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Environmental impacts and demand-supply balance of minerals for the transition to a low-carbon energy system

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Abstract

Comprehensive perspectives are essential to address environmental problems that have become more challenging in recent years. Energy problems are one of the most fundamental challenges that humankind faces. Therefore, it is necessary to examine whether long-term energy scenarios are sustainable from a wide range of viewpoints, including their use of mineral resources. This paper focused on the energy-mineral nexus as a one of the examples of complex interconnection and investigated the availability of minerals in the transition to a low-carbon energy system. Moreover, in order to give more comprehensive perspectives to policy makers and industries, the environmental impacts associated with mining under low-carbon energy scenarios were evaluated. Results indicate that the introduction of low-carbon technologies affects future mineral demand significantly and supply may not keep up with increased demand without recycling. Furthermore, the environmental impacts (for example, CO2 emissions, water pollution and land uses) caused by increase in mineral production could be concentrated in specific countries such as China, Australia and South Africa, and the energy demand for mining could be also increased massively in Congo and Chile. A circular economy promoting recycling, remanufacturing plus strategies which reduce and reuse should be considered in parallel to introducing low-carbon technologies to boost mineral supply and reduce the environmental impacts.

Keywords: Low-carbon energy system, critical mineral, environmental impact, life cycle analysis, sustainability

1. Introduction

Environmental problems are becoming more complicated at local and global scales and society should address these problems by taking the complex interconnections of various environmental and resource issues into account. The energy-mineral nexus, for example, is an important complex interconnection that should be considered to realize a sustainable society [1]. This is because the introduction of low-carbon technologies – which have significant potential to mitigate global warming – require specific mineral resources in significant quantities. The increase in mineral production caused by an expanded uptake of those technologies could raise energy consumption (from mining required resources) and make additional environmental impacts. In other words, the strategy that only considers one aspect could bring about serious problems in other aspects which are not considered.

Based on the concerns described above, some papers have examined interactions between energy systems and mineral resources, and most of these have calculated the mineral demand for the expected introduction of low-carbon technologies [2]–[7]. However, previous studies have typically compared the projected demand with current production or reserves, and there are few papers that evaluated whether future supply can meet projected demand. That is, the viewpoint of the supply side tends to be missing or under-emphasised. Since resource constraints become obvious not only when depletion occurs but also

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when supply cannot keep up with the rate of increase in demand, it is important to project mineral supply in parallel to demand forecasts. Additionally, the change in environmental impacts accompanying mining under the transition to a low-carbon energy system has largely been missed up to now [8]. Policy makers and industry, however, need to know the potential extent of environmental impacts that could be brought about by an increase in mineral production, in order to make appropriate policy decisions.

Therefore, this paper addresses the following questions to clarify the elements required to achieve a sustainable energy transition in terms of energy, minerals and environment; (1) What quantity of minerals could be required in a transition to a low-carbon energy system? (2) Can we increase mineral production sufficiently to keep up with the increased demand? (3) Which countries will incur increased environmental impacts associated with mining? (4) What solutions do we have to mitigate or avoid potential future supply problems? Regarding question (4), we have focused on the effect of recycling as one of the potential strategies [9]–[11].

2. Author Artwork

This paper considers a low-carbon energy system to be comprised of several target technologies, namely, solar power systems, wind power systems and next-generation vehicles (hybrid electric vehicles, plug-in hybrid electric vehicles, electric vehicles, hydrogen fuel-cell vehicles). 15 key minerals used in these target technologies are analysed. Fig. 1 shows the conceptual framework of this study, which consists of four phases. Details of each phase are explained in following sections. Phase 1 and 2 are adapted from the authors` earlier study [7].

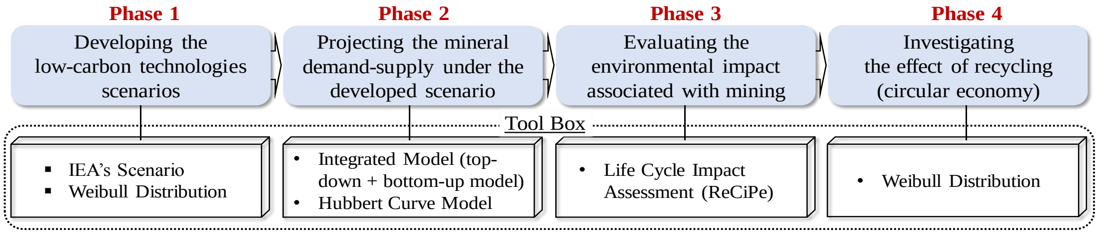

Fig.1. Analysis flow of this study that consists of four phases.

