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Total material requirement for the global energy transition to 2050: A focus on transport and electricity

Takuma Watari[a,b,*], Benjamin C. McLellan[a], Damien Giurco[b], Elsa Dominish[b], Eiji Yamasue[c], Keisuke Nansai[d,e]

[a] Graduate School of Energy Science, Kyoto University, Yoshida Honmachi, Sakyo-ku, Kyoto, 606-8501, Japan
[b] Institute for Sustainable Futures, University of Technology Sydney, Ultimo, NSW, 2007, Australia
[c] School of Science and Engineering, Ritsumeikan University, 1-1-1, Noji-Higashi, Kusatsu, Shiga, 525-8577, Japan
[d] Center for Material Cycles and Waste Management Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki, 305-8506, Japan
[e] Integrated Sustainability Analysis (ISA), School of Physics, The University of Sydney, Camperdown, NSW, 2006, Australia

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ABSTRACT

Global energy transitions could fundamentally change flows of both minerals and energy resources over time. It is, therefore, increasingly important to holistically and dynamically capture the impacts of large-scale energy transitions on resource flows including hidden flows such as mine waste, as well as direct flows. Here we demonstrate a systematic model that can quantify resource flows of both minerals and energy resources under the energy transition by using stock-flow dynamics and the concept of Total Material Requirement (TMR). The proposed model was applied to the International Energy Agency's scenarios up to 2050, targeting 15 electricity generation and 5 transport technologies. Results indicate that the global energy transition could increase TMR flows associated with mineral production by around 200–900% in the electricity sector and 350–700% in the transport sector respectively from 2015 to 2050, depending on the scenarios. Such a drastic increase in TMR flows is largely associated with an increased demand for copper, silver, nickel, lithium and cobalt, as well as steel. Our results highlight that the decarbonization of the electricity sector can reduce energy resource flows and support the hypothesis that the expansion of low-carbon technologies could reduce total resource flows expressed as TMR. In the transport sector, on the other hand, the dissemination of Electric Vehicles could cause a sharp increase in TMR flows associated with mineral production, which could offset a decrease in energy resource flows. Findings in this study emphasize that a sustainable transition would be unachievable without designing resource cycles with a nexus approach.

1. Introduction

Transitioning to a low-carbon energy system is vital for realizing sustainable development, and has already been under way for the last few decades. Solar and wind power systems, for example, provided 328 TW h and 958 TW h globally in 2016, which were approximately 10 and 3 times respectively, compared to 2010 (IEA, 2018a). According to a report published by the International Energy Agency (IEA, 2017), over 70% of electricity must come from renewable energy sources (including hydro) in 2050 in order to hold global temperature rise within 2°C up to 2100. Considering the current energy system where renewable sources only provide around 14% of total demand, this change can be considered extreme. Additionally, decarbonization will also need to occur in the transport sector as well. The EV30@30 Campaign, which was launched at the 8th Clean Energy Ministerial (CME) meeting in June 2017, is aiming to reach a 30% sales share for Electric Vehicles (EVs) by 2030 (IEA, 2018b). Since members supporting this campaign include big economies such as China, Japan and India, a future where EVs dominate the majority of vehicle market share may not be unreasonable to consider. Low-carbon energy systems including renewable energy sources and EVs are supported by various studies as environmentally friendly technologies, with less harmful emissions such as CO_2 and toxic gases (Hawkins et al., 2013; Hertwich et al., 2015; Nugent and Sovacool, 2014; Pehnt, 2006; Plötz et al., 2017). Such radical changes, however, could potentially affect not only the energy sector but also other sectors that are as yet under-emphasized. Thus, we should consider and prepare for potential adverse impacts which could offset the original benefits by viewing the system

* Corresponding author at: Graduate School of Energy Science, Kyoto University, Yoshida Honmachi, Sakyo-ku, Kyoto, 606-8501, Japan.
E-mail address: wataritakuma.0930@gmail.com (T. Watari).

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Table 1
Summary of studies evaluating mineral availability for the low-carbon energy transition.

Studies	Energy Scenario	Period	Subject to supply constraints	Bottleneck Materials
(de Koning et al., 2018)	Original	2000-2050	Solar PV, EVs	Dy, In, Li, Nd
(Elshkaki and Graedel, 2013)	GEO-3	2010-2050	Solar PV	Ag, Ge, In, Te
(Grandell et al., 2016)	Original	2010-2050	Solar, Wind, EVs, Fuel cells, LED	Ag, Co, Dy, In, La, Pt, Ru, Te
(Månberger and Stenqvist, 2018)	ETP 2017	2015-2060	EVs	Co, Li
(Mclellan et al., 2016)	Original	2010-2050	Solar PV, Wind	Dy, In, Nd, Se, Te
(Moss et al., 2013a)	EU SET-Plan	2011-2030	Solar PV, Wind, Nuclear	Dy, Ga, In, Nd, Te
(Tokimatsu et al., 2017)	Original	2010-2100	Solar PV, Nuclear, EVs	Co, In, Li, Mn, Ni, Se, Te
(Valero et al., 2018)	Original	2016-2050	Solar PV, Wind, EVs, Solar CSP	Ag, Cd, Co, Cr, Cu, Ga, In, Li, Mn, Ni, Sn, Te, Zn
(Watari et al., 2018)	ETP 2017	2015-2060	Solar PV, EVs	Ag, In, Li, Ni, Pt, Se, Te

Note: GEO-3: Third Global Environmental Outlook developed by the United Nations Environmental Program (UNEP), ETP 2017: Energy Technology Perspectives 2017 developed by International Energy Agency (IEA), Strategic Energy Technology Plan (SET-Plan) developed by European Union.

holistically across all sectors with nexus thinking (Liu et al., 2018).

The energy-mineral nexus, for example, is one of the important interconnections that has been currently under-estimated in the context of energy futures. As previous studies have stated (Giurco et al., 2014; McLellan et al., 2012), there are a variety of mutual influences in these sectors, and they are likely to become more important over time (both as individual sectors, but more importantly as interconnected systems) due to economic growth and technological development. One of the largest factors, which is expected to make the energy-mineral nexus more important, is the expansion of low-carbon energy technologies. This is because these emerging technologies – which have significant potential to mitigate global warming – require specific mineral resources in significant quantities and make resource depletion a real concern. Reflecting this concern, a growing number of studies have examined the availability of minerals for the low-carbon energy transition in recent years as shown in Table 1. Although, there are differences in the targeted technologies, materials and analysis methodology, these studies have largely concluded that the decarbonization of the energy and transport sectors could potentially be restricted by mineral availability in the long-term, and emphasized the importance of recycling for boosting mineral supply to meet demand.

Although mineral availability has attracted more attention in recent years in the context of low-carbon energy futures, there has been less attention on the risks and trade-offs in the mining sector caused by radical changes in the energy system. Specifically, environmental impacts associated with resource extraction, which could potentially change in conjunction with the energy system transformation, have been largely omitted so far (Ali et al., 2017). This is crucial, because extraction of some minerals which are required for giving functionality to low-carbon technologies creates adverse impacts on both local ecosystems and human health that are expected to increase (Lee and Wen, 2018; Mancini and Sala, 2018; McLellan et al., 2013). In general, mining and processing of rare metals such as indium, cobalt and platinum generate larger environmental impacts to obtain a given amount of minerals than bulk minerals such as steel and aluminium (Nuss and Eckelman, 2014). This is attributed to many factors such as ore grades, by-product ratio and maturity of infrastructure. Importantly, high grade deposits of many rare metals are concentrated in a small number of countries, and in some cases, these are developing countries with insufficient environmental legislation (Natural Resource Governance Institute, 2017; U.S. Geological Survey, 2018). In such cases, resource extraction could possibly lead to more adverse impacts on local community in these countries than developed countries such as Australia and Canada where concern about the environment has been more strongly institutionalised (Natural Resource Governance Institute, 2017).

