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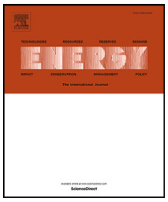

Exploring the effects of mineral depletion on renewable energy technologies net energy returns

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ABSTRACT

The energy transition poses a set of new challenges related to mineral scarcity and depletion. The process of mineral depletion is characterised by increasing energy consumption per tonne of valuable minerals mined (i.e. energy intensity of mining), due to the decline in the quality of mined deposits. As renewable energy technologies are heavily reliant on a range of minerals, some of them scarce, the net energy returns (i.e., the share of energy available to provide energy services) of renewable energy technologies may be significantly affected by this decline. This may in turn jeopardise the ability of renewable energy technologies to provide sufficient net energy, and hence, support decent living standards. The aim of this article is therefore to explore, using net energy analysis techniques combined with Life Cycle Analysis data, the effects of mineral depletion on the net energy returns of four renewable energy technologies: solar photovoltaic, concentrated solar power, onshore wind, and offshore wind.

The results indicate that the effects of mineral depletion on the net energy returns of renewable energy technologies will be marginal. Indeed, even for very high increases in the energy intensities of mining, the share of net energy returns decreases by less than 3 percentage points by 2060 for each technology analysed — 2.3% for wind offshore, 1.6% for solar photovoltaic and concentrated solar power, and 1.1% for wind onshore. These results are validated with a Monte Carlo simulation conducted on the energy intensities of mining. In addition, the article discusses that technological factors, such as improvements in metallurgical energy efficiencies and material intensities of manufacturing have the potential to somewhat offset the effects of mineral depletion. Hence, although constraints related to mineral scarcity and depletion may be critical for the energy transition, concerns regarding the impacts of these issues on the net energy returns of renewable energy appear to be unfounded.

1. Introduction

1.1. Background

Global final energy consumption has considerably increased in last decades as a results of economic growth and industrialisation, and more than doubled in the period 1971–2019 according to the International Energy Agency (IEA) [1]. Despite increasing awareness of the damaging consequences of fossil fuel use, notably in causing climate change, 81% of global primary energy supply is still based on fossil fuel energy [1]. As such, significant research has been conducted to understand the drivers of energy consumption (see e.g. [2,3]), to model future energy consumption (see e.g. [4,5]) and options to reduce future energy demand (see e.g. [6,7]), and to understand the conditions for delivering good living standards at low energy use (see e.g. [8,9]). Without decisive action, future final energy consumption is likely to keep increasing [10], as a result of economic development in developing countries, making strong mitigation measures urgently needed.

A large uptake in renewable energy technologies is required in a short timespan to achieve climate mitigation targets [10]. However, the transition from traditional, fossil fuel based energy systems towards renewable energy systems poses a set of challenges. These include the widespread electrification of end-uses [11], the intermittency of electricity generation [12], the need for energy storage [13], and the land requirements of renewable energy systems [14]. A key challenge for the energy transition is the issue of mineral scarcity and mineral resource depletion. Indeed, most renewable energy technologies have a high reliance on non-renewable mineral resources [15,16]. Recent studies have highlighted concerns about the future availability of some

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minerals in a context of growing mineral demand [17], and raised the question of whether mineral reserves will be sufficient to meet mineral requirements for the energy transition and the broader economy [18–20].

One way in which mineral depletion may affect the energy transition is through the capacity of renewable energy systems to yield *net* energy. All energy systems need to consume some energy for their manufacturing and functioning, so that a given fraction of the produced energy needs to be reinvested in the energy system itself, and only the remaining fraction, i.e. the net energy, can be used for productive and beneficial purposes [21]. The net energy returns (i.e., the fraction of the energy output available as net energy) of energy systems are often assessed through the Energy Return On Investment (EROI) metric, which is defined as the ratio of energy output delivered over the lifetime of an energy system to the energy required for its manufacturing, operation, maintenance and decommissioning [22,23]. Understanding the net energy returns of different energy systems is crucial, as net energy returns determine the capacity of energy systems to provide energy services and to foster economic activity. The question of EROI has notably been discussed as a critical factor potentially affecting energy prices [24,25] and economic growth [25,26].

The effects that the energy transition may have on the net energy available to society has been an important question under scrutiny in recent research [20,27], and understanding the difference in the net energy returns of renewable energy systems and fossil fuel-based systems appears critical. While renewable energy technologies have been conventionally thought to have lower net energy returns than fossil fuel-based systems, recent research has shown that when adopting equivalent boundaries and analysing the energy output at the final energy stage, renewable energy technologies have net energy returns comparable to fossil fuel energy [28,29].[1] However, such research did not consider the effects of mineral depletion, whereby mineral deposits of ever lower qualities (in terms of ore grades, grinding size, accessibility, etc.) need to be extracted, so that the energy intensities of mining (i.e. the energy required to extract one unit mass of valuable mineral) tend to increase over time. Renewable energy systems may therefore present declining net energy returns as they face the effects of mineral depletion. Quantifying such effects is crucial to better understand the possible downstream effects that the energy transition may have on the delivery of net energy and energy services to society, and on economic activity.

1.2. Literature review

Decreasing ore grades resulting from a decrease in the quality of mined deposits have been identified for the mining of numerous mineral materials (see e.g., [30–34]). The result is an increase in the energy intensities of mining, as more energy is needed to mine, haul, crush and purify the mineral of interest. Such trends have been reported at the level of individual mines and companies [35], have been identified as a factor hindering the productivity of the mining sector by the Australian Government Productivity Commission [36], and can be identified in the reports of the national Chilean Copper Commission (energy intensity of copper mining found to increase by 60% from 2001 to 2019) [37]. Although technological improvements are a key factor that may counter the effects of mineral depletion, recent work shows that the effects of mineral depletion have been predominant in the period 1970–2010 [38]. Further, this situation may continue considering that there practical and theoretical limits to the energy efficiency of processes [39–41].

Recent research has attempted to capture the effects of the increasing energy intensities of mining to model the future energy consumption and greenhouse gases emissions of the metallurgical sector, globally [42–44], for the EU28 [45], and for China [46]. Two different approaches can be identified. First are studies that model exogenously the evolution of ore grades over time using historical trends, which mostly rely on average ore grade time series [42,44,46]. Second are studies that model endogenously the evolution of grades, using a model linking cumulative production and the decline in ore grades using ore grade-tonnage relationships, and which are therefore much more reliant on geological data [43,45]. Both approaches then determine the corresponding energy requirements and greenhouse gas emissions using life cycle analysis.

Very few works have attempted to capture the impacts of these trends on the net energy returns of renewable energy technologies. First, Harmsen et al. [47] use an endogenous model linking cumulative copper extraction and ore grade-tonnage distributions of copper reserves to analyse the change in wind turbine EROIs that may be induced by the decrease in copper deposit qualities and finds a moderate impact, with the EROI decreasing from 25.2 to 24.4. However, a key limitation of the study is that only the increasing energy requirements associated with copper mining are considered, while wind turbines require the extraction of wide range of metals, so that the effects of mineral depletion may be underestimated. While the approach of Harmsen et al. links endogenously critical variables and has a strong theoretical underpinning (see Section 2.1), it cannot be generalised to all relevant minerals, as it relies on data that is not readily available in many cases. Further, the results and uncertainty analysis conducted by the authors show that even for a major metal like copper, for which there are significant data available, there are significant uncertainties in the ore grade-tonnage distributions, and consequently, on the evolution of energy intensities.

Second, Fizaine and Court [48] estimated the decrease in renewable energy technologies EROIs as a function of decreasing ore grade deposits. The authors found that the effect of mineral depletion, when considered jointly for all minerals, may significantly affect the EROI of renewable energy technologies, particularly if ore grades decrease to very low concentrations. However, the study does not provide a range of plausible evolutions for ore grades, so that the increase in the energy intensities of mining that can *actually* be expected, and the associated decrease in the EROI of renewable energy technologies, cannot be inferred from this study. Furthermore, the work of Fizaine and Court [48] does not differentiate the energy consumption of mining processes those of downstream metallurgical processes. Consequently, increasing energy intensities are also applied to metallurgical processes, potentially leading to an overestimation of the effects of mineral depletion.

1.3. Gaps, contributions, and structure

This paper therefore aims at overcoming the shortcomings identified in previous studies through the following contributions. First, it provides an assessment of the effects of mineral depletion on the net energy returns of renewable energy technologies considering all the relevant mineral materials that they require. Second, the analysis clearly differentiates the ore mining stage from the downstream metallurgical processes, and only applies increasing energy intensities to the mining stage. Third, the paper uses a range of plausible mid-term evolutions for the energy intensities of mining when conducting the analysis.

The analysis builds on the methodology developed by Fizaine and Court [48] to explore the potential effects of increasing energy intensities of mining (denoted as energy intensities in the rest of the article) on the net energy returns of renewable energy technologies when covering all relevant mineral materials. The recent work by Aramendia et al. [49] is used to overcome previous limitations by clearly differentiating the ore mining stages of mineral extraction from downstream

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[1] The comparison however depends on the specific type of fossil fuel and renewable energy technology analysed, as well as on the geographical setting and conditions (wind potential, solar irradiation, etc.).

metallurgical processes. This article also expands previous work by assessing and critically discussing the extent to which improvements in metallurgical energy efficiencies and material intensities of renewable energy technologies manufacturing may compensate for such increases in energy intensities. The paper is structured as follows: Section 2 describes the theoretical underpinnings and methodology, Section 3 presents the results, which are discussed in Section 4. Last, Section 5 presents the conclusions and implications.

