Journal of Cleaner Production 312 (2021) 127698

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Sustainable energy transitions require enhanced resource governance

Takuma Watari [a,b,*], Keisuke Nansai [a,c], Kenichi Nakajima [a,b], Damien Giurco [d]

[a] Global Resource Sustainability Research Section, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki, 305-8506, Japan
[b] Graduate School of Frontier Sciences, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba, 277-8563, Japan
[c] Integrated Sustainability Analysis, School of Physics, Faculty of Science, The University of Sydney, Camperdown, 2006, NSW, Australia
[d] Institute for Sustainable Futures, University of Technology Sydney, Ultimo, NSW, 2007, Australia

ARTICLE INFO

Handling editor: Yutao Wang

Keywords:
Responsible sourcing
Climate change
Net zero
Carbon neutral
Mining

ABSTRACT

The global transition to fundamentally decarbonized electricity and transport systems will alter the existing resource flows of both fossil fuels and metals; however, such a transition may have unintended consequences. Here we show that the decarbonization of both the electricity and transport sectors will curtail fossil fuel production while paradoxically increasing resource extraction associated with metal production by more than a factor of 7 by 2050 relative to 2015 levels. Importantly, approximately 32–40% of this increase in resource extraction is expected to occur in countries with weak, poor, and failing resource governance, indicating that the impending mining boom may result in severe environmental degradation and unequal economic benefits in local communities. A suite of circular economy strategies, including lifetime extension, servitization, and recycling, can mitigate such risks, but they may not fully offset the growth in resource extraction. Our findings underscore the importance of institutional instruments that enhance the resource governance of entire low-carbon technology supply chains, along with circular economy practices. In the absence of such actions, the decarbonization of electricity and transport sectors may pose an ethical conundrum in which global carbon emissions are reduced at the expense of an increase in socio-environmental risks at local mining sites.

1. Introduction

Avoiding the catastrophic impacts of climate change will require, inter alia, the transformation of both the electricity supply and transport systems on an unprecedented scale in the coming decades (International Energy Agency (IEA), 2017). Such a transition will fundamentally alter the existing resource flows of metals and fossil fuels (Watari et al., 2019), which could in turn induce serious trade-offs, such as land degradation (Werner et al., 2020), biodiversity loss (Sonter et al., 2020), damage to human health (Banza Lubaba Nkulu et al., 2018), supply chain disruption of (de Koning et al., 2018), and the catastrophic collapse of tailings dams (Owen et al., 2020). A key challenge in mitigating these trade-offs is to elucidate the anticipated resource flows in the coming decades, and to design policies and strategies to mitigate against these issues based on scientific knowledge.

Reflecting the importance and urgency of this issue is the emergence of large-scale studies in this domain. However, based on an extensive review of 88 existing studies (Table S1 in the Supplementary Material), we identified several limitations that need to be addressed. First, although the quantities of resources used directly for low-carbon technologies is increasingly well understood, previous studies have generally failed to capture hidden resource extraction, such as waste rock and overburden. This deficit in our understanding will likely mask the full impact of resource extraction in response to the energy transition (Kosai et al, 2020, 2021), which will ultimately lead to insufficient attention being paid to potential trade-offs by government, industry, and the community. Another limitation of previous studies is that they largely lack the geographical resolution to identify which countries will support the global energy transition through resource extraction. Without this information, it is difficult to discuss areas of concern where policy interventions will be most needed (Lèbre et al., 2020). Lastly, the expectations of many studies regarding the circular economy strategies required for sustainable resource supply are very high (Stahel, 2016); however, despite the potential of the circular economy (Reuter et al., 2019), empirical analyses of its effect is heavily biased toward end-of-life (EoL) recycling. Consequently, a full range of other possibilities, such as reuse, repair, remanufacturing, and servitization (Dominish et al., 2018), are being overlooked. The omission of these

* Corresponding author. Global Resource Sustainability Research Section, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan.

E-mail address: watari.takuma@nies.go.jp (T. Watari).

https://doi.org/10.1016/j.jclepro.2021.127698
Received 10 September 2020; Received in revised form 5 May 2021; Accepted 25 May 2021
Available online 29 May 2021

other possibilities prevents decision makers from understanding the true potential and/or limitations of such strategies.

This study therefore addresses these knowledge gaps by linking global energy scenarios with a resource demand-supply models on a county-by-country basis. Our approach captures all used and unused resource extraction by using the total material requirement (TMR) indicator (Bringezu et al., 2004; Nakajima et al., 2019), which can be used to estimate the magnitude of resource extraction impacts in mining countries. We also link circular economy strategies (i.e., lifetime extension, servitization, and EoL recycling) to the models to obtain a quantitative understanding of the potential roles of such strategies in sustainable energy transition. Among the various sectors and related technologies in the decarbonization process, this study focuses on the electricity and automotive technologies, because of their large contribution to decarbonization (approximately 60% of the expected CO_2 emissions reduction by 2060 is projected due to these two sectors (IEA, 2017)) and their high impact on resource extraction (Deetman et al, 2018, 2021; The World Bank, 2020; 2017).

2. Methods

2.1. Model overview

Our approach for quantifying used and unused resource extraction under a global energy transition scenario consists of the following steps:

1. Estimate technology flows under a well below 2 °C scenario.
2. Transform technology flows into metal and fossil fuel demand.
3. Convert metal and fossil fuel demand to used and unused resource extraction.
4. Allocate used and unused resource extraction to each mining country.

The details of each step are described in detail below. Graphical representation of the calculation steps can be found in Fig. S1 in the Supplementary Material.

2.1.1. Estimating technology flows under a well below 2 °C scenario

The starting points of our analysis are the future electricity generation capacity and car ownership (S) for each year (t) under the Beyond 2 Degree Scenario proposed by the IEA (IEA, 2017). This scenario assumes that the rise in global temperatures will remain below 1.75 °C to 2100 compared to preindustrial levels. We estimated the annual installed capacity (I) to 2050 by using a dynamic stock-flow model with a stock-driven approach (Pauliuk and Heeren, 2019; Wiedenhofer et al., 2019):

$$I(t) = \Delta S(t) + \sum_{t'=0}^{t} I(t')\varphi(t-t') \quad (1)$$

where φ denotes the lifetime distribution.