While the low-carbon energy transition may expand demand for metalliferous minerals, it is also likely to change energy resource flows such as coal and oil and the environmental impacts associated with their extraction. Thus there may be an opportunity to mitigate these environmental consequences in addition to CO_2 emissions. It is therefore apparent that the energy transition has both opportunities and trade-offs with regards to resource flows and the environmental impacts associated with resource extraction. It is increasingly important, therefore, to understand the impacts of decarbonization of the energy system on resource flows holistically by taking into consideration the balance of these impacts. Since the energy transition will take several decades, a dynamic analysis of resource flows and their consequences over time is crucial to provide policy-makers with a long-term perspective on the issue.

One of the well-known methodologies to quantify resource flows and their implications on environments is Material Flow Analysis (MFA) (Brunner and Rechberger, 2016). This methodology is applied to quantify the flows, outflows and stocks within the societal system. There are however, shortcomings which should be highlighted. Notably, hidden resource flows are not fully taken into consideration in typical MFA. Mining can impact on vegetation, landforms, biodiversity as well as producing tailings, waste rock and mine water (Gavin Bridge, 2000; Giurco et al., 2010; Mudd, 2010, 2009, 2007; Prior et al., 2007; Taelman et al., 2016). These hidden material flows, however, are largely unevaluated in MFA, despite the high correlation with environmental burden (Halada et al., 2001; Kosai and Yamasue, 2019). Since hidden flows involving mine waste can negatively affect the site where extraction is undertaken, it is desirable to holistically analyse resource flows including these hidden flows.

One indicator that addresses these hidden flows by taking into account ore grades and strip ratio is the Total Material Requirement (TMR), originally developed by the Wuppertal Institute (Adriaanse et al., 1997; Bringezu, 1993; Spangenberg et al., 1999; Stiller, 1999; Wuppertal Institute, 2014, 2011). TMR is defined as the total mass of resource flows caused by economic and non-economic activities, which includes hidden flows arising from non-economic activities such as waste rock disposal, as well as direct and indirect flows from economic activities. Although TMR does not indicate environmental impacts directly, it can be considered as indicative of the 'potential' impacts from the total mass of natural resources induced by selected human activities (Bringezu et al., 2003; Kosai and Yamasue, 2019). Some examples of studies using the concept of TMR are the evaluation of resource efficiency at the scale of an economy (Arto, 2009; Bringezu et al., 2004; Bringezu and Schütz, 2001; Fischer-Kowalski et al., 2011; Kristof and Hennicke, 2010; Meyer, 2012; Moriguchi and Hashimoto, 2010; Risku-Norja, 1999; Ščasný et al., 2003; Schütz and Welfens, 2000; Wang et al., 2013), or the effect of recycling on specific products and material substitution (Kosai and Yamasue, 2019; Yamasue et al., 2013a, 2013b, 2009a, 2009b). However, there has not yet been an examination trying to quantify the changes in resource flows including hidden flows under long-term decarbonization scenarios, although at least one study has compared various type of electrical energy storage technologies regarding their TMR (Mostert et al., 2018).

As described above, although a growing number of studies have investigated the mineral requirements for low-carbon technologies such as solar PV, Wind and EVs, there have been few (if any) attempts to quantify changes in resource flows caused by energy transitions that have included not only the expansion of low-carbon technologies but also an associated decline in conventional technologies such as coal fired power plants. When we further expand the scope to examine energy resource flows as well as mineral flows, there has been no analysis of these resource flows in the same framework under energy transitions. Therefore in this study we propose a model that can quantify resource flows including not only direct flows but also hidden flows under the low-carbon energy transition, by linking long-term energy scenarios to MFA and incorporating the concept of TMR. The proposed model was applied to the IEA's long-term energy scenarios at a global level up to 2050, which are referred to by many decision-makers. To the best of our knowledge, this is the first time that the associated resource flows will be quantified holistically and dynamically taking into account both minerals and energy resources, and evaluating potential environmental implications by using TMR.

One of the most significant contributions of this paper is that our dynamic model makes it possible to incorporate time-series changes of various factors such as ore grades, capacity factors of each electricity generation technology and the electricity generation mix, which affect both mineral and energy resource flows. In other words, the holistic impacts of large-scale and long-term energy transitions on resource flows can be evaluated in time series, beyond just the comparison of individual products at a certain period of time. Importantly, our model allows us to dynamically evaluate the implications of flows of both minerals and energy resources on the environment, within the same framework by quantifying the extracted natural resources.

2. Materials and methods

The following steps were undertaken to quantify resource flows including hidden flows under the various energy scenarios up to 2050:

1) Estimating technology flows and outflows based on long-term energy scenarios presented by the IEA, using stock-flow dynamics.
2) Calculating mineral intensity and TMR intensity related to minerals in each energy technology by surveying various literature and taking into consideration future ore grade decline.
3) Exploring hidden flows associated with energy resource usage for generating electricity and running vehicles with consideration of changes in electricity generation share.
4) Analysing hidden flows associated with both mineral production and energy resource usage expressed by TMR under various energy scenarios.

Fig. 1 shows the conceptual framework of this study and detailed explanations of these steps are described in the following sections.

2.1. Stock-Flow Dynamics (step 1)

MFA is a well-developed methodology for quantifying material flow, outflow and in-use stock in society (Moriguchi and Hashimoto, 2010), and has been expanded from static to dynamic analysis (Müller et al., 2014). Here, we refer to time-expanded MFA as the stock-flow dynamics. Various studies have analysed material flows in a certain period of time, focusing on specific technologies or minerals by using stock-flow dynamics (Busch et al., 2017, 2014; Elshkaki and Graedel, 2013; Gerst, 2009; Giurco et al., 2019; Hatayama et al., 2010; Krausmann et al., 2018, 2017; Müller, 2005; Watari et al., 2018; Wiedenhofer et al., 2019). This study also employed this modelling approach for evaluating flows and stocks of low-carbon energy technologies from a long-term perspective.

When assuming that the introduced amount of specific technologies (inflow) in year t is I_t, and the discarded amount (outflow) in year t is O_t, then the in-use stock S_t can be expressed by the simple balance:

$$S_t = S_{t-1} + I_t - O_t \tag{1}$$

Where O_t depends on the number of usage years (lifetime) of each product. This useful lifetime varies from product to product. Even within the same product group introduced to society in the same year, the discard year is not constant and there is therefore a statistical lifetime distribution for each product (Murakami et al., 2010; Oguchi et al., 2010). Therefore, if the number of usage years of the product is assumed as a, the lifetime distribution can be defined as $g(a)$. Hence, O_t is given by the following:

$$O_t = \sum_{a=0}^{a_{max}} I_{t-a}\, g(a) \tag{2}$$

Where a_{max} is the maximum value of the product life. Therefore, I_t can be calculated by Eq. (3).

$$I_t = S_t - S_{t-1} + \sum_{a=0}^{a_{max}} I_{t-a}\, g(a) \tag{3}$$

In this study, S_t of low-carbon technologies up to 2050 was obtained from the Energy Technology Perspectives 2017 (IEA, 2017), which was the latest long-term energy scenario published by the IEA, and historical S_t was collected from various sources (Earth Policy Institute, 2018; Global Wind Energy Council, 2018; U.S. Energy Information Administration, 2018). Target technologies are 15 electricity generation technologies including Oil, Coal, Coal with CCS, Natural gas, Natural Gas with CCS, Nuclear, Biomass and waste, Biomass and waste with CCS, Hydro, Geothermal, Wind onshore, Wind offshore, Solar PV, Solar CSP and Ocean. Five transport technologies are also taken into account - namely, Internal Combustion Engine Vehicles (ICEV), Hybrid Electric Vehicles (HEV), Plug-In Hybrid Electric Vehicles (PHEV), Electric Vehicles (EV) and Fuel Cell Vehicles (FCV). Detailed assumptions for estimating future flows of low-carbon technologies such as average lifetime and shape parameter are provided in Table S1 and S2 in the supplementary material.