2. Methodology

Section 2.1 presents the theoretical underpinnings of this work. Then, the methodology, which is divided in two main parts, is introduced. First, Section 2.2 presents the method for estimating the effects of mineral depletion on the net energy returns of renewable energy technologies. Second, Section 2.3 presents the method for estimating the extent to which improvements in metallurgical energy efficiencies and material intensities of renewable energy technologies manufacturing may offset mineral depletion effects.

2.1. *Theoretical underpinnings*

The core theoretical underpinning for this study is the view that Earth's mineral resources are finite. Far from meaning that humanity will "run out" of a given mineral resource, the finiteness of the Earth's mineral resources implies that the average quality of mined deposits decrease as a result of mineral extraction (and of technological progress, which allows to mine deposits of lower qualities). Indeed, the process of mineral depletion may therefore be characterised as a process whereby the energy requirements of mining, as well as the associated environmental impacts (such as the gross ore extracted, and the emissions and use of polluting substances) increase [50]. As early as the 1970s, some authors argued that the absolute limit to the amount of minerals that would be extracted would not result from the total amount of minerals in the ground, but instead, would be determined by the increasing energy requirements of mining [51,52]. A physical view of mineral depletion therefore emphasises that the inputs to mining processes and the associated impacts tend to increase over time, as extraction gradually moves towards lower quality deposits, and that these increasing requirements and impacts may eventually deter, or prevent, further extraction.

The ore grade has been identified as a good indicator of the quality of mineral deposits and of the decrease of quality over time [30,35] (although many other factors come into play, such as rock hardness, the presence of impurities, depth and remoteness of the deposit — see e.g., [51,53]). Specifically, the ore grade has been shown to be inversely related to the energy requirements of mining [40,54], and is therefore an excellent candidate to model the variation of energy requirements. However, ore grade time series are scarce, and modelling their evolution is an extremely complex task, as there is significant uncertainty regarding the ore grade-tonnage distribution of minerals. As a matter of fact, it is not clear whether the geological distribution of minerals follows a unimodal or bimodal distribution [55], which may have significant implications for the evolution of the energy requirements of mining. In this work, therefore, the approach is to use an exogenous parameter α_t representing the average increase in energy intensities over time associated with the decrease in mineral deposit qualities (see Section 2.2.2). The use of the exogenous parameter α_t, which is calibrated on historical and empirical data following previous work [49] allows this study to explore a range of plausible increasing energy intensities, without modelling the evolution of ore grades for all the minerals analysed.

In turn, increasing energy requirements of mining entail an increase in the energy requirements associated with the downstream applications of mineral materials. Of particular importance to net energy analysis are the energy requirements associated with energy yielding systems themselves. Indeed, only the energy available as surplus (i.e., the net energy), once the energy requirements of the energy system are subtracted, is available to contribute to economic activities, to provide energy services, and to deliver welfare and well-being [21,56]. The net energy returns of energy yielding systems are usually measured using the EROI, which is defined as:

$$\text{EROI} = \frac{e_{\text{output}}}{e_{\text{invested}}}, \tag{1}$$

where e_{output} stands for the energy output, and e_{invested} for the energy that had to be invested in the energy yielding system. However, the EROI is well-known for its highly non-linear behaviour (see e.g., [29]), making its interpretation complex (this is critically discussed in the light of results in Section 4.4). Therefore, we also introduce the share of net energy returns, which represents the share of energy output available as net energy, and which is defined as the ratio of net energy output divided by total energy output:

$$\begin{aligned} \eta &= \frac{e_{\text{output}} - e_{\text{invested}}}{e_{\text{output}}} \\ &= 1 - \frac{e_{\text{invested}}}{e_{\text{output}}}. \end{aligned} \tag{2}$$

2.2. *Quantifying the effects of mineral depletion on the net energy returns of renewable energy technologies*

The first part focuses on mining processes. Fig. 1 shows the different steps undertaken to assess the effects of mineral depletion on the net energy returns of renewable energy technologies.

2.2.1. *Material intensities of renewable energy technologies*

First, this study requires the material intensities (i.e. the material requirements for manufacturing and operating 1 MW of a given energy technology) for each of the four reviewed renewable energy technologies: solar photovoltaic (solar PV), concentrated solar power (solar CSP), wind onshore, and wind offshore. We base the material intensities on previous work by de Castro and Capellán-Pérez [57] and Beylot et al. [58]. The material intensities used for each technology as well as the source study can be found in the supplementary material associated with the paper (see Data Statement).

2.2.2. *Modelling future energy intensities*

Following Aramendia et al. [49], the current final energy intensity f_m of mining a mineral m are defined as the final energy that is currently required to extract one tonne of the mineral m — a nomenclature is provided in Appendix A. The values used for f_m are based on previous work by Aramendia et al. [49][2] and are fully available in the supplementary material associated with the paper (see Data Statement). Then, the future final energy intensity $e_{m,t}$ (in the rest of the paper, energy intensity refers to *final* energy intensity, unless stated otherwise) are defined as the actual energy intensity of mining a mineral m at a given time t, once the effects of mineral depletion are taken into consideration. The parameter $\alpha_{m,t}$ is defined as the coefficient modelling the increase in energy intensities over time for a mineral m, so that:

$$e_{m,t} = \alpha_{m,t} f_m. \tag{3}$$

For the sake of simplicity, each mineral is considered equally affected by mineral depletion, so that the parameter α is independent of

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[2] The values are first compiled in primary energy terms from the literature and then converted in final energy terms using a recently developed Multi-Regional Physical Supply Use Table (MR-PSUT) framework [59]. The code to determine the primary-to-final energy coefficient (0.58 for the mining industry) is available in the online repository associated to the paper (link in Data Statement). See [49] for more details).

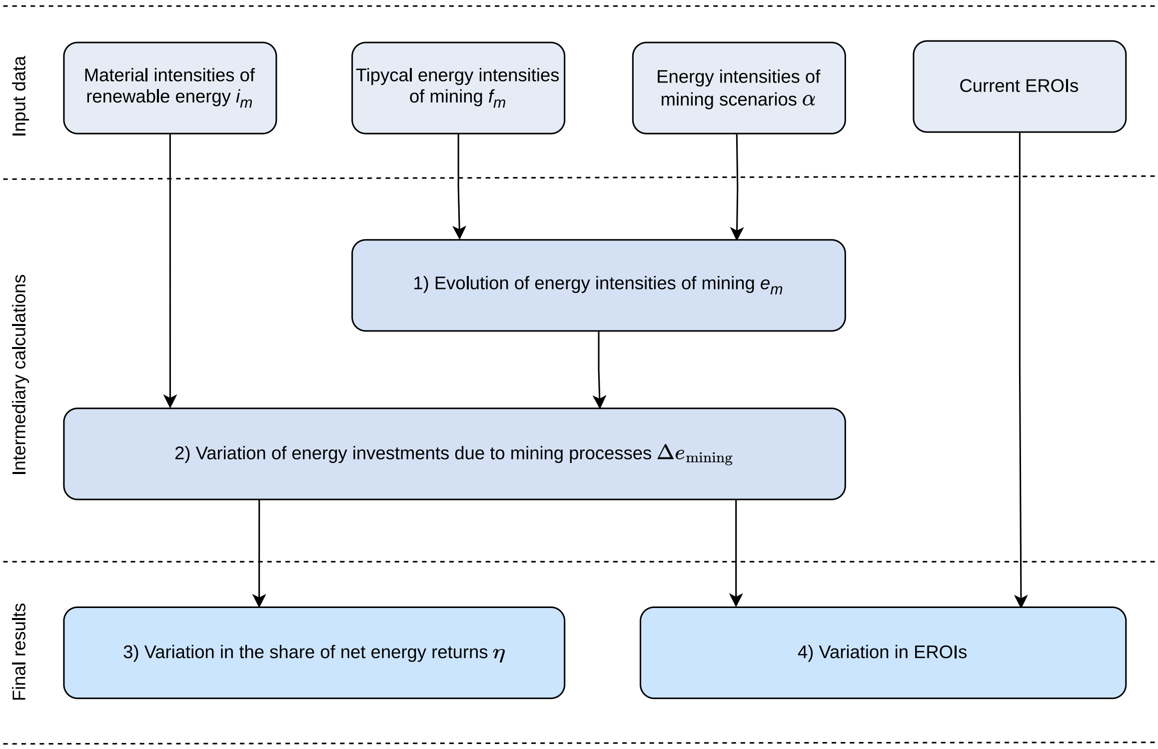

Fig. 1. Summary workflow of the steps undertaken to determine the effects of mineral depletion on the net energy returns of renewable energy technologies.

the mineral m and should thus be interpreted as an average increase in the energy intensities over time. The scenarios developed for the α coefficients by Aramendia et al. [49] are adopted; such scenarios extrapolate trends in energy intensities based on historical data for copper derived from previous works and reports by Calvo et al. [35] and reports from the Chilean Copper Commission (see [37]). In addition, a scenario is added in which α values increase even faster, by a yearly rate of 2.9%, which is the average increase reported by the Chilean Copper Commission over the period 2001–2019. Note that using energy intensity scenarios based on copper for all minerals is a pessimistic assumption which tends to overestimate the effects of mineral depletion. Indeed, the mining of abundant minerals such as iron or aluminium is unlikely to be significantly affected by increasing energy intensities, as the energy consumption of crushing and grinding the ore only increases significantly at concentrations much lower than those at which these metals are currently mined [40,60]. The different scenarios used for α, alongside a baseline scenario of no increasing energy intensities, are displayed in Fig. 2.