The average lifetime of each technology is determined with reference to the literature (Ashby, 2012) (Table S2 in Supplementary Material). Lifetime is assumed to follow a normal distribution with a standard deviation equivalent to 30% of the mean (Pauliuk et al., 2013). The technologies considered in this paper include 15 electricity generation technologies (oil, coal, coal with carbon capture and storage (CCS), natural gas, natural gas with CCS, nuclear, biomass and waste, biomass and waste with CCS, hydro, geothermal, wind onshore, wind offshore, solar photovoltaics (solar PV), concentrating solar thermal power, and ocean), and five vehicle types (internal combustion engine vehicles (ICEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), electric battery vehicles (BAV), and fuel cell vehicles (FCV)).

2.1.2. Transforming technology flows into metal and fossil fuel demand

Metal demand for low-carbon transition can be calculated by multiplying the technology flow (GW or cars/year) by the material intensity, MI (t/GW or car). Here, we used data from 37 sources (Table S3 in Supplementary Material) to obtain the material intensity for 20 technologies. This leads to a total of 36 metals being considered, with 209 data points (Tables S4 and S5 in Supplementary Material). We assumed that the compiled material intensities were constant over time, meaning that our analysis provides an upper bound estimate that does not consider any potential decrease in material intensity due to developments in engineering and design. The metal demands are obtained from both mine production (P) and EoL scrap (E) as shown in equations (2) and (3):

$$P(t) = I(t)\mathrm{MI}(t) - E(t) \quad (2)$$

$$E(t) = \gamma(t)\sum_{t'=0}^{t} I(t')\mathrm{MI}(t')\varphi(t-t') \quad (3)$$

where γ denotes the EoL recycling rate (scrap collection rate × recycling yield).

Fossil fuel demand for operating electric technologies can be calculated by multiplying the annual electricity consumption (TWh/year) by the fossil fuel intensity (MJ/TWh). In this case, the electricity consumption data can be obtained directly from the original scenario (IEA, 2017) and fossil fuel intensity is described in the literature (Nakajima et al., 2006). The fossil fuel demand for vehicle operation can be estimated by multiplying the vehicle stock (car/year) by the annual mileage (km/car-year) and fuel consumption (MJ/km), which can be obtained from the literature (IEA, 2018, 2010) (Table S6 in Supplementary Material). Importantly, there has been no inclusion of feedback loops in the modelling of fossil fuel demand. That is, there is no modelling of the additional energy demand required to provide the additional required metals (mining through to production), nor is there a secondary feedback mechanism to more closely examine the additional metal requirements for providing this additional energy; this is something that could be considered in future studies.

2.1.3. Converting metal and fossil fuel demand to used and unused resource extraction

The concept of TMR captures all of the resource extraction in both used and unused extraction (Halada et al., 2001; Nakajima et al., 2019). In this case, used extraction refers to materials that are extracted from the environment and subsequently used in production processes, whereas unused extraction refers to material flows that arise during the course of extraction, but that do not directly enter the economic system (e.g., waste rock and overburden). The used and unused extraction induced by mine production and fuel consumption are calculated by multiplying metal and fuel production by the TMR factor (Halada et al., 2001; Nakajima et al., 2006) (Tables S7 and S8 in the Supplementary Material). In this case, the data for copper, nickel, lead, and zinc were adjusted to consider the decline in ore grade, as in a previous study (Watari et al., 2019). The resource extraction associated with secondary metal production from EoL scrap are not considered here as they are negligibly small (Wuppertal Institute, 2014) and little is currently known about these impacts (Yamasue et al., 2010).

2.1.4. Allocating used and unused resource extraction to each mining country

Estimates for resource extraction were allocated to each mining country by using mine production data on a country-by-country basis. Production modelling is performed by the Geologic Resources Supply-Demand Model (GeRS-DeMo), which determines when to bring idealized mines online using detailed data on exploitable Ultimate Recoverable Resource. Full details of the model are described by Mohr (2010). From multiple references, we obtained data on future production of iron

(Mohr et al., 2015), copper (Northey et al., 2014), zinc (Mohr et al., 2018), lead (Mohr et al., 2018), and lithium (Mohr et al., 2012). The other elements for which such data were not available were supplemented by assuming the 2015 production share to be constant over the scenario period (BGS Minerals UK, 2018; U.S. Geological Survey, 2020). Obviously, as different countries have mines that differ in quality and technological capacity, accurate allocation of used and unused resource extraction to each mining country requires more sophisticated data, including the operational data for each mine (Mudd, 2010; Northey et al., 2013). Thus, the analysis provided here should be regarded as illustrative, rather than a realistic forecast.

We also characterized each mining country by the quality of resource governance using the Resource Governance Index (Natural Resource Governance Institute, 2017), which quantifies the quality of governance of the mining sector in 81 countries (see Table S9 in the Supplementary Material). The quality of governance was evaluated as being good, satisfactory, weak, poor, or failing, with each category assigned based on value realization, revenue management, and enabling environment. Insufficient resource governance means that the increase in mining demand is associated with a high risk of accelerating environmental degradation due to activities such as unclear licensing practices and poor management, as well as negative social impacts, such as misappropriation of funds, corruption, and low economic growth.

2.2. Sensitivity and uncertainty analysis

Since the objective of the model is to explore the “future”, some inherent uncertainty exists in the parameters considered. Therefore, we investigated the impacts of our modelling assumptions by way of a one-factor-at-a-time sensitivity analysis. Investigated parameters included average lifetime, standard deviation of lifetime distribution, type of probability distribution, material intensity, and TMR factor. In addition, a Monte Carlo simulation was conducted in which each parameter was randomly extracted from a specific probability distribution, and the model was run multiple times to derive the uncertainty ranges for the results. Hence, the model can be seen as a stochastic system, where each parameter is understood to be the mean μ of a normal (Gaussian) distribution with an uncertainty parameter σ. In each model run, input parameters are randomly drawn from a distribution $X \sim \mathcal{N}(\mu, \sigma^2)$. Uncertainty ranges for each parameter were established based on a combination of multiple references and information about the reliability of the data sources. A detailed description of the methodology can be found in the Supplementary Material.