2.2. Total Material Requirement Associated with mineral production (step 2)

TMR represents the total amount of materials required to provide resources, including input quantities that typically do not exist in statistical data such as mine waste, in addition to the resources themselves, and it can be expressed through the following equation:

$$TMR_m = \sum M_{direct} + \sum M_{indirect} + \sum M_{hidden} \tag{4}$$

Where TMR_m represents the Total Material Requirement of mineral type m, M_{direct} is direct materials flows, $M_{indirect}$ indicates indirect materials flows and M_{hidden} expresses hidden flows. In this case, the direct flows indicate the inflow of materials directly used by the economy. These are all material flows that form part of products or are used for production and consumption activities. Indirect flows measure the quantity of material accompanying with imports of raw and semi-processed products into the economy. Hidden flows express the quantity of material disturbed by the extraction process but not actually used in the production of products (Office for National Statistics, 2018). Please note that the hidden flows have been used historically not only to cover the unused extraction but also the indirect flows because both hidden and indirect flows could not be measured directly.

For example, mining activities produce direct material flows as an extracted ore. In addition to direct material flows, fuels and reducing agents are required to produce concentrate, and energy is used for transportation which can be defined as in-direct material flows. Furthermore, mining requires the removal of overburden or waste rock in order to access the ore, which may also require land clearing that removes vegetation. Additionally, waste is produced in the form of

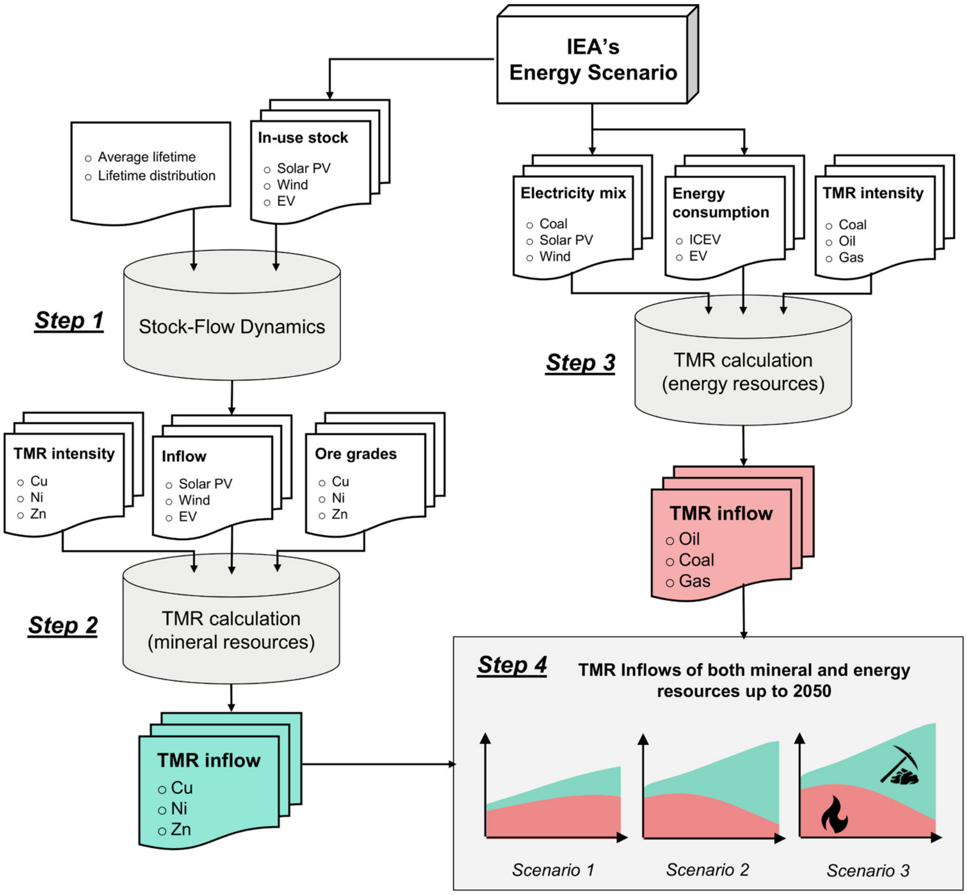

Fig. 1. Conceptual framework of the model to quantify resource flows including hidden flows under the various energy scenarios.

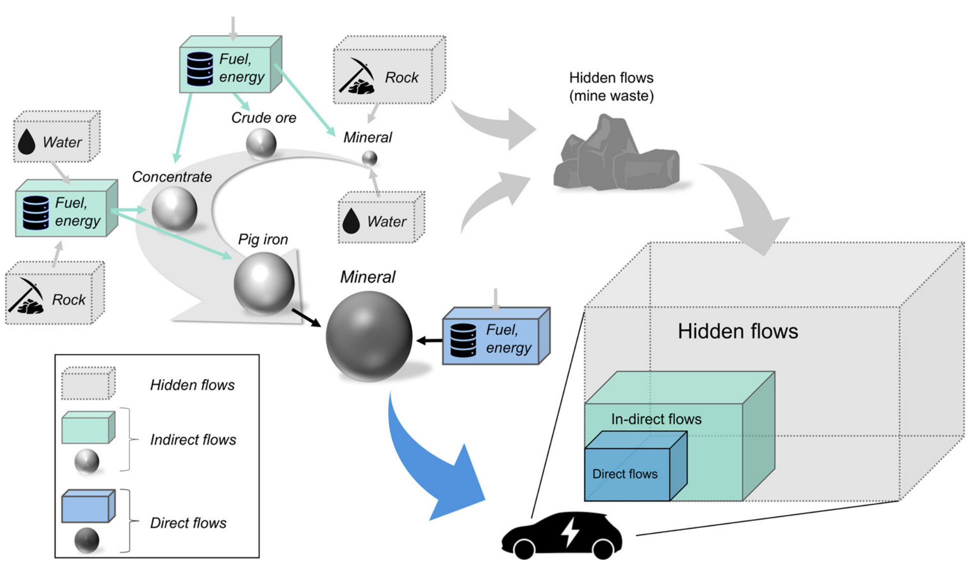

Fig. 2. Conceptual framework of Total Material Requirement.

tailings. These flows are not typically incorporated into statistical data because they are non-economic activities. In TMR, these are referred to as hidden flows, and are incorporated to evaluate all resource changes comprehensively. Fig. 2 shows the conceptual framework of TMR that consists of direct, indirect and hidden flows.

Here, resource flows accompanying a specific technology p in year t can be expressed by Eq. (5):

$$M_{p,t} = \sum_{m=1}^{n} W_m \bullet I_{p,t} \tag{5}$$

Where $M_{p,\,t}$ is the total of direct material flows associated with technology flows in year t, W_m represents the material intensity of material type m and n expresses the total number of used minerals. In this case, we estimated material intensity by taking an average value from a wide range of literature as shown in Table 2, and for the sake of simplicity assumed that the current average value would be constant in the future.