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

$$\begin{aligned}\Delta e_{\text{mining},t} &= \sum_m (\alpha_{m,t}-1) i_m f_m \\ &= (\alpha_t - 1)\sum_m i_m f_m,\end{aligned} \tag{4}$$

where i_m stands for the material intensity in mineral m of the given renewable energy technology. The next step is to assess the effects of mineral depletion on the net energy returns of renewable energy technologies through two key metrics: (i) the share of net energy returns, and (ii) the EROI.

2.2.3. Mineral depletion effects on the share of net energy returns of renewable energy technologies

The methodology introduced by Fizaine and Court [48] is adapted to estimate the effects of the variation in Δe_{mining} on the net energy returns of renewable energy technologies. First, the effects are estimated

Table 1
Summary of capacity factors, lifetimes, and EROI values used for each renewable energy technology assessed. Capacity factors and lifetimes are taken from de Castro and Capellán-Pérez [57]. A low, medium, and high EROI for each technology from the literature, particularly using [57,61–65]. CF: Capacity Factor.

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

on the share of net energy returns η. To do so, one can determine, for a given energy technology of capacity 1 MW, the final energy output over its lifetime e_{output} as:

$$e_{\text{output}} = 8760.\text{CF}.\text{L}, \tag{5}$$

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

$$\begin{aligned}e_{\text{invested}} &= \frac{e_{\text{output}}}{\text{EROI}_{t=0}} \\ &= \frac{8760.\text{CF}.\text{L}}{\text{EROI}_{t=0}},\end{aligned} \tag{6}$$

where $\text{EROI}_{t=0}$ stands for the EROI of the energy technology that is currently observed, in the absence of mineral depletion effects — note that the EROI is here defined as the ratio of *final* energy output to *final* energy invested over the lifetime of a technology. The effects of mineral depletion on the share of net energy returns can then be quantified, at any time t, as:

$$\eta_t = 1 - \frac{e_{\text{invested}} + \Delta e_{\text{mining},t}}{e_{\text{output}}}, \tag{7}$$

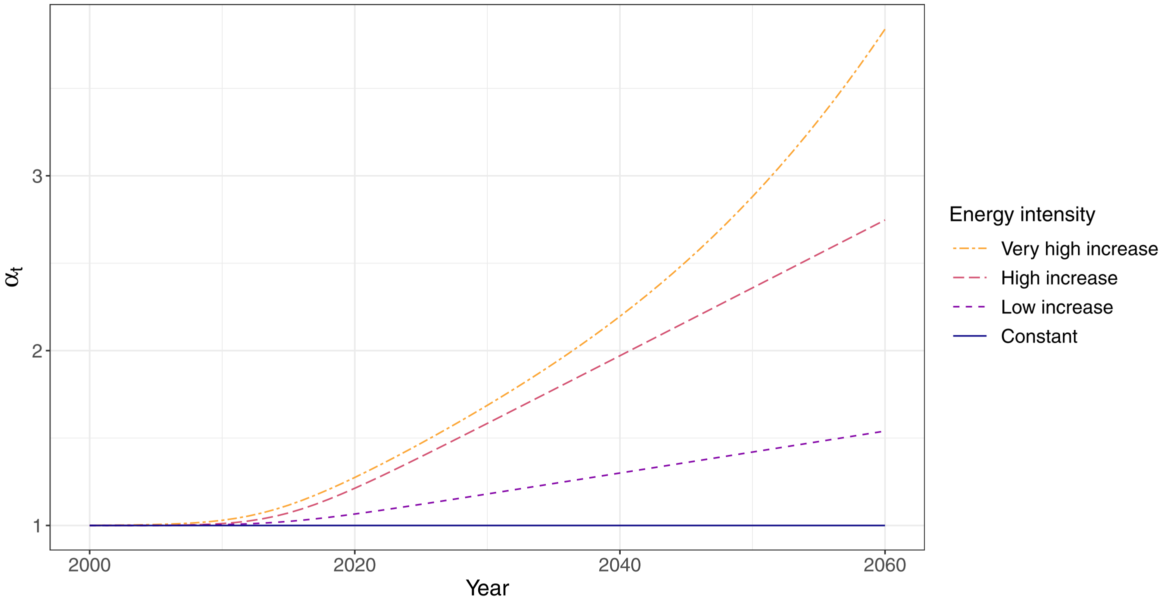

Fig. 2. Values of the increasing energy intensities coefficient α for the three different considered scenarios and the baseline of no increasing energy intensities. *Source:* Figure adapted from Aramendia et al. [49].

and the variation in the share of net energy returns, as:

$$\Delta\eta_t = -\frac{\Delta e_{\text{mining},t}}{e_{\text{output}}}, \tag{8}$$

where $\Delta e_{\text{mining},t}$, e_{output}, and e_{invested} are determined from respectively Eqs. (4), (5), and (6). Note that the variation in the share of net energy delivered to society is independent of the initial value of the EROI and is only a function of the increasing energy consumption of mining processes (considering a given level of energy output).

2.2.4. Mineral depletion effects on the EROIs of renewable energy technologies

The dynamic EROI, i.e. the EROI accounting for depletion effects, can then be determined as:

$$\text{EROI}_t = \frac{e_{\text{output}}}{e_{\text{invested}} + \Delta e_{\text{mining},t}}. \tag{9}$$

Replacing e_{output} using Eq. (6), one obtains:

$$\begin{aligned}\text{EROI}_t &= \frac{e_{\text{invested}}\text{EROI}_{t=0}}{e_{\text{invested}} + \Delta e_{\text{mining},t}}\\ &= \frac{\text{EROI}_{t=0}}{1 + \frac{\Delta e_{\text{mining},t}}{e_{\text{invested}}}}.\end{aligned} \tag{10}$$

As the EROIs of renewable energy technologies are subject to debate in the literature (e.g. due to different system boundaries) and depend upon geographical conditions, A low, medium, and high EROI for each renewable energy technology are taken from the literature (particularly, using [57,61–65]). Table 1 summarises the EROI values used as well as the capacity factor values and average lifetimes, which are taken from de Castro and Capellán-Pérez [57].

2.2.5. Sensitivity analysis: Monte Carlo simulation of current energy intensities

Considering the uncertainty associated with the current energy intensities values f_m used for each mineral m, this paper follows the approach developed by Aramendia et al. [49] and conduct a Monte Carlo simulation (1000 runs) of the changes observed in η when the current energy intensity of each mineral follows independently a normal probability distribution function — see the supplementary material associated with the paper.

2.3. Quantifying the potential of technological levers to offset the effects of mineral depletion

Next, the potential of two technological levers to offset the effects of mineral depletion is assessed. First are increases in the efficiencies of metallurgical processes (i.e. metal manufacturing after the ore has been mined and concentrated) [66] (see studies by the U.S. Department of Energy for analysis focused on e.g. iron, aluminium and titanium [67–69]). Indeed, energy consumption for metallurgical processes is often significantly higher than energy consumption for mining processes [70, 71]. Second are the material intensities of renewable energy technologies, which have been found to decrease in recent years for wind power and solar PV, and such a trend is expected to continue in the short term [15] — for instance, a decrease in the silicon and silver intensities of solar PV by respectively 25% and 30% is expected by the IEA by 2030 [15, p. 56] — although Liang et al. [72] finds that this important aspect is often overlooked in studies.[3] The variation of future energy requirements for a capacity equal to 1 MW of a given renewable energy technology can hence be decomposed following Eq. (11):

$$\Delta e = \Delta e_{\text{mining}} + \Delta e_{\text{refining}} + \Delta e_{\text{manufacture}}. \tag{11}$$

Next sections explain how $\Delta e_{\text{refining}}$ and $\Delta e_{\text{manufacture}}$ are estimated, as well as the condition under which each term may be sufficient to compensate for the increasing energy intensities of mining.