2.3. Circular economy scenarios

We examined the role of circular economy strategies related to solar PV and EVs (PHEVs and BEVs) and their important role in an energy transition. With reference to previous studies (Dominish et al., 2018; Geissdoerfer et al., 2017; Ghisellini et al., 2016; Kirchherr et al., 2017), we summarized the following main circular economy strategies associated with the two abovementioned technologies (i.e., solar PV and EVs) as they relate to reusing, repairing, refurbishing, remanufacturing, recycling, durable design, and servitization. These strategies are reflected in the model parameters of average lifetime, EoL recycling rate, and car ownership.

2.3.1. Lifetime extension (reusing, repairing, refurbishing, remanufacturing, and durable design)

The lifetime of a product can be extended by durable design or replacement of defective parts. In the case of PV panels, the average lifetime is estimated to be approximately 20 years for economic reasons, such as the duration of feed-in tariffs, rather than due to degradation (Ashby, 2012). Technically, a PV panel can be reused at a price that is approximately 70% of its original value after a quality check and/or refurbishment (IRENA and IEA-PVPS, 2016). Therefore, we assume that the average lifetime can be doubled linearly to 2050 by implementing policies that incentivize progress in the PV panel reuse business. For EVs, the International Resource Panel (IRP) indicates that a design that allows for easy replacement of parts that wear faster than structural parts can increase product lifetime by 20% (IRP, 2020). We therefore assume that, as with PV panels, extended use of EVs can be achieved by 2050.

2.3.2. Servitization (carsharing and ridesharing)

Focusing on “service provision” rather than “ownership” of products can reduce the need for product ownership while meeting human needs. Sharing cars or journeys is a typical example, and multiple business models have already emerged in this area. In terms of its effects, Martin et al. (2010) showed that per-capita car ownership of car-sharing subscriber households had decreased by half, based on online surveys in North America. Other scientific evidence indicates that ridesharing can reduce vehicle occupancy by 25–75% (Yin et al., 2018). We assume that car ownership can be reduced by 25% with the penetration of carsharing and ridesharing, which accounts for up to approximately 30% of mileage demand by 2050 (IRP, 2020).

2.3.3. End-of-life recycling

End-of-life recycling has been studied intensively in the scientific literature and in policy analyses (Watari et al, 2020, 2021). However, little statistical data have been published to date on the current EoL recycling rate of solar PV or EVs. Several studies (Dominish et al., 2019; Giurco et al., 2019; Ziemann et al., 2018) have shown that approximately 80% of the metals used in solar PV and EVs could potentially be recovered. We therefore assume that the current recycling rate is 0% and that this can be increased to 80% by 2050. This recycling rate implies a high level of efficiency in the entire recycling chain, consisting of collecting, dismantling, sorting, and concentrating of PV and EV components.

3. Results

3.1. Paradoxical relationship between carbon emissions and resource extraction

Future resource extraction patterns driven by the energy transition show a paradoxical relationship between carbon emissions and resource extraction (Fig. 1). Decarbonizing electricity and transport systems will reduce resource extraction caused by fossil fuel production by about 75% and 35%, respectively, from 2015 to 2050. On the other hand, resource extraction associated with metal production will increase sharply in both sectors, increasing by more than a factor of 7 by 2050. Such a substantial increase is primarily due to the increase in the extraction of iron, copper, nickel, silver, tellurium, cobalt, and lithium used for the production of solar PV and EVs. Combining fossil fuels and metals, we can confirm that the decarbonization of the electricity sector will curtail resource extraction by roughly 60% by 2050 relative to 2015 levels. Conversely, the decarbonization of the transport sector will double resource extraction by counteracting the decline in fossil fuel production with a surge in metal production. These findings suggest that the energy transition may, paradoxically, result in a reduction of carbon emissions while increasing substantially resource extraction.

Such observations are heavily dependent on several important parameters including material intensity, TMR factor, and average lifetime of the product (see Fig. S4 in the Supplementary Material). However, the Monte Carlo simulations suggest that the upward trend in resource extraction associated with metal production through 2050 is relatively robust, even after accounting for the uncertainty inherent in the multiple parameters (Fig. 2). Obviously, there is still a great deal of uncertainty about the actual level of extraction, but our analysis in this domain confirms the existence of an inverse relationship between carbon emissions and resource extraction associated with metal production.