2.1. Developing the low-carbon technologies scenarios (Phase 1)

In this paper, we used the data obtained from the Energy Technology Perspectives 2017 [12] that was published by the International Energy Agency (IEA) to define low-carbon technology scenarios. In this case, three scenarios were set as per the Reference Technology Scenario (RTS), 2 ℃ Scenario (2DS) and Beyond 2 ℃ Scenario (B2DS), and a summary of each scenario is described in Table 1.

Table 1. Summary of each scenario used in this study [12].

Scenario	Explanation
RTS	RTS takes into account the current energy system and voluntary targets of each country pledged in the Paris Agreement, which will lead to a temperature rise of 2.7 ℃ by 2100.
2DS	2DS is a major climate change mitigation scenario from the IEA, delineating a path to keep global temperature rise below 2 ℃ in 2100.
B2DS	B2DS is the most ambitious scenario, which lays out an energy system pathway with achieving 1.75 ℃ of temperature increase.

The annual introduced amount (GW or number of vehicles) was estimated by equation (1) based on the cumulative generation capacity (GW) and in-use stock (number of vehicles) obtained from each scenario.

$$I_t = S_t - S_{t-1} + \sum_{a=0}^{a_{max}} I_{t-a} g(a) \qquad (1)$$

where: I_t is the introduced amount (which accounts for retirement of end-of-life capacity or product), S_t is the accumulated stock amount in year t, a is the number of years of use of the product and $g(a)$ is the product life distribution (which is being used here to estimate the retirement of end-of-life product in any given year). In this calculation, we set many assumptions such as average product lifetime, shape parameter and technology market share. For detailed assumptions, please refer to the authors` previous article [7].

2.2. Projecting the mineral demand-supply under the developed scenario (Phase 2)

In the demand projections, a number of alternative models were used to calculate the future demand, with consideration of two factors of demand increase, which are (a) the global growth in population and economic activity, and (b) the expansion of low-carbon technologies. Regarding the supply projection, a Hubbert Curve Model [13] was utilized. The Hubbert Curve Model has the advantage of being able to estimate future supply trends from only historical production trends and reserves or resources data, and has been used widely for non-renewable resources. The detailed explanations of each model are described in the sub-sections which follow.

2.2.1. Demand projection model

The demand projection is based on models developed by the authors previously [7]. Equation (2) estimates future mineral demand due to (a) the global growth in population and economic activity.

$$f(x) = \alpha x^3 + \beta x^2 + \gamma x + \delta \tag{2}$$

where $f(x)$ is the metal consumption per capita (tonnes), x is GDP per cap and variables are determined by fitting in developed countries such as United States and Japan.

In addition to this factor, mineral demand caused by (b) the expansion of low-carbon technologies is considered by equation (3).

$$M_{p,t} = I_{p,t} \cdot \mathrm{W}_{p,t} \tag{3}$$

where $M_{p,t}$ is mineral demand in a specific product p in year t, and $W_{p,t}$ is the content of the target mineral contained in the product p (i.e. the material intensity). Material intensity is not considered to improve in the period of consideration.

Eventually, the cumulative mineral demand $C_{t_n}^{t_1}$ that takes in account two factors described above from the starting year t_1 to the year t_n is calculated by equation (4).

$$C_{t_n}^{t_1} = \int_{x_{t_1}}^{x_{t_n}} f(x)dx + \sum_{t=1}^{n} \sum_{p \in P} M_{p,t} \tag{4}$$

where p represents a set of target products.

2.2.2. Supply projection model

Future potential supply of minerals was estimated by using a Hubbert Curve Model. In this model, the cumulative production $Q(t)$ up to year t is expressed by equation (5):

$$Q(t) = \frac{URR}{1 + e^{-r(t-t_{max})}} \tag{5}$$

where, URR is the ultimately recoverable resources, t_{max} is the year of peak production, and r is the slope constant. Now, when the peak production assumed is P_{max}, the URR can expressed by:

$$\text{URR} = \frac{4P_{max}}{r} \tag{6}$$

Therefore, the annual production is given by equation (7).

$$P(t) = \frac{dQ(t)}{dt} = \frac{2P_{max}}{1 + cosh\{r(t - t_{max})\}} \tag{7}$$

Basically, URR is estimated as the sum of historical cumulative production and reserves [2]. However, the quantity of reserves could change significantly over time reflecting the market situation (value of mineral) and the technological performance in extraction, as well as new discoveries [14]. Hence, the quantity of "resources" (a greater figure than reserves, but with higher uncertainty) was used to calculate URR in this study to examine the maximum production that could be extracted potentially in the future.