2.3.1. Effects of increases in metallurgical energy efficiencies

Eq. (12) defines the variation in energy requirements due to increasing energy efficiencies of metallurgical processes:

$$\begin{aligned}\Delta e_{\text{refining}} &= \sum_m (1-\beta_m) i_m \varphi_m - \sum_m i_m \varphi_m\\ &= -\sum_m \beta_m i_m \varphi_m,\end{aligned} \tag{12}$$

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[3] Future increases in the recycled input rates of manufacturing processes (i.e. the share of manufactured materials produced from secondary production [73,74], sometimes also referred to as recycled content [75]), may also contribute to lower such energy requirements. Indeed, the energy requirements of secondary material production (i.e. material recycling) are generally considerably lower than those of primary material production [44,71].

where the factor β_m represents the metallurgical energy efficiency improvements (with $\beta_m \in [0,1]$) in manufacturing mineral m, and φ_m representing the energy intensity of the metallurgical process manufacturing mineral m. The values used for φ_m are available in the supplementary material associated with the paper (see Data Statement).[4] For the sake of simplicity, efficiency improvements are assumed to be similar across all minerals, so that β is independent of the mineral m, and Eq. (12) becomes:

$$\Delta e_{\text{refining}} = -\beta \sum_m i_m \varphi_m. \tag{13}$$

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

$$\beta_{\text{offset}} = (\alpha - 1)\frac{\sum_m i_m f_m}{\sum_m i_m \varphi_m}. \tag{14}$$

2.3.2. Effects of improvements in material intensities of manufacturing processes

The variation of energy requirements due to improvements in material intensities can be defined (in the absence of metallurgical energy efficiency improvements) as:

$$\begin{aligned}\Delta e_{\text{manufacture}} &= \sum_m (1-\lambda_m) i_m(\alpha f_m + \varphi_m) - \sum_m i_m(\alpha f_m + \varphi_m) \\ &= -\sum_m \lambda_m i_m (\alpha f_m + \varphi_m),\end{aligned} \tag{15}$$

where λ_m stands for the improvements in material intensity (hence $\lambda_m \in [0,1]$) of mineral m in the manufacture of a given renewable energy technology. In addition, the λ coefficient is assumed to be independent of the mineral m, so that it can be interpreted as the average improvement in manufacturing material intensities, and Eq. (15) becomes:

$$\Delta e_{\text{manufacture}} = -\lambda \sum_m i_m(\alpha f_m + \varphi_m). \tag{16}$$

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

$$\lambda_{\text{offset}} = (\alpha - 1)\frac{\sum_m i_m f_m}{\sum_m i_m(\alpha f_m + \varphi_m)}. \tag{17}$$

2.4. Methodological limitations

A first limitation of this study comes from the undifferentiated treatment of all minerals in terms of energy intensities of mining scenarios. Indeed, mineral depletion dynamics will affect every mineral differently. For instance, the energy intensities of mining abundant minerals may not increase, or do so only negligibly, while scarce minerals will present steep increases in energy intensities. However, applying increasing energy intensities derived from copper data (a rather scarce metal affected by the effects of mineral depletion) to the rest of minerals is likely to overestimate the effects of mineral depletion (some metals such as iron or aluminium are not likely to be significantly affected by these effects in the timespan considered, due to high deposit concentrations [40]). Hence, this methodological choice only makes the findings and conclusions of the study stronger, as the low effects of mineral depletion are demonstrated even in a hypothetical situation where all minerals would be equally affected by geological depletion.

Limited data availability, particularly regarding the energy intensities of mining f_m and of mineral refining φ_m, is also a noteworthy limitation for this study. Indeed, there is significant uncertainty about the energy intensities of mining and mineral refining. In response, (i) a Monte Carlo simulation is conducted when assigning the energy intensities of mining each mineral to a probability distribution function, and (ii) rather unfavourable (because on the lower end) energy intensities for mineral refining are used (see the supplementary material associated with the paper), so that results regarding the capacity of metallurgical energy efficiencies to offset mineral depletion effects are conservative.

An additional important limitation is that the methodology assumes that minerals remain available for renewable energy technologies, although the energy consumption associated with their extraction increases. Hence, this study does not capture the possible effects of limited mineral availability (which can be due to mineral depletion as well as geopolitical or economic factors) on the net energy returns of renewable energy technologies. Indeed, limited availability of specific minerals may incentivise the substitution of scarce minerals by other minerals (e.g. substituting silver with copper in solar PV), which can be expected to result in a drop in the performance of the technology, and hence and in its net energy returns [57].

3. Results

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

3.1.1. Effects on the share of net energy returns

Fig. 3 shows the evolution of the share of net energy returns η over time (Eq. (7)) in the case of a medium initial EROI (see Table 1). Fig. 3 shows that the share of net energy returns is only marginally affected by the increases in the energy intensities of mining, even in the case of the highly increasing energy intensities scenario.

Then, Fig. 4 shows the variation of the share of net energy returns $\Delta\eta$ (Eq. (8)) obtained by 2060, both for the default analysis (barplots), and results obtained when conducting the Monte Carlo simulation (boxplots) — note that the variation of the share of net energy returns in independent of the initial EROI adopted. Even in the very high increase in energy intensities scenario, the decline in the share of net energy returns stays very low (lower than 2 percentage points, except for wind offshore — lower than 3 percentage points). Wind offshore is the technology most affected by increasing energy intensities of mining, due to high chromium and nickel intensities (corrosion prevention) and copper intensities (connection to grid). Results obtained with the Monte Carlo simulation show that the decline in the share of net energy returns are lower than 3 percentage points for all simulations, with the exception of wind offshore, for which the decline is above 3 percentage points in a few simulations (0.75% of simulations using the very high increase in energy intensities scenario). Hence, the uncertainty related to the current final energy intensities f_m of each mineral m is moderate, and unlikely to change the conclusions of this research — the influence of mineral depletion effects on net energy returns is found to be marginal in all simulations.

Results obtained when increasing and decreasing material intensities by 50% can be found in Supplemental Information (SI) and show robustness in the magnitude of $\Delta\eta$. The reason why the increasing energy intensities of mining have such moderate effects on the net energy returns of renewable energy technologies is that the energy invested due to mining processes represent only a minor share of total energy investments — see Table 2. Further, Fig. 5 shows the contribution of the energy invested due to mining processes for each renewable energy technology by mineral (so that the sum across minerals will add up to unity). The minerals with highest weight in the contribution depend upon the considered technology, with iron (for steel production) being the highest for solar CSP, aluminium the highest

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[4] The values are first compiled in primary energy terms from the literature and then converted in final energy terms using the MR-PSUT framework [59]. The code to determine the primary-to-final energy coefficient (0.54 for the mineral processing industry) is available in the online repository associated to the paper (link in Data Statement).

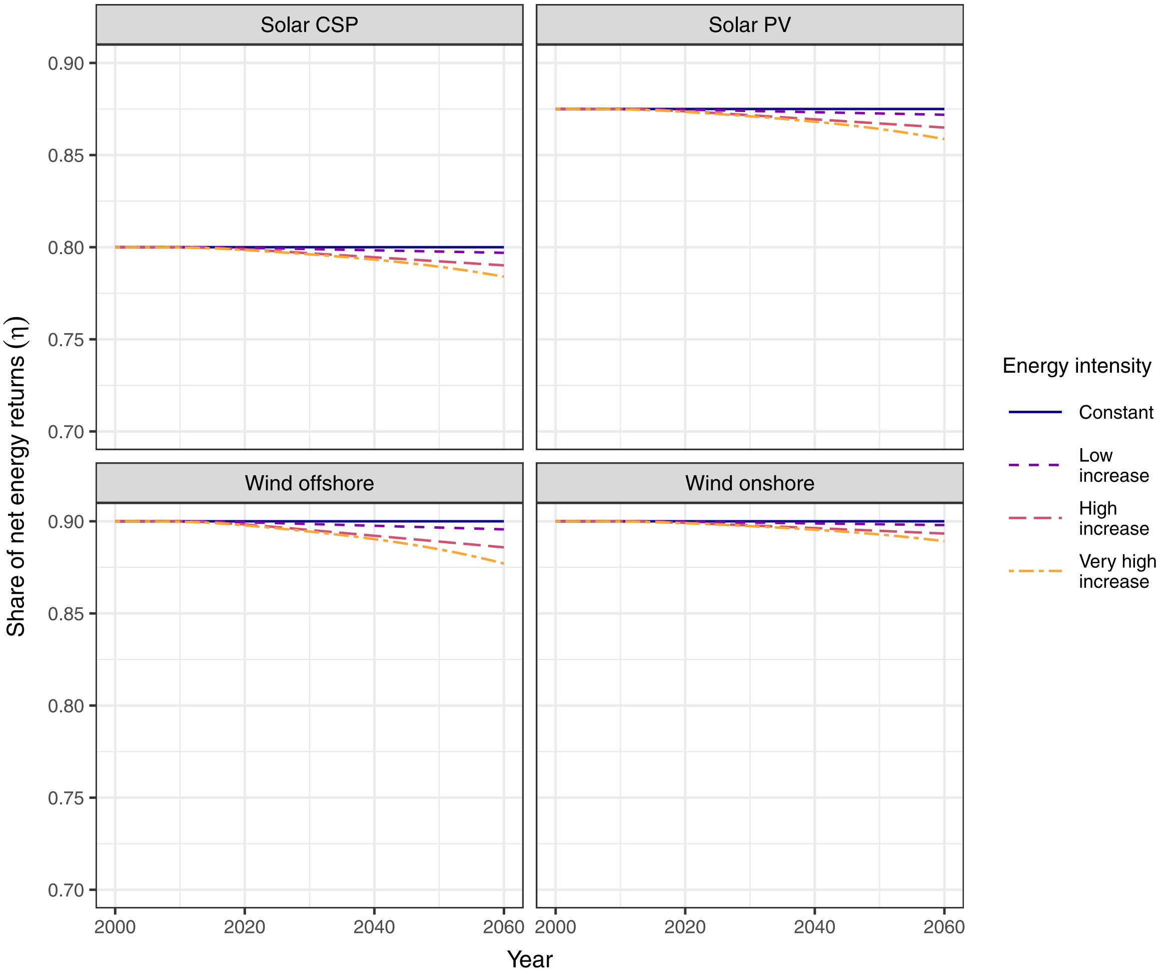


Fig. 3. Evolution of the share of net energy returns η over time when adopting a medium initial EROI, for different energy intensities of mining scenarios.

