickel sulfides Nickel laterites	World	2010–2050	1.30 1.35 1.75 1.12 1.14	Ore grades are extrapolated as a function of time fitting historical data. Then an empirical relationship linking ore grades to energy intensities is applied.
Kuipers et al. (2018)	Copper	World	2010–2050	1.30	Same method and values as (Ester Van der Voet et al., 2019)
Dong et al. (2020)	Copper	China	2010–2050	1.42	Same method as (Ester Van der Voet et al., 2019), different values (specific to China).
Elshkaki et al. (2016)	Copper pyro Copper hydro	World	2010–2050	1.33–2.00 1.36–2.01	Ore grade is determined for each scenario as a function of cumulative extraction, and a energy consumption is determined as function of ore grade.
Ciacci et al. (2020)	Copper	EU-28	NA	NA	Same approach and values as (Elshkaki et al., 2016).
Harmsen et al. (2013)	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.

Appendix D. Ore grade-tonnage distributions

Fig. D.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.

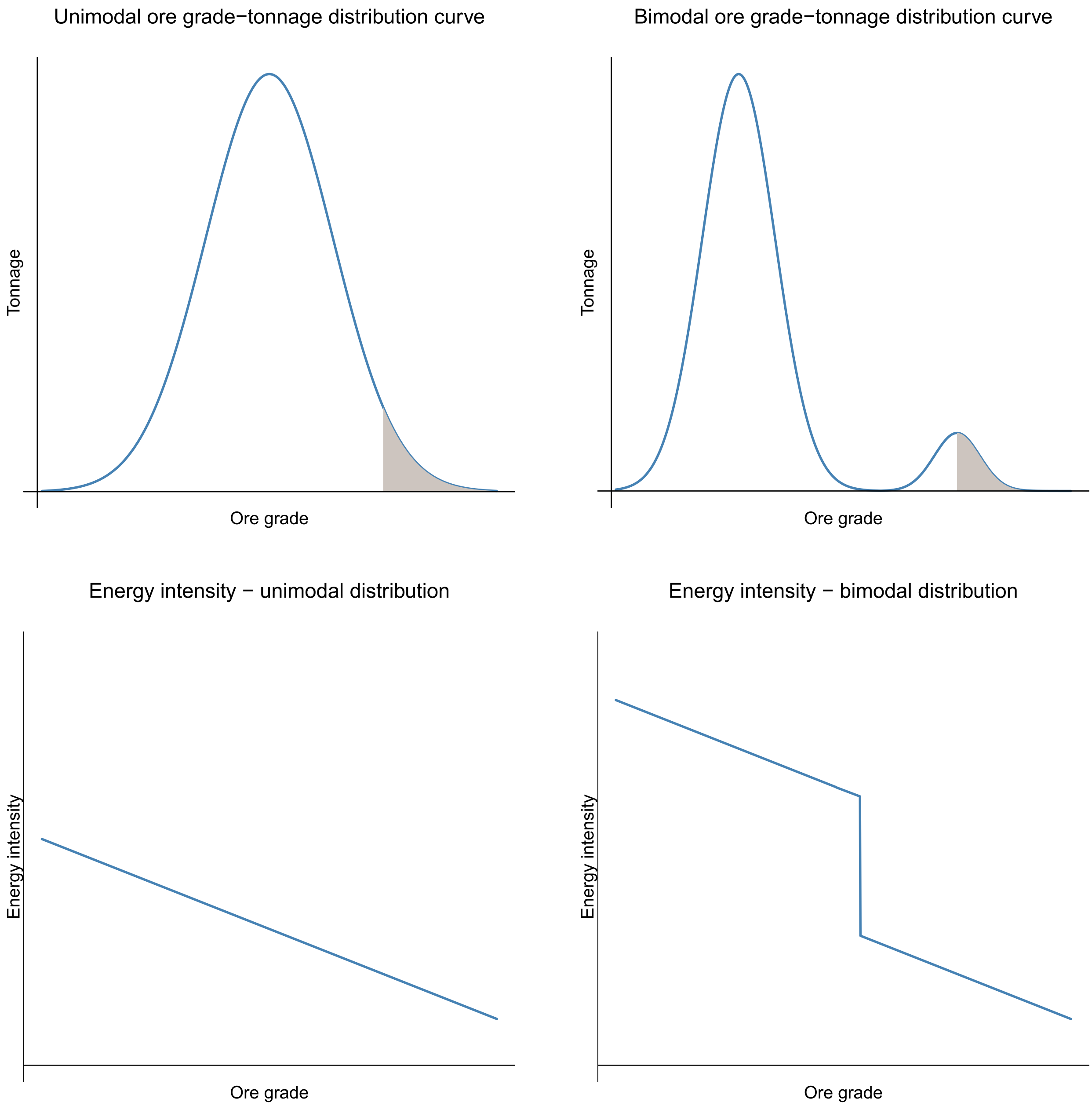

Fig. D.1. Unimodal and bimodal ore grade-tonnage distribution curves, as well as implications of each distribution in terms of evolution of energy intensities as function of ore grades. The grey area corresponds to the tonnage extracted to date.

According to Skinner (1976), in the case of the unimodal distribution, common rocks are constituted by different minerals, "one or more of which contains a geochemically abundant metal as an essential constituent" (Skinner, 1976). 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" (Skinner, 1976). 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 (1976) 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. (2017) 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.

Appendix E. Data used

E.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 IPCC's Special Report on 1.5°C [(Masson-Delmotte et al., 2018, Chap. 2)], from the 1.5°C Scenario Explorer (Huppmann et al., 2019). 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.

E.2. Historical production data