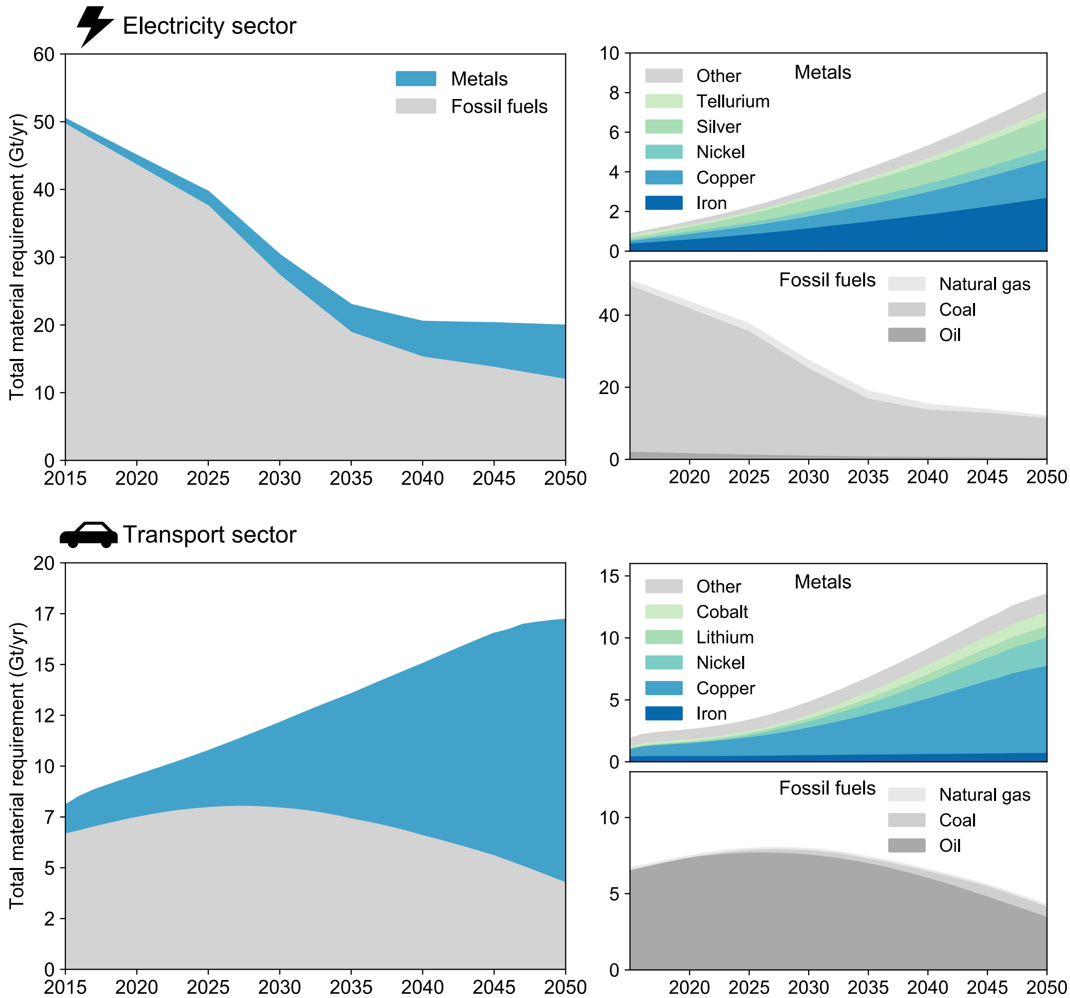

Fig. 1. Total material requirements induced by the global energy transition, 2015–2050. The scenario is based on the pathway toward keeping the rise in global temperatures well below 2 °C by 2100 compared to preindustrial levels (IEA, 2017). The concept of total material requirement captures all of the resource extraction in both used and unused extraction. Used extraction refers to materials that are extracted from the environment and subsequently used in production processes, whereas unused extraction refers to material flows that arise during the course of extraction, but that do not directly enter the economic system (e.g., waste rock and overburden). For a comparison of these values, see Fig. S2 in the Supplementary Material.

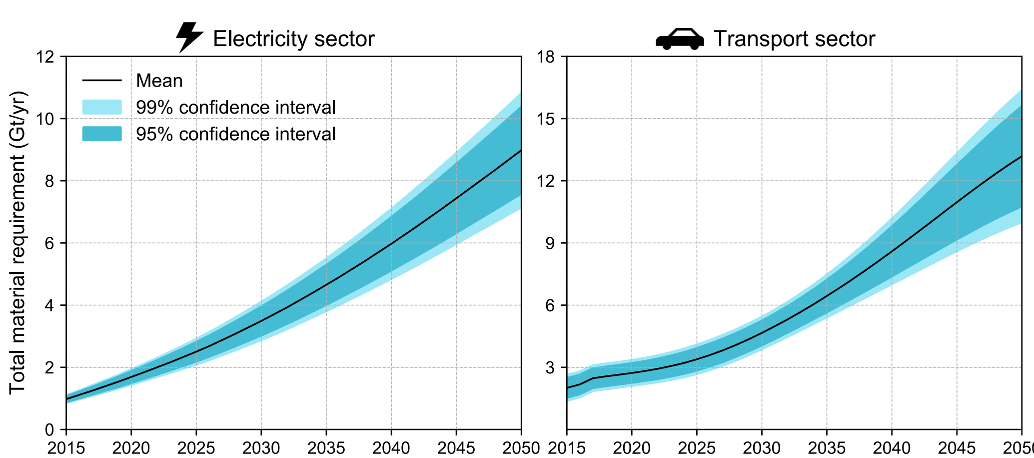

Fig. 2. Uncertainty in the results obtained for total material requirements associated with metal production, 2015–2050. The 95% and 99% confidence intervals are derived from Monte Carlo simulations with a sample size of 1000.

3.2. Countries with poor resource governance will underpin the energy transition

This paradoxical relationship between carbon emissions and resource extraction raises the question of which countries will support the energy transition through mining activities. We find that a substantial amount of resource extraction will occur in countries with weak, poor, and failing resource governance, and that this extraction will underpin the energy transition (Fig. 3). Over the scenario period, around 32% of resource extraction associated with metal production in the electricity sector will take place in countries with weak, poor, and failing governance. The situation is worse in the transport sector, where extraction in countries with weak, poor, and failing resource governance accounts for around 40% of the total. A closer look at the country-level breakdown shows that while Chile and Australia, which have good and satisfactory resource governance, respectively, are the dominant players in resource extraction, countries with weak and poor resource governance are also high on the list (Fig. 4).

The relative change reflects a more problematic picture (Fig. 5). Decarbonization of both the electricity and transport sectors will lead to the largest increase in resource extraction in countries with poor governance, increasing by factors of 13 and 17, respectively, from 2015 to 2050. This category includes the DR Congo, a major producer of cobalt and copper; Madagascar and Cuba, which are nickel-rich countries; and Guatemala, which is rich in silver. This suggests that, if current trends continue, the rapid increase in mining activities that will be induced by the energy transition is likely to have negative consequences, such as environmental degradation and misappropriation of funds, rather than benefiting local communities.

3.3. Circular economy strategies may not fully offset resource extraction growth

The analysis described above indicates that the energy transition will induce a sharp increase in resource extraction in countries with insufficient resource governance. An emerging question is to what extent the circular economy strategy can complement the growth of resource extraction. We find that a suite of circular economy strategies can reduce resource extraction associated with metal production in the electricity sector by 23% in 2050, compared to the case where no such strategies are implemented (Fig. 6). Specifically, a 13% reduction could come from lifetime extension and the other 10% reduction from recycling. Looking at the transport sector, a 60% reduction can be achieved by 2050, reflecting the more diverse strategies considered. Closer examination of the effects of each strategy reveals that lifetime extension, through measures such as reuse and repair, could decrease resource extraction by

Fig. 3. Share of cumulative total material requirements associated with metal production from 2015 to 2050 in regions with different levels of resource governance. The quality of resource governance is evaluated as good, satisfactory, weak, poor, or failing, which are determined by value realization, revenue management, and enabling environment (Natural Resource Governance Institute, 2017).