Table 2
Correspondence between the material intensities for low-carbon technologies and references.

Technologies	References
Oil, Coal, Natural gas	(Vidal et al., 2013)
Carbon Capture and Storage	(Moss et al., 2011, 2013a)
Nuclear	(Moss et al., 2011, 2013b)
Biomass and Waste	(Ashby, 2013)
Hydro	(Ashby, 2013)
Geothermal	(Ashby, 2013; Moss et al., 2011, 2013a)
Wind (onshore and offshore)	(Ashby, 2013; Bödeker et al., 2010; Falconer, 2009; Fizaine and Court, 2015; García-Olivares et al., 2012; Guezuraga et al., 2012; Habib et al., 2016; Habib and Wenzel, 2016, 2014; Hoenderdaal et al., 2013; Kleijn and Van Der Voet, 2010; Lacal-Arantegui, 2015; Martínez et al., 2009; Mclellan et al., 2016; Moss et al., 2013b; Roelich et al., 2014; Teske et al., 2016; U.S. Department of Energy, 2011; VESTAS, 2006; Wilburn, 2011; World Bank Group, 2017; Zimmermann, 2013)
Solar (c-Si, CIGS, CdTe)	(Andersson and Jacobsson, 2000; Ashby, 2013; Berry, 2012; Bleiwas, 2010; Bödeker et al., 2010; Elshkaki and Graedel, 2013; Fizaine and Court, 2015; Fthenakis, 2012; Kavlak et al., 2015; Mclellan et al., 2016; Moss et al., 2013a; Stamp et al., 2014; Teske et al., 2016; The Warren Centre, 2016; U.S. Department of Energy, 2011; Valero et al., 2018; Woodhouse et al., 2013; World Bank Group, 2017)
Solar CSP	(Ashby, 2013; Bödeker et al., 2010; Moss et al., 2011; Pihl et al., 2012; Teske et al., 2016; World Bank Group, 2017)
Ocean	(Ashby, 2013)
Vehicles (ICEV, HEV, PHEV, EV, FCV)	(Fishman et al., 2018; Forster and Rutherford, 2011; Moss et al., 2013b; U.S. Department of Energy, 2011; Valero et al., 2018; World Bank Group, 2017)

While this is likely to be an overestimate of the material requirement, as technology is expected to improve the material intensity (particularly for expensive or rare materials), the use of current values is expected to give a conservative estimation that could be considered an upper limit. The detailed calculations of material intensity for each technology are provided in Table S3-13 of the supplementary material.

Then, TMR flows associated with mineral production arising from the energy transition $TMR_{mineral,t}$ were calculated using Eq. (6).

$$TMR_{mineral,t} = \sum_{m=1}^{n} \sum_{p\in P} M_{p,t} \bullet TMR_{m} \tag{6}$$

Where p represents the set of target technologies and TMR_m indicates TMR intensity (tonnes-TMR/tonne) in the production of each element from cradle to refinery gate. In this case, since TMR intensity of each mineral highly relates to their ore grades, the value of some minerals is expected to increase in future, reflecting future ore grade declines (Prior et al., 2013). This study also takes into account this potential change by estimating ore grade declines with Eq. (7).

$$Ore\ grades_t = \alpha \bullet t^{\beta} \tag{7}$$

Where t is time, α and β represent constants which determine the shape of the trendline fitted to historical data. Based on the literature survey, only the case of copper, zinc, lead and nickel show decline trends in the past (Van der Voet et al., 2018) and there is no evidence to justify that all minerals' ore grades will be declined. This study, therefore, estimated the TMR intensity taking into consideration the future decline in ore grades only in the case of these minerals. Fig. 3 shows the TMR intensity of each mineral in 2015 at the global level. Details are given in Figure S2 and S3 in the supplementary material.

2.3. Total Material Requirement Associated with energy resources (step 3)

In addition to mineral production, a low-carbon transition could change flows of energy resources for generating electricity and running vehicles because each energy technology requires different types of energy resources which have their own TMR intensity (tonnes-TMR/TWh or tonnes-TMR/MJ). This study also takes this change into account by estimating TMR flows associated with energy resource usage under the transition to a low-carbon energy system. TMR flows of energy resources used for electricity generation and vehicle use in year t are estimated by following equation:

$$TMR_{energy,t} = \sum_{p\in P} E_{p,t} \bullet TMR_{p,t} \tag{8}$$

Where $E_{p,t}$ represents the energy consumption (expressed in units of TWh or MJ) by technology type p in year t, and $TMR_{p,t}$ expresses the TMR intensity of the energy resources.

In the case of electricity generation technologies, $E_{p,t}$ was obtained from scenarios in the literature (IEA, 2017). Meanwhile, $E_{p,t}$ at the time of using the vehicle was calculated using following assumptions from

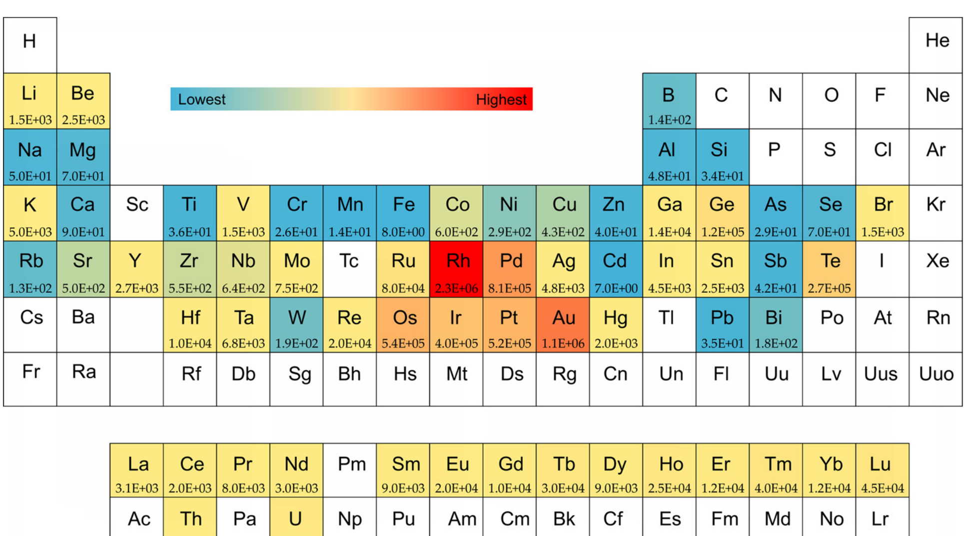

Fig. 3. Total Material Requirement (TMR) intensity of each mineral in 2015 at the global level. The values for Cu, Zn, Pb and Ni were calculated by the authors and the other minerals were obtained from (Halada, 2007; Halada et al., 2001). Note: TMR intensity of Cu, Zn, Pb and Ni are changing over time, reflecting ore grade projections. Detailed results are provided in Figure S2 and S3 in the supplementary material.

the literature (IEA, 2018b, 2010). In this case, we simply assumed that ICEV and HEV require gasoline and PHEV and EV use electricity for operation. Although FCV require hydrogen for operation of the vehicles, this has been assumed to be zero because of the lack of data and low level introduction in the energy scenarios. The TMR intensity of gasoline was obtained from the literature (Nakajima et al., 2006), and the TMR intensity for generating electricity used by EVs was calculated by multiplying the TMR intensity of each electricity generation technology by the electricity generation ratio in each year. That is, TMR intensity of electricity generation is assumed to change over time, reflecting the mix of generation technologies. Detailed assumptions are presented in Table S14 and 15 of the supplementary material.