2.2.3. Demand-supply balance analysis

Based on the demand and supply projections described above, the demand-supply balance in the starting year t_1 to the year t_n was evaluated by equation (8).

$$D_{t_n}^{t_1} = \frac{\sum_{t=1}^{n} \theta_t}{n} \tag{8}$$

where θ indicates the scale of supply shortage in year t, and was estimated using the following:

$$\theta_t = \frac{M_t - P_t}{M_t + P_t} \tag{9}$$

In this case, it was assumed that $\theta = 0$ when $M_t < P_t$.

2.3. Evaluating the environmental impact associated with mineral supply (Phase 3)

This study focuses on the environmental impacts caused by an increase in mineral production, because mining can cause significant damage to both ecosystems and human health. Nevertheless, this viewpoint has been largely unquantified until now, therefore, this study is the first time for this to be evaluated under the consideration of a low-carbon energy transition.

This study considers the following standard environmental impact categories by referring to the literature [14]: Climate Change, Ozone Depletion Potential, Terrestrial Acidification, Freshwater Eutrophication, Marine Eutrophication, Human Toxicity, Photochemical Oxidant Formation, Particulate Matter formation, Terrestrial Ecotoxicity. Freshwater Ecotoxicity, Marine Ecotoxicity, Ionizing Radiation, Agricultural Land Occupation, Urban Land Occupation, Natural Land Transformation, and Water Depletion. The cumulative environmental impact $E\,{}_{t_n}^{t_1}$ in a specific region from the starting year t_1 to the year t_n was estimated by equation (10):

$$E\,{}_{t_n}^{t_1} = \sum_{t=1}^{n} \sum_{r \in R} (P_t \cdot X_r) \tag{10}$$

where, P_t is the mineral production in year t that is estimated by equation (7), X_r is the environmental impact intensity that is given as impact per kilogram and obtained from literature [15], [16], and r indicates a set of target environmental impacts. In this case, each environmental impact was normalized from 0-1 before integration. In addition, this study estimated the energy demand associated with mining as well. Impact rates (impact per kilogram) are considered to be constant across the period of consideration, despite real concerns that declining grades, complex ores and deeper mining may increase the impacts over time.

2.4. Investigating the effect of recycling (Phase 4)

The circular economy is considered as one important concept in the creation of a sustainable society, and recycling of end-of-life products is one aspect of this that has been heavily focused-on in recent years. However, there are few studies focusing on the opportunity for recycling in low-carbon technology industries [17], [18], compared with mobile phones and personal computers [19]–[23]. One reason for this, perhaps, is the longer lifetimes of many low-carbon technologies and their low volumes (until recently), and the uncertainty about their recyclability. Although the authors calculated the potential additional supply from recycling low-carbon technologies previously [7], demand-supply balance was not adequately considered. It is effective information for policymakers and industries regarding how recycling of these new technologies would affect the future demand-supply balance and the environmental impacts. In this study, therefore, future mineral supply considering recycled material flows from low-carbon technologies was calculated by equation (11).

$$P_t' = P_t + O_t \cdot Recycling\ rate \tag{11}$$

where O_t is the amount of discarded minerals in year t and was estimated by the Weibull distribution. In this study, the $Recycling\ rate$ is set as 90% for all minerals to simplify the estimation of the potential. However, it should be noted that the recycling rate could vary depending on multiple factors such as market size, size of products, location, regulations, etc. and that there is no guarantee that 90% recycling could be practically achieved – although in its favour, large-scale renewable energy plants are often high density “deposits” of minerals that would make them attractive for recovery through recycling [24]. It is anticipated that recycling would not just reduce the need for additional primary mineral supply, but would likely reduce environmental impacts simultaneously.