8% in 2050. Combining car- and ride-sharing activities could provide an additional 27% reduction. Further, the addition of EoL recycling could achieve a 25% reduction, resulting in a total reduction of 60%. This finding clearly underscores the importance of implementing circular economy strategies along with the energy transition.

However, another key perspective in this domain is that the series of the circular economy strategies considered in this paper may not completely offset the increase in resource extraction. Namely, at least a seven-fold increase in resource extraction is inevitable in countries with poor resource governance, even if circular economy strategies are fully implemented (Fig. S3 in the Supplementary Material). This simply means that the set of circular economy strategies alone may not completely eliminate the paradox in which energy transition leads to a substantial increase in resource extraction in countries with insufficient resource governance. A truly sustainable energy transition will require the implementation of complementary measures to enhance resource governance.

4. Discussion

Our analysis showed that decarbonizing the electricity and road transport systems will reduce fossil fuel production while rapidly increasing resource extraction associated with metal production. More importantly, such an increase in resource extraction could be heavily concentrated in countries with weak, poor, and failing resource governance. This means that the impending mining boom driven by the energy transition could result in severe environmental damage and lower economic growth rather than benefitting local communities. Such outcomes should be carefully considered by energy policymakers, particularly with detailed knowledge of local contexts and using deliberative approaches, to navigate potentially deleterious trade-offs in this complex area. Accordingly, in the absence of effective mitigation measures, the energy transition may present policymakers and shareholders with an ethical conundrum in which a reduction in global carbon emissions is associated with a variety of socio-environmental risks at the local mining site. This can ultimately lead to a worsening of the spatial disparities between “resource-consuming” and “resource-producing” countries (Prior et al., 2013).

Our analysis highlights the considerable potential of circular economy strategies regarding such issues. In particular, a set of strategies comprising lifetime extension, sharing and recycling of EVs can reduce resource extraction by more than half compared to not implementing these strategies by 2050. In this context, while previous studies have indicated that EoL recycling has the greatest potential for reducing the primary demand for metals (Dominish et al., 2019; Watari et al., 2019), our analysis adds another perspective that needs to be considered. That is, other strategies, including lifetime extension and sharing practices, have the same or even greater potential to reduce resource extraction as EoL recycling. This clearly emphasizes the importance of exploring a cross-cutting strategy that spans the entire life-cycle of low-carbon technologies, not just the waste management stage.

In this regard, another important perspective obtained from our analysis is that a suite of circular economy strategies alone will not entirely offset the concomitant increase in resource extraction in countries with weak, poor, and failing resource governance. Responsible sourcing will be required where supply cannot be met by circular resource flows. In this context, initiatives related to responsible sourcing or ethical minerals schemes, such as the Responsible Sourcing Initiative, the IRMA Standard for Responsible Mining, CERA (certification of raw materials), and the Responsible Cobalt Initiative could play a significant role (Ali et al., 2017; Brink et al., 2021). For these approaches, independent third-party auditing augments credibility. Given the characteristics of low-carbon technologies that utilize a diversity of metals and which have a high reliance on mining countries with weak, poor, and failing governance, these initiatives need to be adapted widely and immediately to achieve truly sustainable energy transition. Clearly,

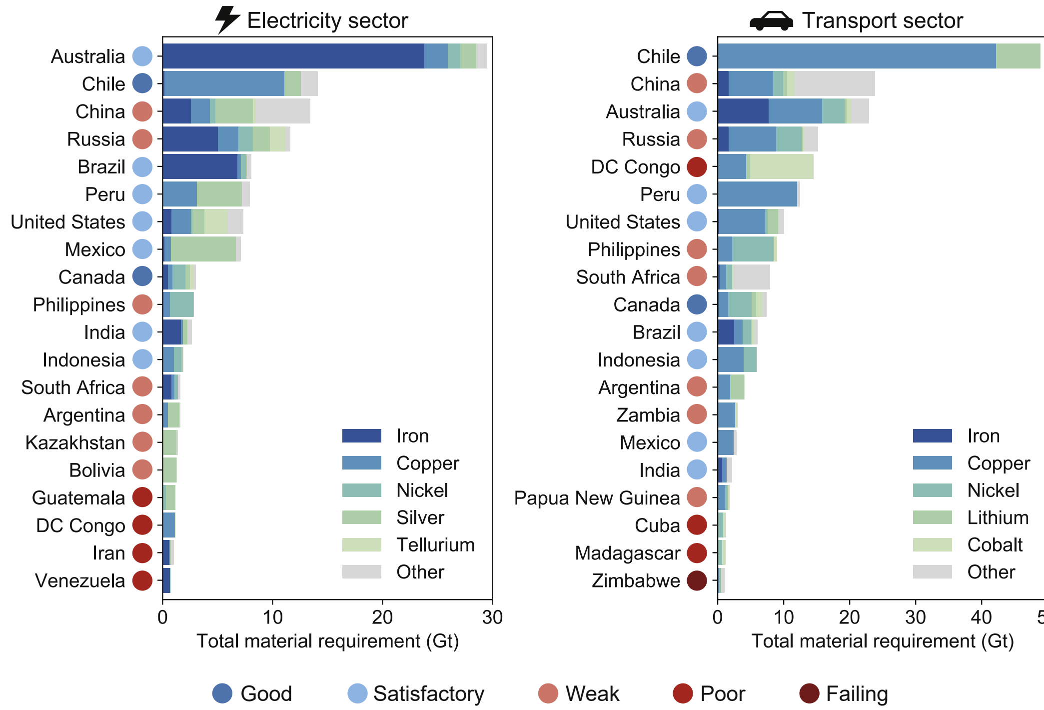

Fig. 4. Cumulative total material requirements associated with metal production from 2015 to 2050 in different countries. The top 20 countries with the largest cumulative extraction volume in each sector have been selected. The color of the circle to the right of the country name reflects the quality of resource governance. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