2.4. Scenario analysis (step 4)

In this study, changes in resource flows expressed by TMR were quantified under various energy scenarios. Namely, the Reference Technology Scenario (RTS), 2 °C Scenario (2DS) and Beyond 2 °C Scenario (B2DS) which were set based on IEA publications (IEA, 2017). In this case, the 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 °C by 2100. In contrast, the 2DS can be considered as a major climate change mitigation scenario from the IEA, delineating a path to keep global temperature rise below 2 °C in 2100. The B2DS is the most ambitious scenario, which lays out an energy system pathway achieving only 1.75 °C temperature increase. Scenario analysis allows us to quantitatively and dynamically evaluate the difference in the impact of each climate change scenario from the perspective of resource flows. Although resource flows including hidden flows do not directly indicate the environmental implications accompanying the energy transition, this analysis can make it possible to comprehensively grasp the total resource transformation caused by large-scale technological changes and can quantify ‘potential’ adverse impacts which have not yet been well-covered in the context of energy futures.

2.5. Limitations and sensitivity analysis

Uncertainties of some assumptions for predicting future resource flows are inevitable. In order to examine the potential effects of varying assumptions, a sensitivity analysis targeting three parameters was conducted. The analysed parameters were: the average lifetime of low-carbon technologies, the shape parameter of lifetime distribution and the material intensity. The transport sector in the B2DS is used as an example. In this case, we evaluated the effect on the results by varying the above three indicators up and down by 30%, respectively.

The potential change in TMR flows caused by more detailed assumption differences was also examined by taking the transport sector in the B2DS as an example. First, although the ore grade decline of some minerals was predicted in this study, new deposits which have high grades might be discovered and developed in the future. Second, despite the fact that the proportion of primary and secondary production could affect TMR flows significantly, this study has not taken this into consideration. Here we set various scenarios for investigating these uncertainties as shown in Table 3. In this case, potential secondary production was calculated by multiplying recycling rates and outflows, which was estimated based on stock-flow dynamics with Weibull distribution shown in Eq. (2). This is basically the same methodology as in previous authors’ works (Giurco et al., 2019; Watari et al., 2018). TMR intensity of secondary production was determined as 1.5% of primary production based on the examples of aluminium, copper and lead, which both TMR intensity of both primary and secondary production could be obtained from literature (Wuppertal Institute, 2014).

3. Results

3.1. Total material requirement for global energy transition

Fig. 4 shows the integrated resource flows of both mineral and energy resources expressed as their respective TMR at the global level. What we can see from this figure is that the low-carbon energy transition could mitigate TMR flows in the electricity sector over time, reflecting the decreasing energy resource flows. In the transport sector, on the other hand, increases in TMR flows would be inevitable even if we introduce EVs, capable of decreasing energy resource usage for vehicle operations. In both sectors, the ratio of flows associated with mineral production is increasing drastically over time in the case of 2DS and B2DS, whereas the flows induced by energy resources dominate in the case of RTS.

When we consider the ‘TMR flows/MWh or vehicle in-use’ as shown in Fig. 5, which implies the resource intensity of this sector of society, all scenarios express a decreasing trend in the case of the electricity sector. On the contrary, the transport sector suggests that the more decarbonization progresses, the more resource flows are needed. That is, the decarbonization of the transport sector would lead to larger resource flows, and as a result it may increase the degree of environmental burden around the sites where mining activities would be conducted. The reason why the value in the B2DS is decreasing since around 2045 is that the number of vehicles in-use is continuing to increase despite the TMR flows is showing a saturation trend around that time. This could be due to the average lifetime of the vehicles which is assumed as more than 10 years in this study. Although TMR does not indicate the environmental impacts directly, these results highlighted that the long-term energy transition could change existing resource flows and potentially bring about adverse implications in mining countries in terms of how much natural resources are transformed. The significant message here is the importance of considering the whole resource cycle, including hidden resource flows of minerals as well as energy resources, in order to be prepared and make appropriate mitigation policies for a truly ‘sustainable’ energy transition.

When we examine the TMR flows associated with mineral production shown in Fig. 6 in more detail, all scenarios indicate that resource flows involving hidden flows would increase drastically over time. In the 2DS, TMR flows are increased by around 450% to 500% from 2015 and 2050 in the electricity and transport sectors, respectively, whereas in the RTS, which can be considered as the ‘business as usual scenario’ TMR increases by 200% and 350% respectively. Moreover, in the B2DS, which is the most ambitious scenario, TMR increases by approximately 900% and 700% from 2015 to 2050 in the electricity and transport sectors respectively.

Such drastic increases in TMR are mostly from emerging technologies such as solar PV and EVs. Solar PV, for example, dominates around

Table 3
Scenario summary for sensitivity analysis.

Scenario summary	Description
Original Scenario	Ore grade will decline over time, and all flows will come from primary production.
New Deposit Discovery Scenario	New deposits including high grade ores will be discovered to retain the current value of ore grades.
Low Recycling Scenario	50% of outflows will be recovered and supplement supply as secondary production.
High Recycling Scenario	90% of outflows will be recovered and supplement supply as secondary production.

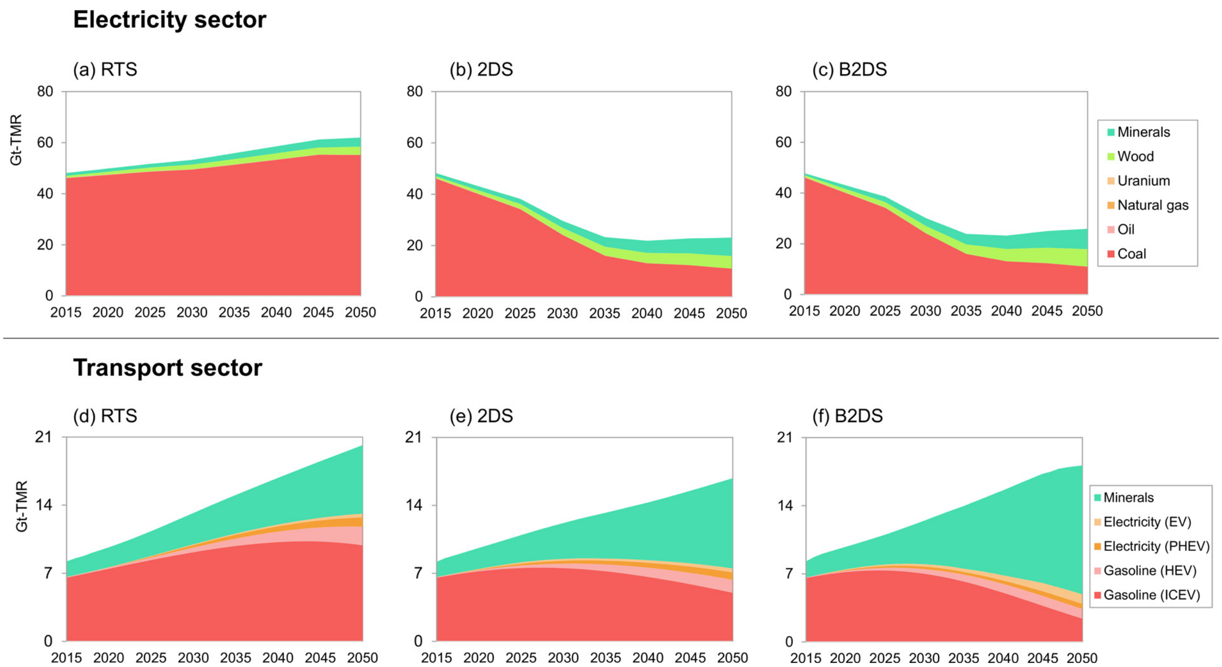

Fig. 4. Estimated Total Material Requirement (TMR) flows associated for generating electricity and operating vehicles up to 2050 at the global level. (a) Reference Technology Scenario (RTS) in the electricity sector (b) 2 Degree Scenario (2DS) in the electricity sector (c) Beyond 2 Degree Scenario (B2DS) in the electricity sector (d) RTS in the transport sector (e) 2DS in the transport sector (f) B2DS in the transport sector.