3. Results

Fig. 2 indicates the estimated annual demand and supply of mineral resources and recycled quantities from low-carbon technologies when assuming a 90% recycling rate. In this paper, the target period is from 2015 to 2060 based on the IEA’s scenarios [12], and only indium, dysprosium and lithium are presented as representative of minerals used in solar power systems, wind power and next-generation vehicles respectively (although 15 metals are analysed). It can be observed that the introduction of low-carbon technologies affects future mineral demand significantly, and supply may not keep up with demand increases, particularly without recycling. The summary of demand-supply analysis in the case of 2DS as calculated by equation (8) is shown in Fig. 3. It can be seen that minerals used in solar power systems, such as tellurium and silver, and minerals for next-generation vehicles such as nickel would have severe supply constraint potential up to 2060. From a dynamic perspective, supply constraints of indium could occur around 2030 and the risk or magnitude of shortages could increase out to 2060. On the contrary, in the case of dysprosium and lithium, the supply shortage could be a short-term problem as there is not a large observed divergence between demand and supply, considering recycling, out to 2060 (see Fig. 4).

Fig. 5 shows the cumulative environmental impact associated with mining from 2015-2060. We chose 15 countries where mining is currently important for supplying materials for low-carbon technology. The country where the largest environmental impact could occur is indicated to be China (mostly dysprosium and neodymium), followed by Australia (mainly from nickel and silver). These countries produce a lot of minerals that are vital for the functionality of low-carbon technologies and have large quantities of resources, which makes their impacts higher than other countries. Additionally, South Africa and Mexico, where there is projected large supply of platinum and silver respectively, show high values as well.

The calculation of energy demand for the mining of target minerals is shown in Fig. 6 and 7. It can be seen that the energy demand is expected to increase significantly in the future, especially in Congo, where the energy demand will increase by more than 10 times in 2060 compared with 2015, due to the increase in production of cobalt.

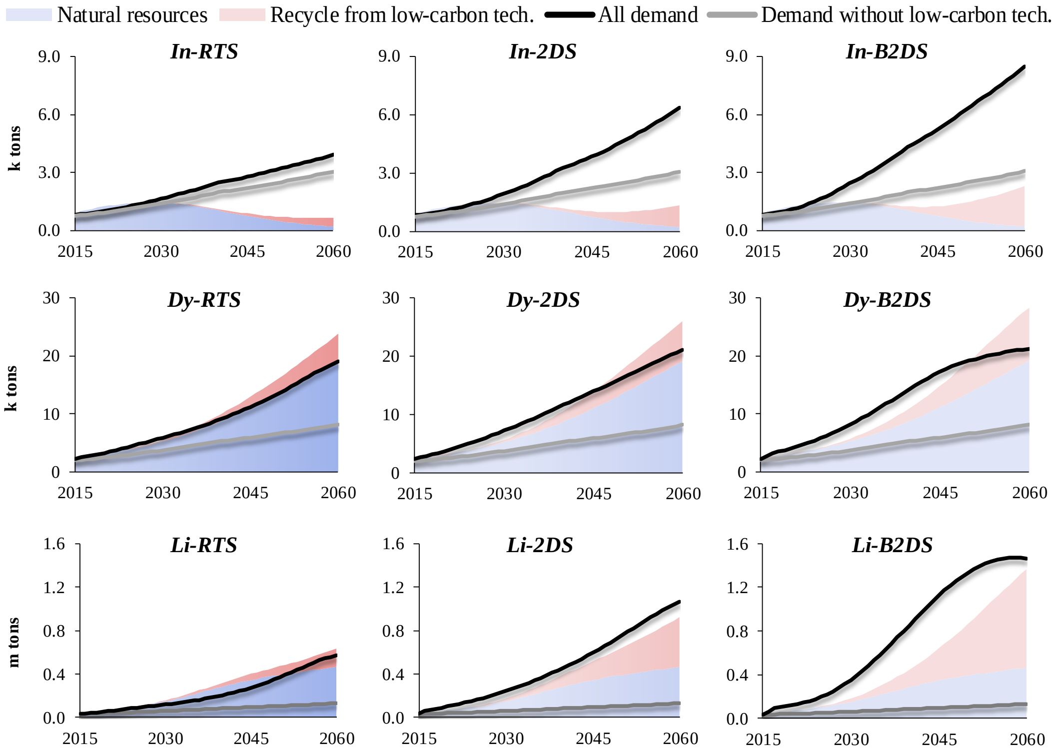

Fig. 2. Potential of future mineral demand, supply and recycling amount in the low-carbon energy scenario from 2015-2060.