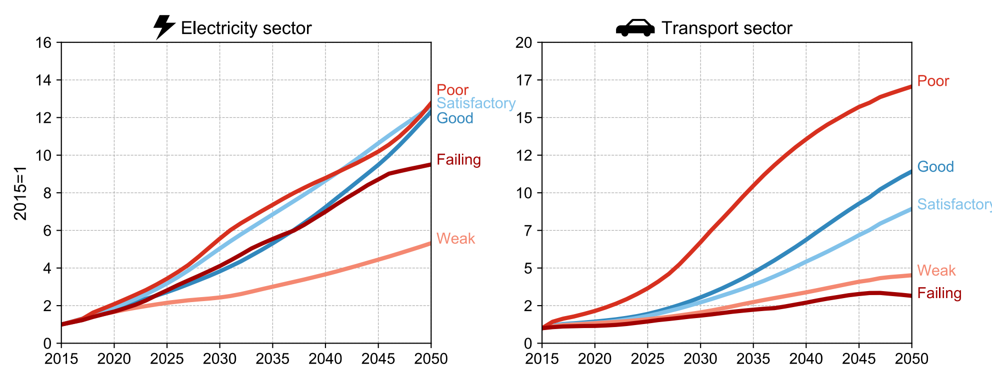

Fig. 5. Relative changes in total material requirements associated with metal production in each region with different levels of resource governance, 2015–2050.

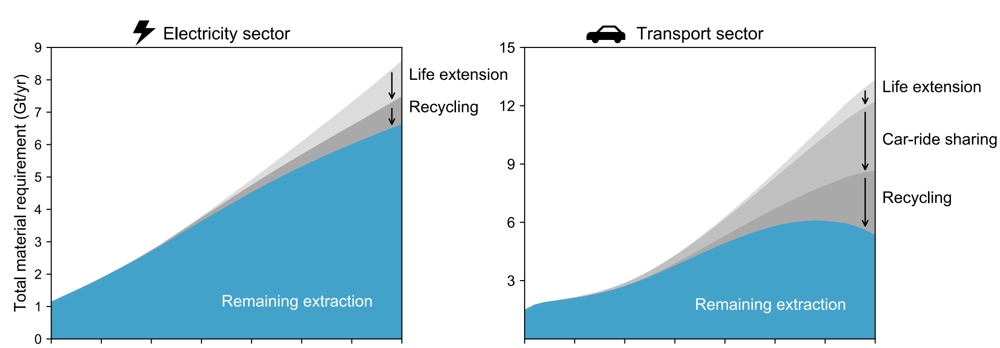

Fig. 6. Effects of circular economy strategies on total material requirements associated with metal production, 2015–2050. The circular economy strategies include lifetime extension, servitization (car and ride sharing), and end-of-life recycling.

improving resource governance is not a trivial task, and improvements will require a variety of approaches, not just certification schemes (Ali et al., 2017). Our analysis does not directly identify the best way in which resource governance can be improved, but it does identify the main areas of concern, including technologies, metals, and countries, that require attention.

Overall, our message is clear. First, a set of circular economy strategies spanning the entire life-cycle of low-carbon technologies, not just EoL recycling, needs to be implemented to effectively mitigate the rapid increase in resource extraction in countries with weak, poor, and failing resource governance. Second, there is a need for widespread adaptation of responsible sourcing frameworks, such as verified certification schemes, to compensate for supplies that cannot be met by circular resource flows. If such instruments can be optimized, then increased mining demand could be an important source of economic growth and adverse socio-environmental impacts could be avoided (IRP, 2019; Sovacool et al., 2020). Furthermore, the UN Environment Assembly resolution on mineral resource governance higlights the importance of improved resource governance globally (UNEP, 2019). Delivering an energy transition with enhanced resource governance therefore presents important opportunities, not only for mitigating climate change, but also for achieving a broader set of sustainable development goals (United Nations, 2015), such as SDGs1 (no poverty) and SDGs8 (decent work and economic growth).

5. Conclusion

The transition to a 1.5–2 °C world will fundamentally change existing the resource flows of both metals and fossil fuels. However, assessment of the potential impacts of such an energy system transition for mining countries is largely missing from existing studies. This study addresses this knowledge gap by linking global energy scenarios with a resource demand-supply models on a county-by-country basis. Our approach captures all used and unused resource extraction by using the total material requirement indicator, as well as the characteristics of each country in terms of the quality of their resource governance policies. The main findings of the study were as follows: (1) An inverse relationship exists between carbon emissions and resource extraction; (2) growth in resource extraction will be concentrated in countries with weak, poor, and failing resource governance; and (3) circular economy strategies, including lifetime extension, servitization and recycling, can moderate resource extraction growth, but mine development is inevitable. Our findings underscore the importance of institutional instruments governing the global supply chains of low-carbon technologies, such as product based certification and effective labelling schemes. If such responses are implemented properly, the energy transition could be a catalyst for achieving broader sets of sustainable development goals, not solely for mitigating climate change.

CRediT authorship contribution statement

Takuma Watari: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **Keisuke Nansai:** Conceptualization, Methodology, Writing – review & editing. **Kenichi Nakajima:** Conceptualization, Writing – review & editing. **Damien Giurco:** Conceptualization, Visualization, Writing – review & editing.

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.

Acknowledgements

This research was supported in part by Grants-in-Aid for Research (Nos. 21K12344 and 19K24391) from the Japanese Ministry of Education, Culture, Sports, Science and Technology, from the Environment Research and Technology Development Fund (SII-6-2 (JPMEERF20S20620)) of the Environmental Restoration and Conservation Agency of Japan, and from the Japan Society for the Promotion of Science (PE19729). We thank Mr. Wataru Takayanagi for providing helpful comments on graph visualization, and Dr. Stephen Northey and Dr. Steve Mohr for sharing data from their work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.127698.