70% of TMR in 2050 in the case of the electricity sector, depending on the scenarios. Additionally, around 45%–95% of resource flows in 2050 are induced by EVs (PHEV and EV). These results strengthen the argument that the low-carbon energy transition could change existing resource flows associated with hidden flows significantly, and imply increasing environmental consequences from the generation of mine waste and changing landscapes in the mining countries.

Regarding the fractional contribution of each of the minerals, copper flows are increasing over time especially in the transport sector and play a large role in pushing up the resource flows. The share of steel is limited to 5%–10% and the remaining resource flows are largely from nickel, lithium, cobalt and copper. In the electricity sector, on the other hand, the proportion of steel is relatively higher than in the transport sector, and copper and silver mostly dominate remaining shares in all scenarios.

It is important to note that there has been no inclusion of feedback loops in the modelling of energy demand. That is, there is no modelling of the additional energy requirement to provide the additional required minerals (mining through to mineral production), nor is there a secondary feedback to then further examine the additional mineral requirement to provide this additional energy. This is something that could be added in future studies.

3.2. Sensitivity analysis

Fig. 7 shows the results of sensitivity analysis indicating that the material intensity has the largest potential to change the results, which are shown as TMR flows associated with mineral production. In addition to the material intensity, the average lifetime changes the timing of product replacement and affects the direct resource flows to a significant extent – particularly if recycling is not considered to mitigate primary resource requirements. These results perhaps emphasize the necessity of analysis that takes into account differences in average lifetime and material intensity for each region. Although uncertainty cannot be avoided in prediction, coping with it could be a future task undertaken by developing comprehensive databases or promoting collaboration with industry, for example.

Fig. 8 shows TMR flows in the transport sector of B2DS under the various scenarios with different assumptions on ore grades and recycling shown in Table 3. Both the new deposit discovery and high

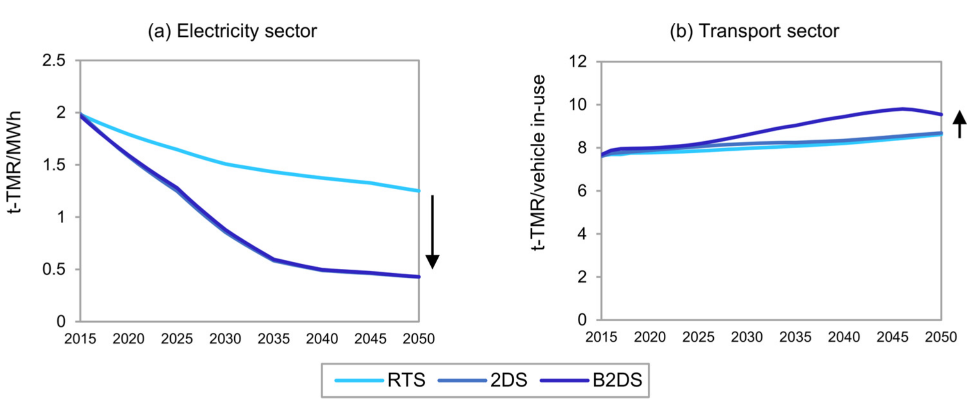

Fig. 5. Resource intensity for electricity generation and vehicle operation up to 2050 at the global level estimated by TMR flows per MWh or in-use vehicles. (2015 = 1) (a) Electricity sector (t-TMR/MWh) (b) Transport sector (t-TMR/vehicle in-use).