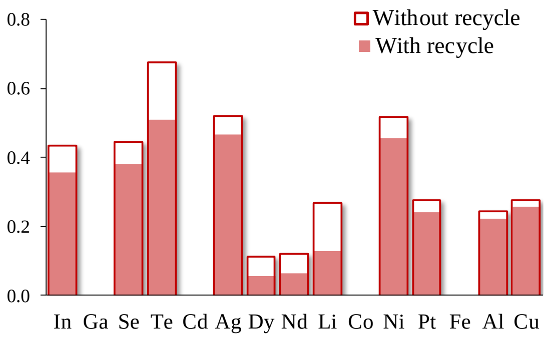

Fig. 3 Demand-Supply Balance in the case of 2DS average from 2015-2060 estimated by equation (8). Where the vertical axis indicates the scale of demand-supply disruption in the target period and larger value represents greater gap between the expected mineral demand and supply amount.

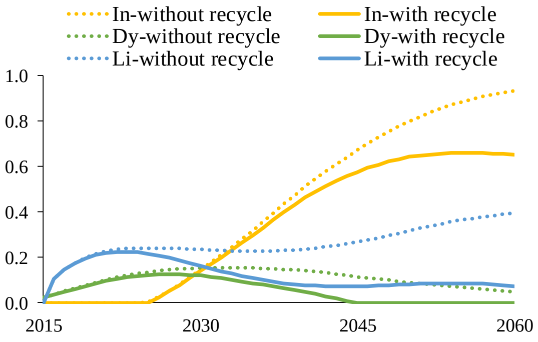

Fig. 4 Dynamic perspectives of demand-supply balance in the case of 2DS estimated by equation (9). Where the vertical axis presents the annual scale of demand-supply disruption in each year. 0 indicates there is not gap between demand and supply, and larger value indicates there is greater gap in that time.

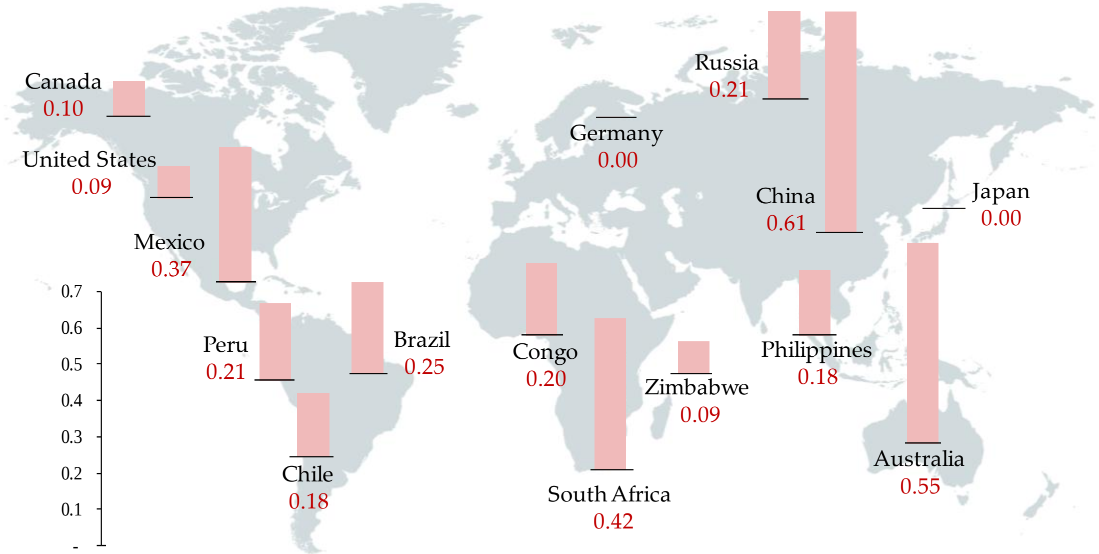

Fig. 5. The cumulative environmental impacts for production of target minerals under the low-carbon energy scenario from 2015-2060 (the value was integrated for all impacts after normalization from 0 to 1).