for solar PV, and chromium, nickel, copper, and iron (for stainless steel) being predominant for wind technologies. Such a breakdown should be considered carefully because of the uncertainty associated with the energy intensities of mining each mineral, and because of the different breakdown that would be observed for each subtechnology (e.g. monocrystalline, polycrystalline, CIGS, CdTe for solar PV). Indeed, the material intensities used are determined using weighted average of the market shares of each subtechnology in the case of solar PV for instance [57]. Despite this uncertainty, Fig. 5 shows that iron and aluminium are responsible for a very large fraction of the mining energy consumption for solar CSP and PV, respectively. As the mining of these metals is unlikely to be significantly affected by increasing energy intensities, the results are likely to significantly overestimate the effects of mineral depletion on the net energy returns of solar CSP and PV. In the case of wind power technologies, the effects are probably overestimated as well, as iron and aluminium account for approximately 20% of the mining energy consumption, and chromium, which is also a metal mined at relatively high concentrations [60, p.99], for approximately 30% of the mining energy consumption.

Table 2
Initial share of energy investments due to mining processes over total energy investments for each renewable energy technology.

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

Next, Fig. 6 combines Eqs. (4) and (8) to determine the decline in the share of net energy returns $\Delta\eta$ obtained as function of the increasing energy intensities of mining (represented by α). Fig. 6 shows that the share of net energy returns is only significantly affected for extremely high values of α: even a value of 30 for α would only decrease the share of net energy returns by approximatively 11 (wind onshore), 16 (solar CSP and PV), and 23 (wind offshore) percentage points. To decrease the share of net energy returns by a modest 5 percentage points, the value of α would need to reach a value of approximatively 7 for wind offshore, almost 10 for solar PV and solar CSP, and 14 for wind onshore, representing respectively a sevenfold, tenfold, and fourteenfold increase in the energy intensities of mining. The evolution of the shares of net energy returns η as function of the increasing energy intensities of mining (through the α coefficient) is further shown in SI.

3.1.2. *Effects on the Energy Return On Investment*

Fig. 7 shows that conversely to the variation in the share of net energy returns (Fig. 4), the variation in the EROI of renewable energy technologies may be significant, particularly when using the medium

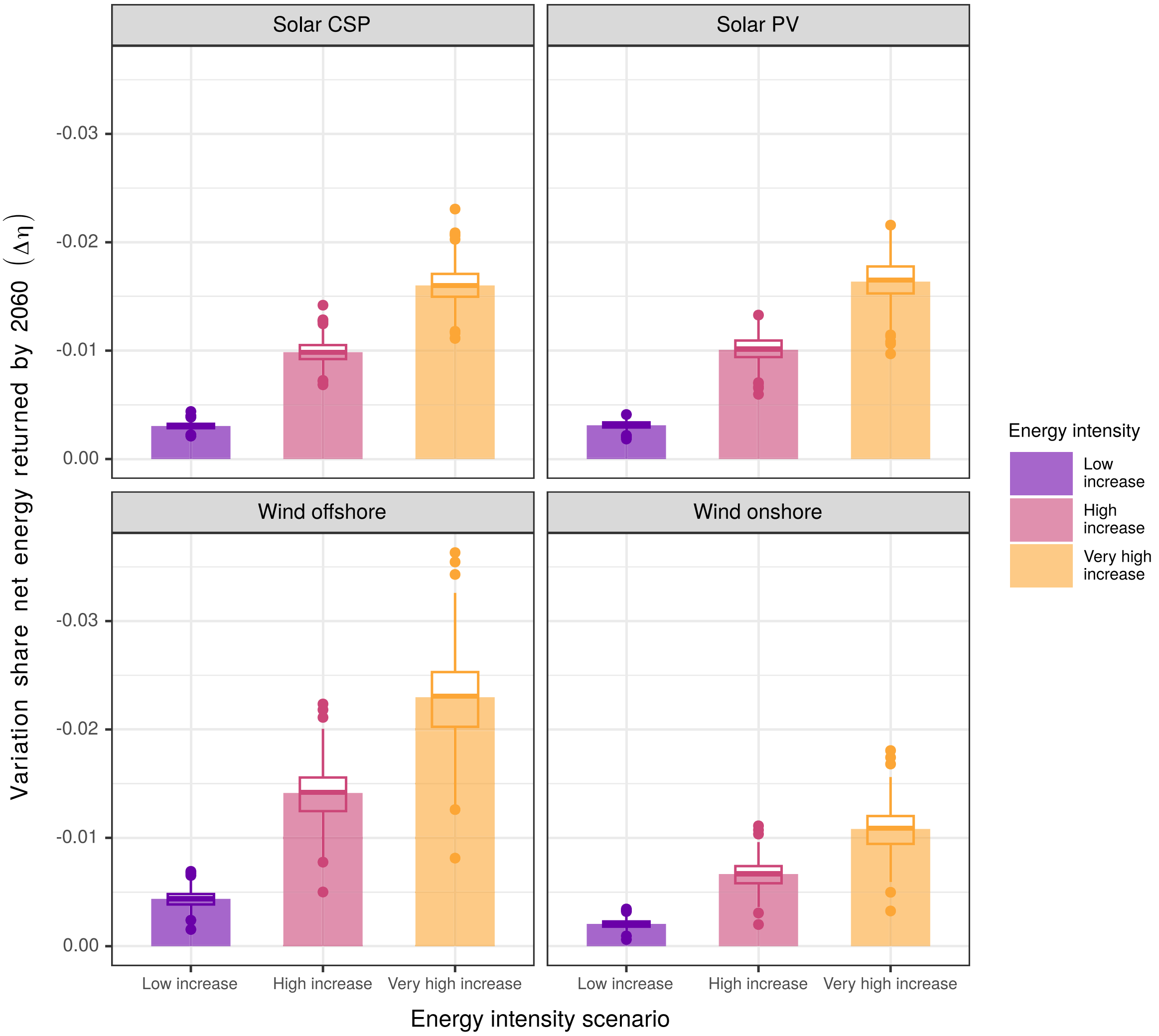
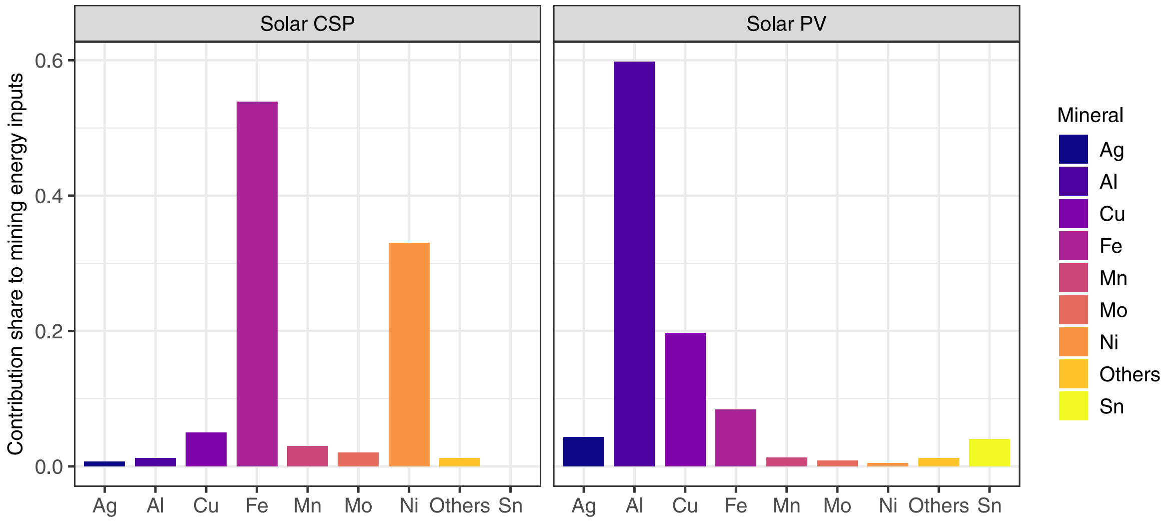


Fig. 4. Variation in the share of net energy returns $\Delta\eta$ by 2060, for different energy intensities of mining scenarios. Barplots shows the default analysis, and boxplots show the results of the Monte Carlo simulation. Values are independent of the value of the initial EROI.