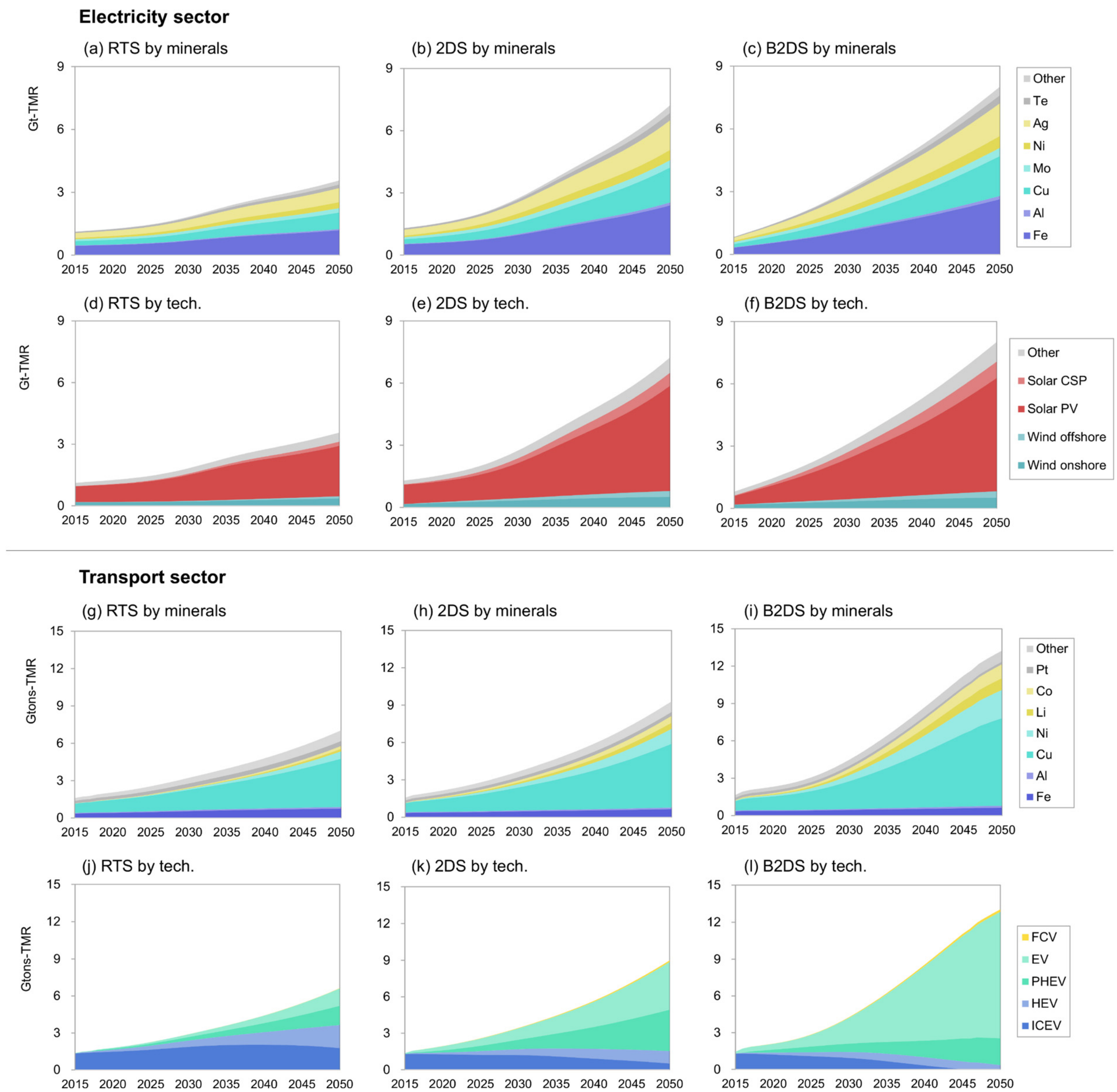

Fig. 6. Estimated TMR flows associated with mineral production in the electricity sector and transport sector up to 2050 at the global level. (a) Reference Technology Scenario (RTS) by mineral in the electricity sector (b) 2 Degree Scenario (2DS) by mineral in the electricity sector (c) Beyond 2 Degree Scenario (B2DS) by mineral in the electricity sector (d) RTS by technology in the electricity sector (e) 2DS by technology in the electricity sector (f) B2DS by technology in the electricity sector (g) RTS by mineral in the transport sector (h) 2DS by mineral in the transport sector (i) B2DS by mineral in the transport sector (j) RTS by technology in the transport sector (k) 2DS by technology in the transport sector (l) B2DS by technology in the transport sector.

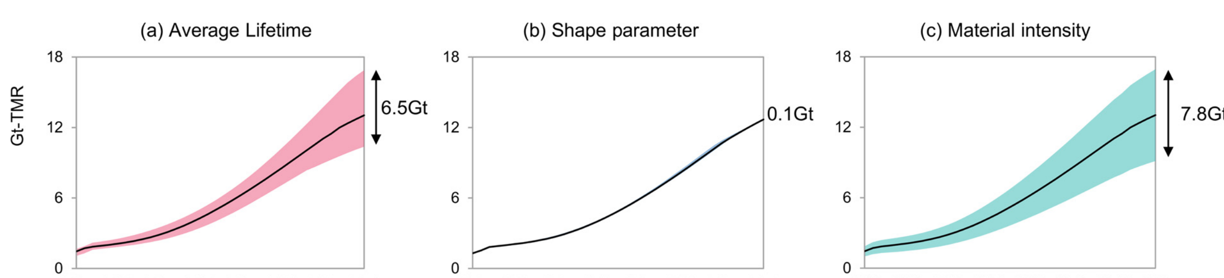

Fig. 7. Results of sensitivity analysis on TMR flows associated with mineral production in transport sector in Beyond 2 Degree Scenario. (a) average lifetime of low-carbon technologies. (b) shape parameter of lifetime distribution. (c) material intensity in each technology. Note: Line represents the mean value and the flow pane shows the range of results when changing each parameter up and down by 30%. The value indicates the width of the maximum and the minimum in 2050.

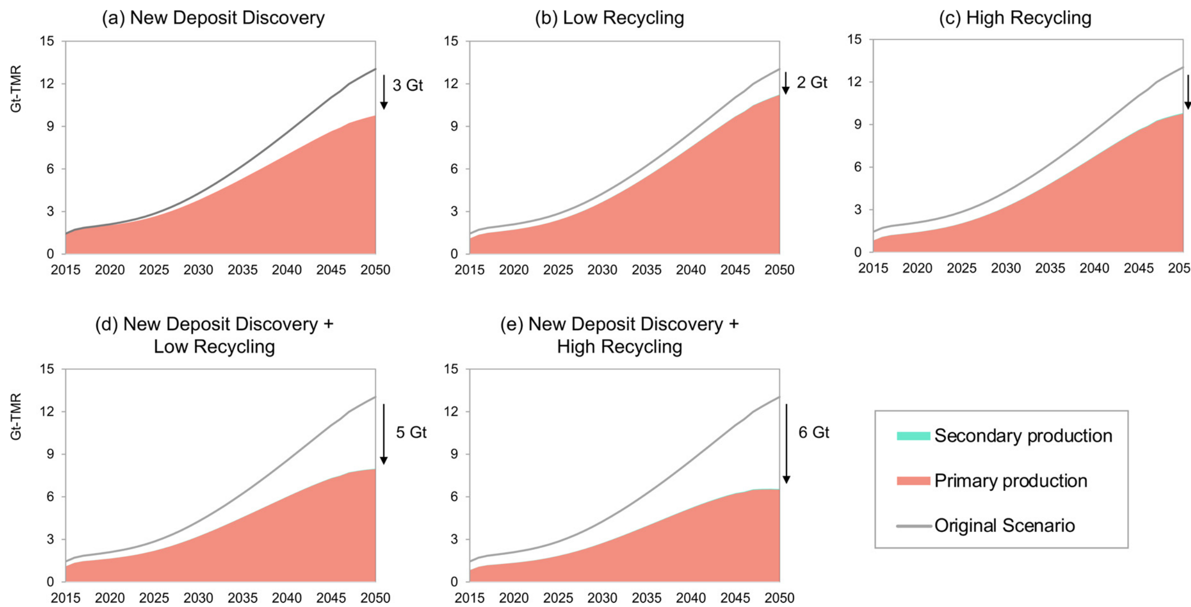

Fig. 8. TMR flows for the transport sector in Beyond 2 Degree Scenario at the global level under various scenarios with varying ore grade and recycling rate. (a) New deposit discovery scenario (b) Low recycling scenario (c) High recycling scenario (d) combination of new deposit discovery and low recycling scenario (e) combination of new deposit discovery and high recycling scenario.

recycling scenarios have the potential to reduce TMR flows by around 3 Gt in 2050 compared to the original scenario, and when combining both, TMR flows in 2050 could be half of original scenario. This might imply the importance to invest for new ore deposits with high grades as well as recycling, to reduce the environmental consequences.

4. Discussion

4.1. What can be understood from TMR for energy transitions?

Based on the IEA's energy scenarios and our analysis, the energy transition over the next few decades would increase resource flows associated with mining activities considerably, including hidden flows as well as direct flows with the concept of TMR. That is, the low-carbon energy transition could change landscapes and generate mine waste representing a potential environmental burden for mining countries. Minerals which have a large potential to change natural landscapes under the energy transition are indicated as steel, copper and silver. Nickel, cobalt, and lithium which are vital for battery technologies also have large potential to produce adverse impacts on environment.

On the other hand, it can be also clearly seen that the low-carbon energy transition can reduce energy resource flows such as coal in the use phase and the reduction of TMR in the electricity sector adds support as a co-benefit of decarbonization. However, although the energy transition in the transport sector could decrease the usage of energy resources, it causes a sharp increase in mineral production and, as a result, the amount of resources per vehicle would increase over time. That is, our results emphasize the possibility that the energy transition in the transport sector could bring about adverse impacts in resource extracting countries in the future. The most significant message here is the importance of managing the resources cycle not only to mitigate the concerns about mineral availability, but also to reduce adverse impacts associated with mining activities.

Specifically, this study emphasizes the necessity of proper management of copper and other rare metals such as nickel, lithium and cobalt from the viewpoint of TMR as well as steel that accounts for the majority of material intensity. This trend is more pronounced in the case of vehicles, in which the TMR of copper has been rapidly increasing with the spread of EVs, whereas steel still dominates most of the material use in EVs. In other words, analysis using the concept of TMR could give us an insight to discuss the resource cycle not only from the viewpoint of "quantity" but also from the "quality" considering environmental burden. That is, the mitigating strategies such as recycling could be explored based on the potential environmental implications as well as the absolute quantities. From this point of view, the necessity of horizontal recycling of rare metals, not cascade recycling accompanied by deterioration of quality is emphasized, and it is urgent to develop product designs and decomposition technologies that make it possible to recycle while keeping the original material or component quality, rather than minor components being lost in slag or larger metal streams due to the increased miniaturization and complexity of parts.