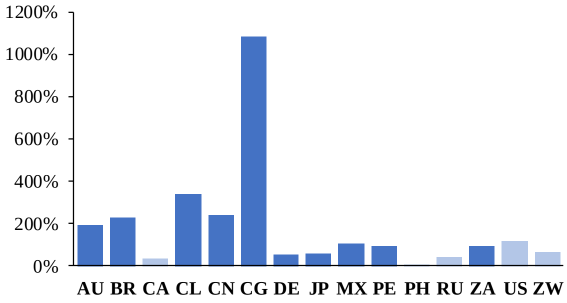

Fig. 6. Ratio of energy demand associated with mining between in 2015 and 2060; country name abbreviations are accordance with [25]

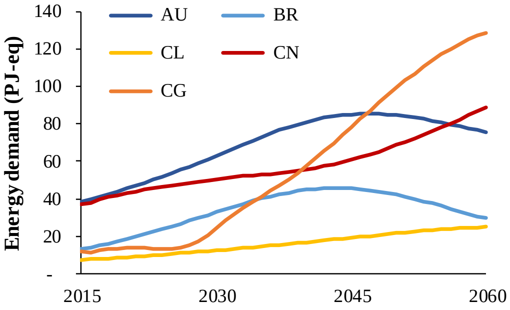

Fig. 7. Dynamic perspectives of energy demand associated with mining from 2015-2016 in the case of top 5 countries.

4. Discussion

Based on the analysis of results incorporating estimates of known resources, it is indicated that mineral supply constraints could occur under the transition to a low-carbon energy system. Therefore, it is doubtful that the IEA's energy scenario is sustainable in terms of currently known mineral availability (acknowledging that new mineral discoveries can be made, together with technology improvements which use fewer resources). Moreover, the environmental impact associated with mining of minerals used in low-carbon technologies could severely impact developing countries such as South Africa and Congo, as well as China and Australia. This means that the introduction of low-carbon technologies could affect both ecosystems and human health of local residents because the environmental and safety regulations are not fully prepared in many cases in these developing countries [26]. Therefore, it is necessary to tighten these regulations looking ahead to the future demand increase. In addition to this, recycling of low-carbon technologies can be considered one of the promising options to address supply constraints. It will be effective in reduction of environmental impacts in developing countries as well as boosting supply volumes. Furthermore, as Figure 6 and 7 indicate, it is also important to generate the energy used for mining in a clean way. That is, it may be necessary to introduce low-carbon technologies even to countries where they are not currently expected to introduce these technologies to a large extent, such as Congo. Here, it should be noted that despite the fact that increase in mineral production due to the expansion of low-carbon technology make additional energy demand, this feedback loop has not been accounted in this study.

Based on the results, it is apparent that the following strategies could be considered to achieve a sustainable energy transition in terms of energy, minerals and environment: (a) Establishing environmental regulations and better practices in the mining industry in developing countries; (b) developing technology to minimize the environmental impact that accompanies mining; (c) investigating technologies that use “less” or “non” critical materials so that they can reduce demand for these minerals; (d) designing technology components that are easily disassembled and recycled; (e) research into recycling technology with environmental friendly processes; (f) creating business models to build closed-loop cycles for low-carbon technologies in parallel to introducing these technologies.

5. Conclusion

The main purpose of this study was to clarify factors that are needed to realize a sustainable energy transition in terms of energy, minerals and environment. To this end, we examined the availability of minerals in low-carbon energy scenarios by predicting the mineral demand-supply balance including potential recycling flows from low-carbon technologies based on the IEA’s scenarios. Additionally, the environmental impact caused by a subsequent increase in mineral production, which had not been comprehensively investigated until now, was evaluated by mineral supply projection and the use of LCA indicators.

The results indicate that mineral demand will increase significantly for the expansion of low-carbon technologies and that the long-term energy scenarios presented by the IEA are not sustainable in terms of currently known mineral availability. Furthermore, the environmental impacts caused by the increase in mineral production will be concentrated in specific countries such as China, Australia and South Africa. Moreover, it is indicated that the energy demand required to increase mineral production will also increase significantly such as in Congo and Chile. Therefore, establishment of environmental regulations and better working conditions in the mining industry in these countries, and development of recycling processes in an eco-friendly way should be considered to minimize environmental and health impacts.

In conclusion, the strategies that take into account the interconnection between energy, minerals and environment are indispensable to realize a sustainable energy transition. Accelerating a circular economy including recycling, reducing and reuse in parallel with introducing low-carbon technologies could be one strategy to address the problems presented here.

Conflict of Interest

The authors declare no conflict of interest.

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