Historical data of mineral production (1970–2015) are taken for most minerals from the United States Geological Survey (Kelly and Matos, 2016). For uranium production, data are taken from Grancea and Hanly (2018) (p. 89), and for clays, sand and gravel, and limestone, from Krausmann et al. (2018), 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 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. (2018) 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.

E.3. Initial recycling rates

Recycling rates in terms of recycled content are taken from Graedel et al. (2011) (Appendix C) for metals (when more than one value is reported, we use the average of the lowest and highest value), and from Haas et al. (2005) (Table S1) for other minerals, using the average values reported for industrial minerals and construction minerals.

E.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:

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

E.5. Historical energy intensities

The initial GERs (which represent the *primary* energy intensities) of mineral extraction are derived from the work of Norgate et al. (2011); Nuss et al. (2014); Norgate et al. (2012); Rankin (2011); Mudd (2012); Hammond et al. (2011); and Calvo et al. (2018), and reported in SI-2, alongside comments regarding assumptions for their estimation – assumptions were sometimes needed when the literature did not allow to obtain directly the GER associated to 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 International Energy Agency and a recently developed Physical Supply Use Table framework for the energy industry (Heun et al., 2018; Aramendia et al., 2022), which yields the *final* energy intensity. SI-1 explains briefly the methodology for the calculations using the Physical Supply Use Table framework.

E.6. Projections of mineral demand for Energy Transition Technologies

The mineral requirements reported in Watari (2020) are available as supplemental information of the cited paper. The mineral requirements of the energy transition scenarios conducted in Capellán-Pérez et al. (2019) are shared in the online repository associated to this paper, with agreement of the authors of the study.

Appendix F. Linear regression examples

Fig. F.1 shows the linear regressions conducted for 8 of the main minerals to assess the mineral requirements of the rest of the economy following Eq. 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 Fig. F.1 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 3.2.1.