References

Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M.A., Kinnaird, J., Littleboy, A., Meinert, L.D., Oberhänsli, R., Salem, J., Schodde, R., Schneider, G., Vidal, O., Yakovleva, N., 2017. Mineral supply for sustainable development requires resource governance. Nature 543, 367–372. https://doi.org/10.1038/nature21359.

Ashby, M.F., 2012. Materials for low-carbon power. Mater. Environ. 349–413. https://doi.org/10.1016/b978-0-12-385971-6.00012-9.

Banza Lubaba Nkulu, C., Casas, L., Haufroid, V., De Putter, T., Saenen, N.D., Kayembe-Kitenge, T., Musa Obadia, P., Kyanika Wa Mukoma, D., Lunda Ilunga, J.M., Nawrot, T.S., Luboya Numbi, O., Smolders, E., Nemery, B., 2018. Sustainability of artisanal mining of cobalt in DR Congo. Nat. Sustain. 1, 495–504. https://doi.org/10.1038/s41893-018-0139-4.

BGS Minerals UK, 2018. World Mineral Statistics Data [WWW Document].

Bringezu, S., Schütz, H., Steger, S., Baudisch, J., 2004. International comparison of resource use and its relation to economic growth: the development of total material requirement, direct material inputs and hidden flows and the structure of TMR. Ecol. Econ. 51, 97–124. https://doi.org/10.1016/j.ecolecon.2004.04.010.

Brink, S. Van Den, Kleijn, R., Tukker, A., Huisman, J., 2021. Approaches to responsible sourcing in mineral supply chains. Resour. Conserv. Recycl. 145, 389–398. https://doi.org/10.1016/j.resconrec.2019.02.040.

de Koning, A., Kleijn, R., Huppes, G., Sprecher, B., van Engelen, G., Tukker, A., 2018. Metal supply constraints for a low-carbon economy? Resour. Conserv. Recycl. 129, 202–208. https://doi.org/10.1016/j.resconrec.2017.10.040.

Deetman, S., de Boer, H.S., Van Engelenburg, M., van der Voet, E., van Vuuren, D.P., 2021. Projected material requirements for the global electricity infrastructure – generation, transmission and storage. Resour. Conserv. Recycl. 164, 105200. https://doi.org/10.1016/j.resconrec.2020.105200.

Deetman, S., Pauliuk, S., Van Vuuren, D.P., Van Der Voet, E., Tukker, A., 2018. Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. Environ. Sci. Technol. 52, 4950–4959. https://doi.org/10.1021/acs.est.7b05549.

Dominish, E., Retamal, M., Sharpe, S., Lane, R., Rhamdhani, M.A., Corder, G., Giurco, D., Florin, N., 2018. "Slowing" and "narrowing" the flow of metals for consumer goods: evaluating opportunities and barriers. Sustain 10. https://doi.org/10.3390/su10041096.

Dominish, E., Teske, S., Florin, N., 2019. Responsible Minerals Sourcing for Renewable Energy.

Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.

Giurco, D., Dominish, E., Florin, N., Watari, T., McLellan, B., 2019. Requirements for minerals and metals for 100% Renewable scenarios. In: Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5C and +2C. https://doi.org/10.1007/978-3-030-05843-2_11.

Halada, K., Ijima, K., Katagiri, N., Okura, T., 2001. An approximate estimation of total materials requirement of metals. Nippon Kinzoku Gakkaishi/J. Japan Inst. Met. 65, 564–570. https://doi.org/10.2320/jinstmet1952.65.7_564.

IEA, 2018. Global EV Outlook 2018. Towards Cross-Model Electrification, Electric Vehicles Initiative, 2016.

IEA, 2017. Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations Together Secure Sustainable. Paris, France. https://doi.org/10.1787/energy_tech-2017-en.

IEA, 2010. Energy Technology Systems Analysis Programme. France, Paris. https://doi.org/10.1007/978-3-319-18639-9.

IRENA, IEA-PVPS, 2016. End-of-Life Management : Solar Photovoltaic Panels.

IRP, 2020. Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future. Nairobi, Kenya. https://doi.org/10.5281/zenodo.3542680.

IRP, 2019. Mineral Resource Governance in the 21st Century: Gearing Extractive Industries towards Sustainable Development. United Nations Environment Programme, Nairobi, Kenya.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Kosai, S., Matsui, K., Matsubae, K., Yamasue, E., Nagasaka, T., 2020. Natural resource use of gasoline, hybrid, electric and fuel cell vehicles considering land disturbances. Resour. Conserv. Recycl. 166, 105256. https://doi.org/10.1016/j.resconrec.2020.105256.

Kosai, S., Takata, U., Yamasue, E., 2021. Natural resource use of a traction lithium-ion battery production based on land disturbances through mining activities. J. Clean. Prod. 280, 124871. https://doi.org/10.1016/j.jclepro.2020.124871.

Lèbre, É., Stringer, M., Svobodova, K., Owen, J.R., Kemp, D., Côte, C., Arratia-Solar, A., Valenta, R.K., 2020. The social and environmental complexities of extracting energy transition metals. Nat. Commun. 11, 4823. https://doi.org/10.1038/s41467-020-18661-9.

Martin, E., Shaheen, S., Lidicker, J., 2010. Impact of carsharing on household vehicle holdings. Transport. Res. Rec. 150–158. https://doi.org/10.3141/2143-19.

Mohr, S., 2010. Projection of World Fossil Fuel Production with Supply and Demand Interactions. Univ. Newcastle. University of Newcastle.

Mohr, S., Giurco, D., Retamal, M., Mason, L., Mudd, G., 2018. Global projection of lead-zinc supply from known resources. Resources 7, 17. https://doi.org/10.3390/resources7010017.

Mohr, S., Giurco, D., Yellishetty, M., Ward, J., Mudd, G., 2015. Projection of iron ore production. Nat. Resour. Res. 24, 317–327. https://doi.org/10.1007/s11053-014-9256-6.

Mohr, S.H., Mudd, G.M., Giurco, D., 2012. Lithium resources and production: critical assessment and global projections. Minerals 2, 65–84. https://doi.org/10.3390/min2010065.