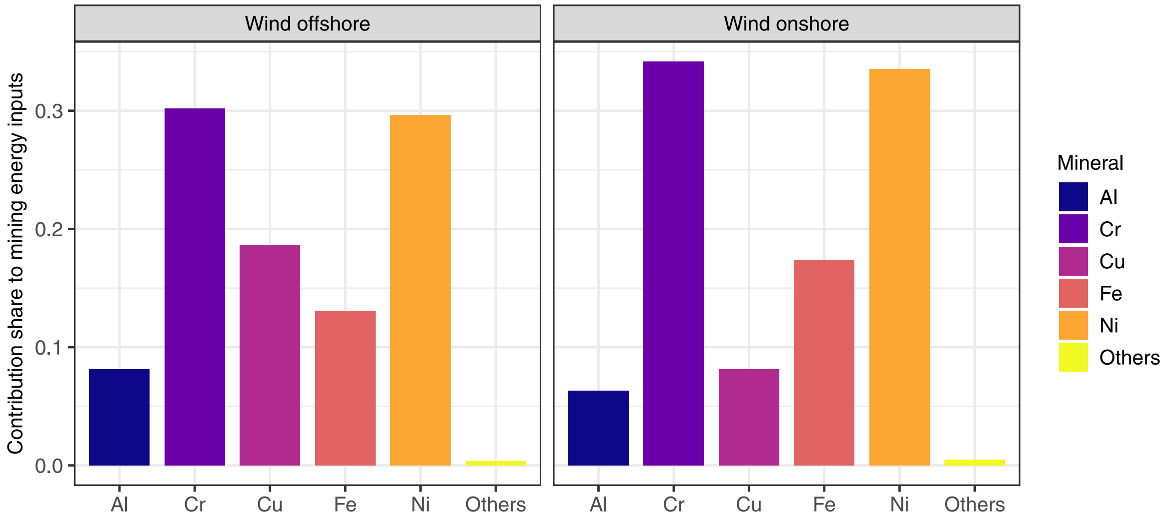
or high initial EROI values and applying the high or very high increase in mining energy intensities scenarios. In the most extreme case of wind offshore, when applying the very high increase in energy intensities scenario, the EROI may decrease from 20 to 13.7 (high initial EROI). Indeed, the higher the EROI, the lower the increasing energy requirements need to be to achieve a significant reduction in the EROI value, which is due to the non-linearity of the EROI metric (see SI). However, such significant decreases in EROIs do not translate into significant decreases in the share of net energy returns metric (Fig. 4). This counter-intuitive result provides a reminder that the EROI metric should be considered carefully. The evolution of the EROIs as function directly of the increasing energy intensities of mining (through the α coefficient) can also be found in SI.

3.2. Quantifying the capacity of technological levers to offset the effects of mineral depletion

Fig. 8 shows the improvements in technological factors (metallurgical energy efficiencies (β) and material intensities of manufacturing (λ)) that would be needed to offset a given value of increasing energy intensities of mining (represented by α), supposing that they are the only factor at play — the value of β and λ should be interpreted as the value required to offset mineral depletion effects assuming that the other factor remains constant over time. The figure shows that at a moderate level of α (approximatively, $\alpha \leq 2.5$, or $\alpha \leq 5$ for solar CSP), there is a reasonable value for the technological factors that offsets the increasing energy intensities of mining. For instance, an increase in metallurgical energy efficiencies by approximately 25% would offset an α coefficient of 2.5 for solar PV, wind offshore and wind onshore — only approximately 10% would be required for solar CSP. For comparison, the energy consumption of steelmaking and aluminium manufacturing in the US could be expected to decrease by respectively 24% and 26% if the best available technologies were systematically implemented (note that the practical minimums that could be obtained with R&D technologies are significantly lower) [67,69]. An improvement in material intensities of manufacturing by approximately 15% would also be sufficient to offset such value of α for solar PV, wind offshore and onshore, and approximately 8% for solar CSP — which seems reasonable in the light of the expected decrease by 25% and 30% in respectively the silicon and silver intensities of solar PV by the IEA [15, p.56]. Such results show that when taken together, these technical levers can significantly offset the increasing energy intensities of mining. However, mineral depletion effects are increasingly hard to offset as the value of α increases, and beyond a given (unknown) level of increasing energy intensities of mining, these technological parameters will not be able to offset mineral depletion effects.



a) Solar technologies



b) Wind technologies

Fig. 5. Breakdown of mining energy investments by mineral for each renewable energy technology, in shares of total energy investments due to mining processes. Ag: silver; Al: aluminium; Cu: copper; Cr: chromium; Fe: iron; Mn: manganese; Mo: molybdenum; Ni: nickel; Sn: tin.

4. Discussion

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

This work has shown that the effects of mineral depletion on the net energy returns of renewable energy technologies are limited. Indeed, for each of the three mining energy intensities scenarios used, the decline in the share of net energy returns of each of the four renewable energy technologies remain lower than 3 percentage points (Fig. 4). Significantly, such results are obtained without consideration of the technological levers that may contribute to offsetting increasing energy intensities of mining. The low influence of mining on the net energy returns of renewable energy technologies is due to the relatively low contribution of mining to the total energy invested for the manufacture and operation of renewable energy technologies (Table 2). It is noteworthy that this study assesses the impacts of mineral depletion on the net energy returns of renewable energy technologies independently of the ongoing debate regarding the actual and current net energy returns of such technologies (see for instance [76–79]). Consequently, the results obtained, in terms of variation of net energy returns, are independent from the current net energy returns of renewable energy technologies.

While there are significant uncertainties related to this study, the results are robust enough to back up the conclusions reached. First, the Monte Carlo simulation conducted shows that the uncertainties related to the energy intensities of mining each mineral are unlikely to substantially modify the results and conclusions (Fig. 4). Second, even when material intensities of renewable energy technologies are increased by 50%, the change in the share of net energy returns remains of the same order of magnitude as in the core result (see SI). Last, it is worth noting that the assumption of equally increasing energy intensities for all minerals, is a pessimistic assumption that tends to overestimate the effect of mineral depletion, hence strengthening the conclusions. Indeed, the mining of abundant minerals, such as iron and aluminium, is unlikely to be significantly affected by increasing energy intensities in the medium term due to high enough deposit concentrations.

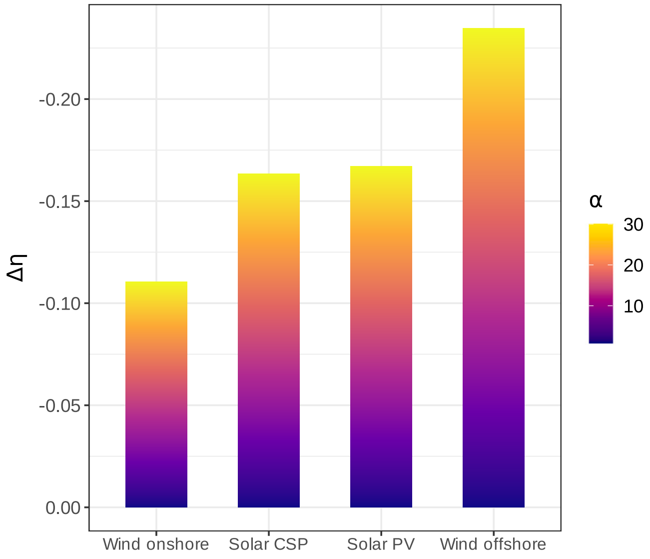


Fig. 6. Decrease in the share of net energy returns $\Delta\eta$ obtained for a given increase in the energy intensities of mining (represented by α) for each of the four renewable energy technologies considered. Values are independent of the value of the initial EROI.

Our results are consistent with the work of Harmsen et al. [47], which finds a decline in the EROI of wind turbines from approximatively 25.2 to 24.4 by 2050 (depending on the scenario), which represents a decrease of approximatively 0.1% in the share of net energy returns. However, the work by Harmsen et al. only considers copper; the present article's results show that the conclusion does not differ when including the whole range of minerals upon which the renewable energy technologies considered depend. Comparing with the work of Fizaine and Court [48] is more difficult, as the authors assess the evolution of EROIs as function of ore grades, and EROIs decline and tend to zero as ore grades tend to zero. This work expands and enhances the work by Fizaine and Court [48] by (i) clearly differentiating the energy requirements of mineral mining from those of mineral refining, which is crucial when focusing on the mining industry and on the effects of geological depletion, and (ii) providing a range of evolutions for the net energy returns of renewable energy technologies considering a range of realistic evolutions for the average future energy intensities of mining.

Results also show that the effects of mineral depletion on the net energy returns of renewable energy technologies only become substantial under extremely high increases in the intensities of mining (Fig. 6). Such high energy intensities of mining would however pose a range of serious constraints and challenges to both the mining industry and the broader economy. Indeed, the profitability of the mining industry may deteriorate as energy inputs (and inputs in general) increase dramatically, and the raw material monetary costs of the rest of industrial activities may increase considerably as a result of such high energy inputs required for mining processes. An increasingly difficult extraction of raw materials may also lead to a reallocation of productive capital and labour towards the mining sector, in a similar way to that which has been described in previous works for the energy sector [80,81]. Considering that all economic processes are based on raw materials inputs [82], and when possible, on cheap raw materials [83], such increases in monetary expenditures, capital and labour requirements of raw materials may have significant adverse effects on the economy, much earlier to affecting the net energy returns of renewable energy technologies.