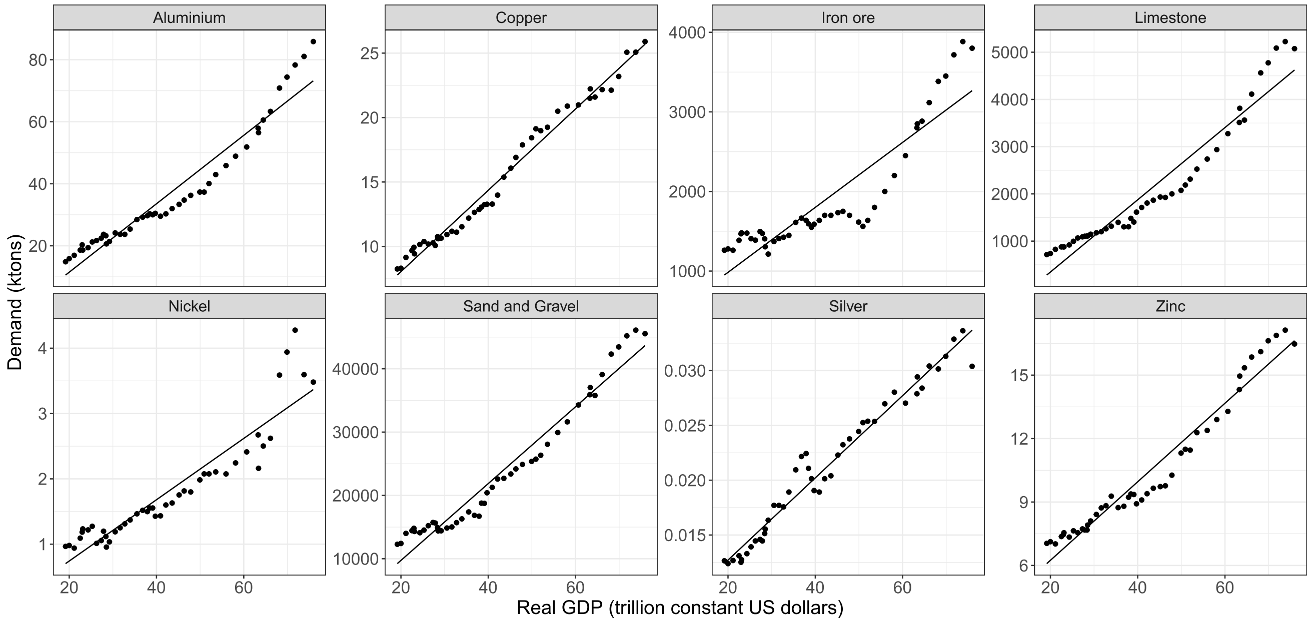

Fig. F.1. Examples for 8 main minerals of the linear regressions conducted to determine the mineral requirements of the rest of the economy (Eq. 3). These 8 minerals always account for 85% of the final energy consumption of extraction, for the subset of minerals which mineral requirements by the rest of the economy are determined with a li.near regression.

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 SI-1; conclusions and trends obtained in the main paper 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 3.3.2, 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 F.1 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.

Table F.1
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	b_m	p	r^2
		Mt/TUS$	Mt	Dmnl	%
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	–	–

(continued on next page)

Table F.1 (*continued*)

Mineral m	Fitting period	a_m	b_m	p	r^2
		Mt/TUS$	Mt	Dmnl	%
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	–	–
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

Appendix G. Energy-economy models review: details

Table G.1 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 G.1
Performance of each reviewed energy-economy model for four 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. No model explicitly represents the increasing energy intensities of mining activities. 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	IEA (2021)	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	Fujimori et al. (2017)	Steel, cement	Linear relationship with sectoral output.	No explicit differentiation.	Modelled through the increase in sectoral output.
IMAGE	Stehfest et al. (2014)	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	Shell (2017)	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 the recycling of metals.

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Table G.1 (*continued*)

Model	Ref	Materials covered in physical units	Determination of material demand	Primary and secondary production	Feedback on energy consumption
REMIND-MAgPIE	Baumstark et al. (2021)	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	Cambridge Econometrics (2019)	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	EIA (2021)	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	Bond-Lamberty et al. (2021)	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	(Le Treut, 2018; Le Treut, 2020)	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.
GEM-E3/ PRIMES	E3Modelling (2017); E3Modelling, 2018	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 a cost optimisation procedure depending on climate policies and prices, which gives an energy intensity of production for each mineral material.
MEDEAS	Capellán-Pérez et al. (2019); Capellán-Pérez et al. (2020)	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	Després et al. (2018)	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	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.

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Table G.1 (*continued*)

Model	Ref	Materials covered in physical units	Determination of material demand	Primary and secondary production	Feedback on energy consumption
			vehicles produced multiplied by steel required for a vehicle).		
MESSAGE	Krey et al. (2020)	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.

Appendix H. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2023.102745.

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