Mudd, G.M., 2010. The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. Res. Pol. 35, 98–115. https://doi.org/10.1016/j.resourpol.2009.12.001.

Nakajima, K., Ijima, K., Halada, K., 2006. Estimation of Total Material Requirement: Energy Resources and Industrial Materials. Tsukuba, Japan.

Nakajima, K., Noda, S., Nansai, K., Matsubae, K., Takayanagi, W., Tomita, M., 2019. Global distribution of used and unused extracted materials induced by consumption of iron, copper, and nickel. Environ. Sci. Technol. 53, 1555–1563. https://doi.org/10.1021/acs.est.8b04575.

Natural Resource Governance Institute, 2017. Natural Resource Governance Index.

Northey, S., Haque, N., Mudd, G., 2013. Using sustainability reporting to assess the environmental footprint of copper mining. J. Clean. Prod. 40, 118–128. https://doi.org/10.1016/j.jclepro.2012.09.027.

Northey, S., Mohr, S., Mudd, G.M., Weng, Z., Giurco, D., 2014. Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. Resour. Conserv. Recycl. 83, 190–201. https://doi.org/10.1016/j.resconrec.2013.10.005.

Owen, J.R., Kemp, D., Lèbre, Svobodova, K., Pérez Murillo, G., 2020. Catastrophic tailings dam failures and disaster risk disclosure. Int. J. Disaster Risk Reduct. 42 https://doi.org/10.1016/j.ijdrr.2019.101361.

Pauliuk, S., Heeren, N., 2019. ODYM — an open software framework for studying dynamic material systems Principles , implementation , and data structures. J. Ind. Ecol. 1–13. https://doi.org/10.1111/jiec.12952.

Pauliuk, S., Wang, T., Müller, D.B., 2013. Steel all over the world: estimating in-use stocks of iron for 200 countries. Resour. Conserv. Recycl. 71, 22–30. https://doi.org/10.1016/j.resconrec.2012.11.008.

Prior, T., Wäger, P.A., Stamp, A., Widmer, R., Giurco, D., 2013. Sustainable governance of scarce metals: the case of lithium. Sci. Total Environ. 461–462, 785–791. https://doi.org/10.1016/j.scitotenv.2013.05.042.

Reuter, Markus, van Schaik, Antoinette, Gutzmer, Jens, Bartie, Neill, Abadías-Llamas, Alejandro, 2019. Challenges of the Circular Economy: A Material, Metallurgical, and Product Design Perspective. Annu. Rev. Mater. Res. 49, 253–274. https://doi.org/10.1146/annurev-matsci-070218-010057.

Sonter, L.J., Dade, M.C., Watson, J.E.M., Valenta, R.K., 2020. Renewable energy production will exacerbate mining threats to biodiversity. Nat. Commun. 11, 6–11. https://doi.org/10.1038/s41467-020-17928-5.

Sovacool, B.B.K., Ali, S.H., Bazilian, M., Radley, B., 2020. Sustainable minerals and metals for a low-carbon future. Science 80, 367.

Stahel, W.R., 2016. Circular economy. Nature 531, 435–438. https://doi.org/10.1038/531435a.

The World Bank, 2020. Minerals for Climate Action : the Mineral Intensity of the Clean Energy Transition.

The World Bank, 2017. The Growing Role of Minerals and Metals for a Low Carbon Future. Washington, DC. https://doi.org/10.1596/28312.

U.S. Geological Survey, 2020. Commodity Statistics and Information [WWW Document]. URL. https://minerals.usgs.gov/minerals/pubs/mcs/.

United Nations, 2015. UN Sustainable Development Goals: 17 Goals to Transform Our World. https://doi.org/10.1038/505587a.

Watari, T., McLellan, B.C., Giurco, D., Dominish, E., Yamasue, E., Nansai, K., 2019. Total material requirement for the global energy transition to 2050: a focus on transport and electricity. Resour. Conserv. Recycl. 148, 91–103. https://doi.org/10.1016/j.resconrec.2019.05.015.

Watari, T., Nansai, K., Nakajima, K., 2021. Major metals demand, supply, and environmental impacts to 2100: a critical review. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2020.105107.

Watari, T., Nansai, K., Nakajima, K., 2020. Review of critical metal dynamics to 2050 for 48 elements. Resour. Conserv. Recycl. 155, 104669. https://doi.org/10.1016/j.resconrec.2019.104669.

Werner, T.T., Mudd, G.M., Schipper, A.M., Huijbregts, M.A.J., Taneja, L., Northey, S.A., 2020. Global-scale remote sensing of mine areas and analysis of factors explaining their extent. Global Environ. Change 60, 102007. https://doi.org/10.1016/j.gloenvcha.2019.102007.

Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W., Krausmann, F., 2019. Integrating material stock dynamics into economy-wide material flow accounting: concepts, modelling, and global application for 1900–2050. Ecol. Econ. 156, 121–133. https://doi.org/10.1016/j.ecolecon.2018.09.010.

Wuppertal Institute, 2014. Material intensity of materials, fuels, transport services. Food.

Yamasue, E., Minamino, R., Numata, T., Nakajima, K., Murakami, S., Daigo, I., Hashimoto, S., Okumura, H., Ishihara, K.N., 2010. Novel evaluation method of elemental recyclability from urban mine - concept of urban ore TMR. Nippon Kinzoku Gakkaishi/J. Japan Inst. Met. 74, 718–723. https://doi.org/10.2320/jinstmet.74.718.

Yin, B., Liu, L., Coulombel, N., Viguié, V., 2018. Appraising the environmental benefits of ride-sharing: the Paris region case study. J. Clean. Prod. 177, 888–898. https://doi.org/10.1016/j.jclepro.2017.12.186.

Ziemann, S., Müller, D.B., Schebek, L., Weil, M., 2018. Modeling the potential impact of lithium recycling from EV batteries on lithium demand: a dynamic MFA approach. Resour. Conserv. Recycl. 133, 76–85. https://doi.org/10.1016/j.resconrec.2018.01.031.

https://wedocs.unep.org/bitstream/handle/20.500.11822/28501/English.pdf?sequence=3&isAllowed=y, 2019.