4.2. *Capacity of technological factors to offset mineral depletion effects*

Results (Section 3.2) have shown that improving the energy efficiencies of metallurgical processes and the material intensities of renewable energy systems are technological levers that can contribute to reducing the energy investments required for the manufacture and operation of renewable energy technologies, hence somewhat compensating for the increasing energy intensities of mining. Results show that under moderate increases in the energy intensities of mining (approximatively, $\alpha \leq 3$, or a yearly increase rate of 2.8% over the period 2020–2060), it seems reasonable to think that these technological factors can offset increasing energy intensities of mining. However, it is clear that beyond a critical (unknown) value of α, such technological factors will not be able to compensate for mineral depletion effects.

Further, the improvements of all the considered technological factors are subject to constraints. Indeed, there are thermodynamic, as well as practical minimums, on the energy consumption of a given metallurgical process (see for instance the studies of the U.S. Department of Energy [67–69,84]), which limit the extent to which energy intensities of mineral refining can effectively decrease. Moreover, efforts to decarbonise the metallurgical sector, for instance using hydrogen as an energy vector [85,86], or carbon capture and storage techniques [87,88], may imply an increase in the energy consumption of some specific metallurgical processes. The material intensities of renewable energy technologies can be expected to decrease to some extent in the future [15], however, a minimum amount of materials will obviously be needed to obtain a reasonable performance, implying that there is a lower bound limit on the future material intensities of renewable energy technologies, the value of which remains unknown.

Last, it is worth noting that other technological factors that have not been considered in this study may also come into play. Particularly, the capacity factors of renewable energy technologies, which have been significantly increasing in recent years, notably in the case of wind turbines (onshore, as offshore is a relatively new technology) [89], are a crucial technological factor in respect to the energy output of renewable energy technologies. In the case of solar PV, the efficiency of modules has considerably increased in recent years [15,90], and may be a key technological factor determining the energy output of solar panels. Increasing the recycling input rate of manufacturing renewable energy technologies may also significantly decrease their energy requirements, although the extent to which recycled materials can be used for such high-tech applications is uncertain, and the literature on this topic remains scarce. In any case, future recycling rates will be constrained by different factors, such as the available flow of end-of-life materials [91,92], the use of minerals in forms which are extremely hard (when not impossible) to recover [93] (for instance recovering metals from superalloys), or the interdependency between different minerals, which adds complexity to recycling processes [94].[5]

4.3. *Other material constraints for the energy transition should not be overlooked*

Mineral scarcity and mineral depletion pose a set of challenges to the energy transition. This study has explored one particular channel through which mineral depletion may hinder the energy transition, i.e. through the potential effects of mineral depletion on renewable energy systems net energy returns. But other key challenges should not be overlooked and need further investigation, as well as consideration in energy planning and policies. The question of whether mineral endowments will be sufficient to meet a surging mineral demand remains under discussion, with different studies showing that future mineral

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[5] In such cases, recycling processes may require extremely high energy consumption to separate and purify the end-of-life materials in high quality metals, in some cases leading to energy requirements even higher than the ones for primary extraction [95]. Alternatively, the recycling of such hard to recycle materials may be much more akin to downcycling, whereby the minerals obtained after recycling are of degraded quality, and hence may not be suitable for highly technological applications such as renewable energy technologies.

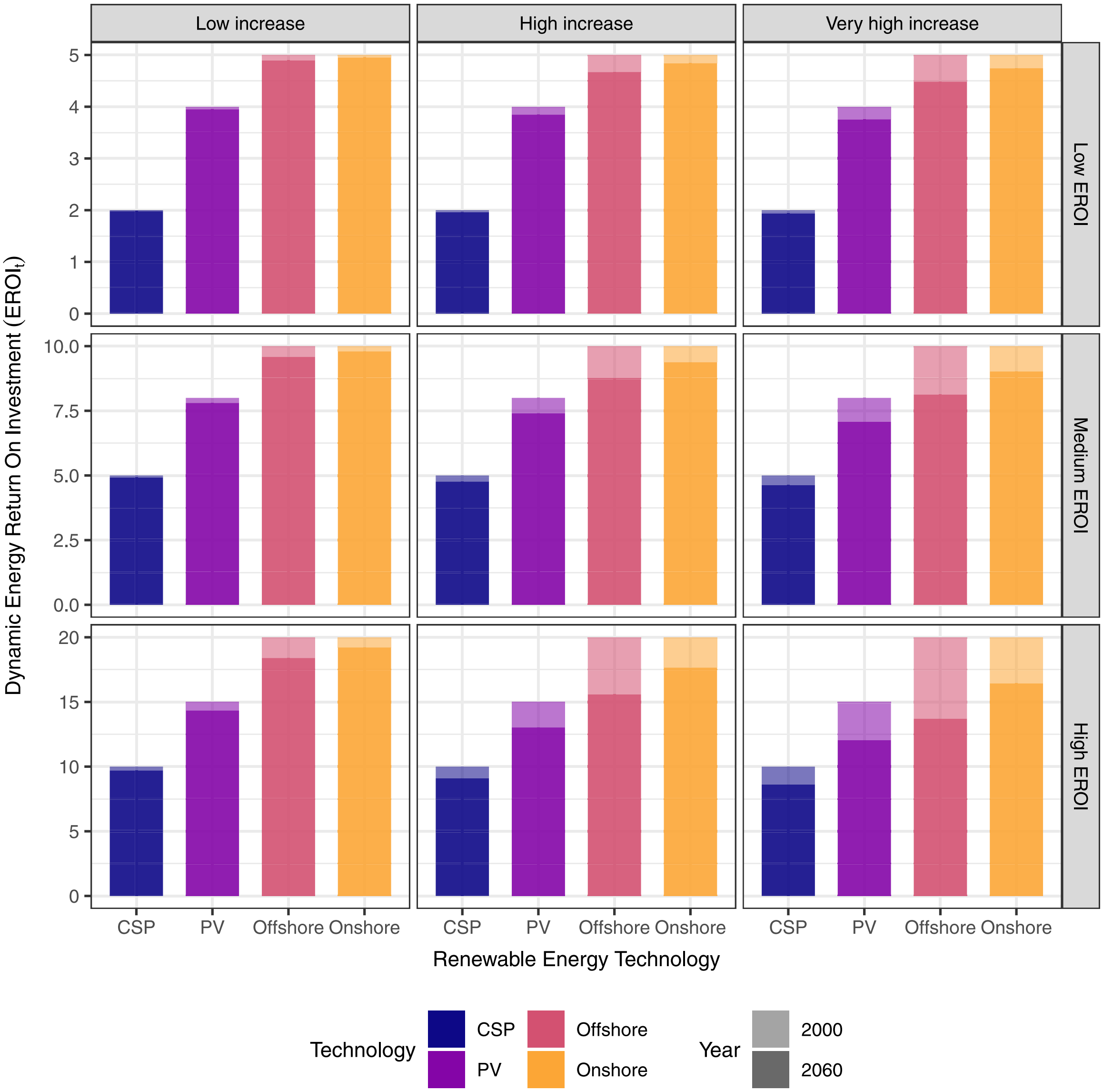

Fig. 7. Variation in the Energy Return On Investment of renewable energy technologies by 2060 for each of the low, medium and high initial Energy Return On Investment values (rows), and each of the mining energy intensity scenarios (columns).

requirements are likely to significantly exceed known reserves for specific minerals (see e.g. [18,20,96,97]), while some authors point to the fact that reserves will keep increasing as technological progress will make new deposits available (see e.g. [98–100]) — current dynamics show that indeed, estimated reserves and resources tend to increase over time as a result of exploration and technological progress [101], but the question of how such a trend will evolve is complex [102]. Additional concerns are related to the risk of supply bottlenecks [103–105], particularly in the context of the high geographical concentration for specific mineral deposits and of geopolitical tensions [106]. Last, the environmental impacts, for instance in terms of biodiversity loss [107,108] and pollution [109,110], as well as social impacts [111,112] of mining activities should not be diminished, particularly as mineral depletion dynamics will increasingly steer extraction towards lower quality deposits, thereby increasing environmental and social impacts [50].