4.2. Social impacts of mining activities for energy transition

The analysis of TMR in this study highlights the scale of resource flows and the minerals which are likely to lead to the greatest environmental impacts through the expansion of mining activities. However, it is also important to consider qualitative data on environmental and social impacts (including health and human rights impacts) of resource demand, to understand the specific risks and trade-offs which are not captured through quantitative analysis of resource flows. It is also crucial to consider the locations on where mining typically occurs for these minerals, and where it is likely to expand to, to mitigate new adverse impacts that may arise as a result of the low-carbon transition.

If not managed appropriately, there are significant environmental and social impacts associated with the mining and processing of minerals for low-carbon technologies in the electricity and transport sector. However, because of the complex nature of many supply chains it is difficult to directly link specific mining impacts to end-uses, particularly if these minerals are used in many applications. For certain minerals where low-carbon technologies are responsible for a high share of consumption and the minerals are mined in only a few locations, such as rare earths or tellurium, it is easier to draw a link between mining impacts to specific technologies (Redlinger et al., 2015; Xiaoyue and Graedel, 2011). This becomes more difficult for minerals such as aluminium and copper which are used in a wide range of technologies, as well as mined in various locations around the world. For particular minerals, including cobalt, lithium, nickel and rare earths, new or expanded mining operations are under development specifically because of increased demand for these minerals from low-carbon technologies (Ali et al., 2018).

The most discussed social and environmental impacts from mining activities associated with low-carbon technologies is the mining of cobalt from Democratic Republic of the Congo (DRC). Mining has led to heavy mineral contamination of air, water and soil, with severe health impacts for miners and surrounding communities (Banza Lubaba Nkulu et al., 2018). Cobalt used for lithium-ion battery manufacture is generally produced as a co-product of copper mining; the exception to this is the 15–20% of cobalt from DRC which is produced from artisanal and small-scale mines (ASM) (BGR, 2017). Artisanal miners work in dangerous conditions in hand-dug mines that are at risk of cave-ins or landslides, and are at most risk for heavy mineral contamination (Tsurukawa et al., 2011). There is extensive child labour, with an estimated 40,000 children under 15 years working in artisanal cobalt mines (Amnesty International, 2016). New cobalt mines are proposed in DRC, as well as in Australia, Canada, Indonesia, the US, Panama and Vietnam.

Other minerals for which significant impacts have been observed include mining of copper, nickel and rare earths. Copper mining can lead to long-lasting heavy mineral contamination of soils and water, as seen in Chile, the largest copper producer, as well as China, India and Brazil (Stowhas et al., 2018). Health impacts that have been observed include pulmonary tuberculosis (PTB) among underground miners exposed to silica in Zambia (Ngosa and Naidoo, 2016) and exposure to arsenic for smelter workers in China (Sun et al., 2015). High purity Class 1 Nickel, which usually comes from sulphide mines, is most suitable for lithium-ion battery manufacturing. Nickel sulphide mining has had historical environmental impacts in Canada and Russia, including damaging lakes and wetlands (Mudd, 2010).

Rare earths processing is complex and requires large amounts of chemicals, which are harmful to human health if not managed appropriately, and produces large volumes of solid waste, gas and wastewater (McLellan et al., 2013). In China, where around 80% of the world's rare earths are produced, wastewater from tailings dams has polluted groundwater, which has led to crop failures and the displacement of farming communities (Bontron, 2012). There have also been social conflicts over the Lynas Advanced Materials Plant (LAMP) in Kuantan, Malaysia, which processes concentrate from Western Australia (Ali, 2014). New mines are proposed for Canada, Greenland, Malawi, South Africa and Uganda.

Although lithium mining is generally considered less risky than many other minerals, there are concerns over water contamination and shortages in the lithium triangle of Argentina, Bolivia and Chile, and the inadequate compensation for affected local communities (Wanger, 2011). For some minerals, such as specialty minerals used in PV, little is known about environmental or social impacts, particularly as they are often mined as by-products. Indium, gallium, selenium, cadmium and tellurium are known to be hazardous to human health, and there are reports of lung disease from exposure to indium in manufacturing processes (White and Shine, 2016).

Although the TMR associated with mineral production increases in a low-carbon transition, the TMR associated with energy resources in the electricity sector decreases in the same scenario. This would lead to a reduction in the impacts associated with fossil fuel extraction, particularly coal mining, which can lead to lung damage from exposure to coal dust and kidney disease from the contamination of groundwater (Castleden et al., 2011). Across all mining associated with energy, responsible operations are necessary to avoid negative environmental health impacts for workers and local communities, ensure the respect of human rights and a sustainable energy transition.

Policies and strategies considering only decarbonization would miss trade-offs and bring about serious problems which have been less highlighted. Since future mineral production, which will have large potential environmental consequences as indicated by TMR changes would be concentrated into a few specific countries (e.g. DRC, South Africa, Australia and Chile) (Natural Resource Governance Institute, 2017), it will be increasingly important to develop technologies and infrastructures for 'sustainable' material cycles for mitigating adverse impacts in countries where mining would be carried out, in parallel with the transition to a low-carbon energy future. From this point of view, nexus thinking is critical to comprehensively understand the trade-offs and synergies arising from the energy transition. Although energy policy and resource policy have been addressed independently so far, the results of this study support the need for collaboration in these sectors and tackling future problems with nexus and life cycle thinking to extend such collaboration to any stakeholders existing in the supply chain of resources (Nakajima et al., 2019).

5. Conclusions

In this paper we have presented a model that can dynamically quantify resource flows in the low-carbon energy transition by using the concept of Total Material Requirement (TMR) and stock-flow dynamics, taking into account hidden flows such as mine waste. The research objective of the study was to identify risks and trade-offs of decarbonization by tracking flows of both mineral and energy resources for designing holistically beneficial strategies. This is important because policies and strategies which only consider one aspect, could bring about severe problems in other areas.

The main findings from the application of the proposed model to the International Energy Agency's scenarios up to 2050 are as follows:

(1) TMR intensity, which indicates the total mass of resource transformation caused by economic and non-economic activities including hidden flows, in each low-carbon technology is dominated by various minerals such as copper, silver and cobalt, while steel accounts for the majority of mineral intensity.
(2) Low-carbon energy transitions could increase TMR flows associated with mineral production by around 200% to 900% in the electricity sector and 350%–700% in the transport sector respectively from 2015 to 2050 globally.
(3) Increases in TMR flows accompanying mineral production have a heavy contribution from copper, silver, nickel, lithium and cobalt in addition to steel.
(4) The expansion of solar PV and EVs produces the largest increases in TMR flows accompanying minerals, and these two technologies account for 50%–80% of the total flows in 2050, depending on scenarios.
(5) Low-carbon energy transitions can reduce energy resource flows for generating electricity and support the theory that the expansion of low-carbon technologies could reduce total resource flows expressed by TMR in the electricity sector.
(6) In the transport sector, although implementation of EVs could decrease the usage of energy resources, it causes a sharp increase in mineral production, and as a result, the amount of resource flows per vehicle will be increased over time.

In summary, our results emphasize the importance of designing resource cycles simultaneously with the energy transition, and the need for collaboration between energy-mineral sectors which tend to be considered separately at present. We believe that this study could help as a step towards developing a nexus approach for achieving a sustainable energy transition in terms of energy, minerals and the environment.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.05.015.

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