4.4. *Implications of the non-linear behaviour of the EROI metric*

The findings also emphasise the importance of the metric used when conducting net energy analysis. Indeed, the results obtained when assessing the variation of EROI as function of increasing energy intensities (Fig. 7) can give, in some cases, the impression of high impacts of increasing energy intensities of mining on net energy returns. For instance, in the case of wind offshore, when applying the very high increase in energy intensities scenario, the EROI decreases from 10 to 8.1 with a medium initial EROI and from 20 to 13.7 with a high initial EROI. Such significant decreases in EROI values however translate in a decrease lower than 3 percentage points in the shares of net energy returns as shown in Fig. 4, which is what ultimately matters to society. The non-linearity of the EROI metric is further discussed in SI. An implication for the field of net energy analysis is that EROI values should be handled with care, and analysts would benefit from translating such values in terms of the corresponding share of net energy returns. A further implication, discussed in-depth in SI, is the fact that to avoid misleading extrapolations, trends should be established at the level of energy requirements, and then translated into their effects on the EROI.[6]

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[6] The extrapolation has often been attempted directly at the EROI level, constructing a curve linking the EROI of a given fossil fuel type (coal, gas, oil) to time (alternatively, to cumulative production) [80,113–116].

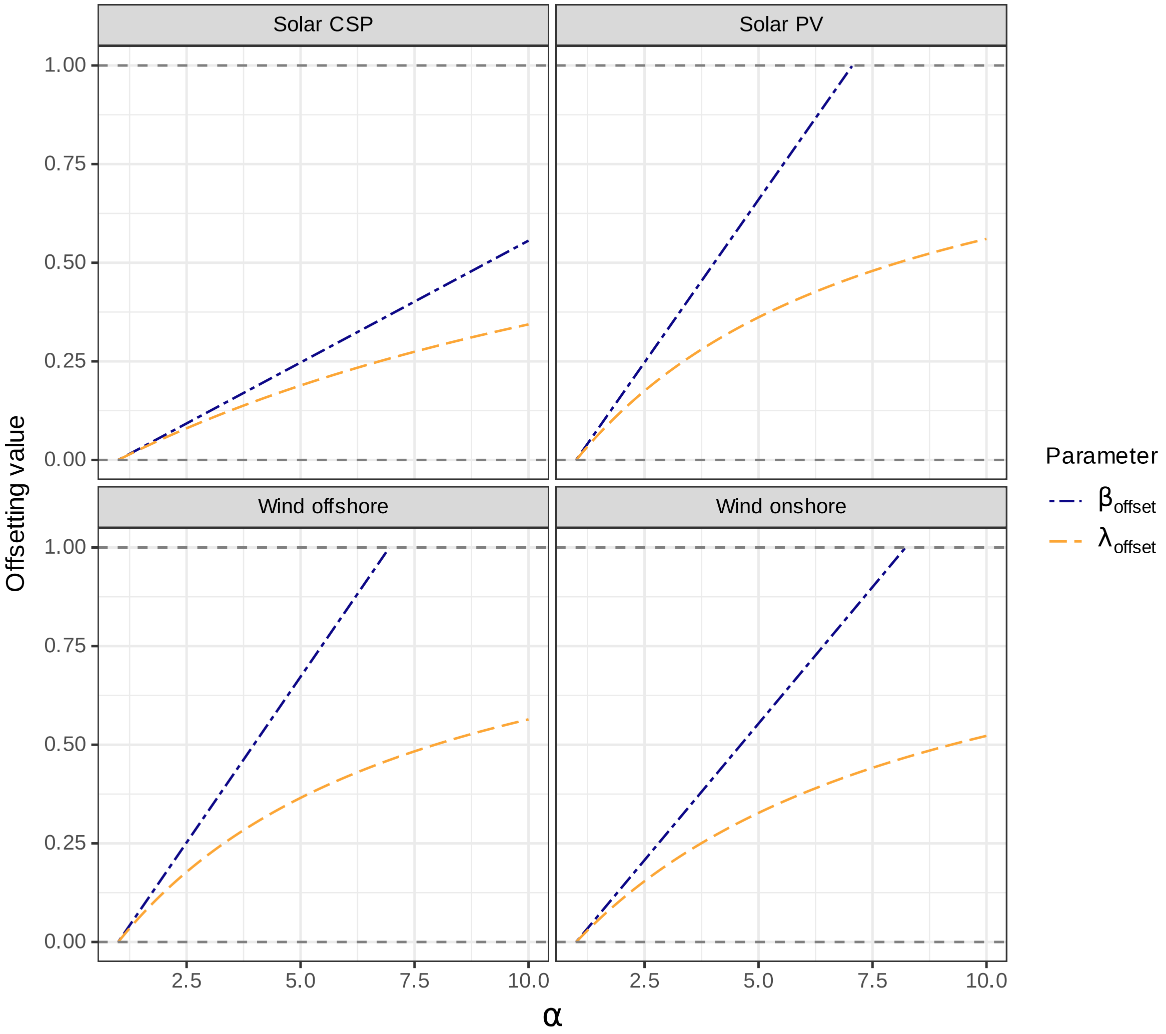

Fig. 8. Required value for improvements in metallurgical energy efficiencies (β) and material intensities of manufacturing (λ) to fully offset increasing energy intensities of mining (α), considering that each other factor remains constant. Each of the β and λ parameters evolve in the range $[0, 1]$, with 0 representing the current situation, and 1 representing a situation where the energy consumption of metallurgical processes and the material intensities of renewable energy technologies reach zero, respectively.

5. Conclusion

In this study, the effects of mineral depletion on the net energy returns of four renewable energy technologies (solar photovoltaic, concentrated solar power, wind onshore, and wind offshore) have been estimated. Results show that such effects will have a very limited impact on the net energy returns of renewable energy technologies. Indeed, the share of net energy returns is found to decrease by less than 3 percentage points by 2060 for all technologies (Fig. 4). The paper shows using a Monte Carlo simulation that results are robust to the uncertainties associated with the energy requirements of mining. Only under extremely high future energy intensities of mining are the net energy returns of renewable energy technologies substantially affected. Reaching such high energy intensities would however pose serious challenges to the mining industry (e.g. economic profitability), and to the broader economy (e.g. economic costs of raw minerals). Last, the paper has critically discussed the potential of technological factors to offset mineral depletion effects.

An important limitation of this study is that the effects of mineral depletion on the net energy returns of renewable energy technologies are analysed in isolation from other effects related to mineral scarcity and depletion. For instance, scarcity and shortages may disrupt supply chains and compel manufacturers to produce technologies of lower qualities (for instance avoiding the use of critical materials), particularly in a context of high geopolitical competition and tension. The effort to reduce reliance on critical materials may in turn lower the technologies' performance as well as their net energy returns. In general, further research needs to be conducted to better understand the risks posed by mineral scarcity and supply bottlenecks on the feasibility of the energy transition, and on the pace at which it may occur (which may vary depending on the region and sector analysed). Particular attention needs to be devoted to mitigation strategies, including the potential for recycling critical materials, extending products lifetimes, but also to reducing the use of critical materials in non-essential applications. Last, further research aiming at identifying a governance system and strategies to foster global cooperation, instead of competition, on access to critical materials and on the fair distribution of the benefits and burdens associated with their extraction, seems also urgently needed.

To conclude, mineral scarcity and depletion poses a set of urgent challenges to the energy transition. This work has investigated one of these challenges, and has shown that the effects of mineral depletion on the net energy returns of renewable energy technologies will be minor. Considering recent findings in the field of net energy analysis, the results suggest that the net energy returns of renewable energy technologies will remain of a similar order of magnitude to those of fossil fuel energy, despite the effects of mineral depletion. Hence, renewable energy technologies have the potential to deliver sufficient

Table A.1
Nomenclature.

Symbol	Description
Letters	
e	Future final energy intensity of mining, specific to a mineral m.
f	Current final energy intensity of mining, specific to a mineral m.
i	Material intensity of a renewable energy technology, specific to a mineral m.
Greek letters	
α	Coefficient modelling the increase in energy intensities of mining.
β	Coefficient modelling the increases in energy efficiency of metallurgical processes.
η	Share of net energy returns of a given renewable energy technology.
λ	Coefficient modelling the increases in material efficiencies of manufacturing.
φ	Final energy intensity of mineral refining, specific to a mineral m.
Others	
CF	Capacity factor.
L	Average lifetime.
e_{input}	Energy input required to manufacture and operate a renewable energy technology.
e_{output}	Energy output delivered over the lifetime of a renewable energy technology over.
Δe	Total variation of energy inputs.
$\Delta e_{\text{manufacture}}$	Variation of energy inputs due to changes in material intensities of manufacturing.
Δe_{mining}	Variation of energy inputs due to mineral mining.
$\Delta e_{\text{refining}}$	Variation of energy inputs due to mineral refining.
Acronyms/abbreviations	
EROI	Energy Return On Investment
PV	Photovoltaic
CSP	Concentrated Solar Power
Subscripts	
m	Refers to a given mineral.
t	Refers to time.
offset	Refers to the value of the parameter that offsets mineral depletion effects.

net energy to provide decent living standards for all, despite the adverse effects of mineral depletion.

Data statement

The input data is available as supplementary material (see spreadsheet file): https://doi.org/10.1016/j.energy.2023.130112. The R code needed to fully replicate the analysis is available in the following online repository: https://doi.org/10.5518/1469.

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, Validation, Writing – review & editing, Supervision, Funding acquisition. **Peter G. Taylor:** Conceptualization, Validation, Writing – review & editing, Supervision. **Jonathan B. Norman:** Conceptualization, 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.

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Appendix A. Nomenclature

See Table A.1.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.energy.2023.130112.

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