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Global environmental cost of using rare earth elements in green energy technologies

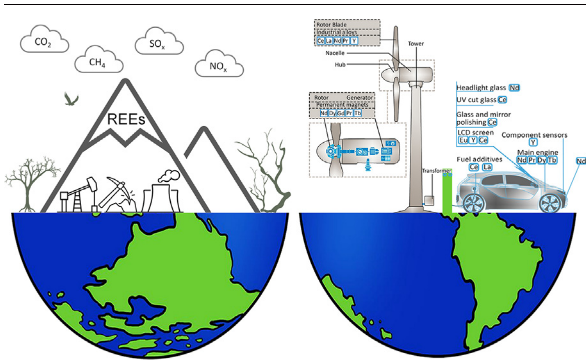
Saeed Rahimpour Golroudbary [a,*], Iryna Makarava [b,c,**], Andrzej Kraslawski [a,***], Eveliina Repo [b]

[a] School of Engineering Science, Industrial Engineering and Management (IEM), LUT University, FI-53851 Lappeenranta, Finland
[b] School of Engineering Science, Department of Separation Science, LUT University, FI-53850 Lappeenranta, Finland
[c] Helmholtz-Zentrum Dresden-Rossendorf, Helmholtz Institute Freiberg for Resource Technology, D-09599 Freiberg, Germany

HIGHLIGHTS

- Generation of green energy must be analyzed in a broad environmental context.
- Increase of green energy production by 1% causes 0.18% depletion of REE reserves.
- Growth of green energy production by 1% leads to 0.90% growth of GHG emissions.
- Mining of known REEs deposits is not sufficient to ensure sustainable development.

GRAPHICAL ABSTRACT



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ABSTRACT

Decarbonization of economy is intended to reduce the consumption of non-renewable energy sources and emissions from them. One of the major components of decarbonization are "green energy" technologies, e.g. wind turbines and electric vehicles. However, they themselves create new sustainability challenges, e.g. use of green energy contributes to the reduction of consumption of fossil fuels, on one hand, but at the same time it increases demand for permanent magnets containing considerable amounts of rare earth elements (REEs). This article provides the first global analysis of environmental impact of using rare earth elements in green energy technologies. The analysis was performed applying system dynamics modelling methodology integrated with life cycle assessment and geometallurgical approach. We provide evidence that an increase by 1% of green energy production causes a depletion of REEs reserves by 0.18% and increases GHG emissions in the exploitation phase by 0.90%. Our results demonstrate that between 2010 and 2020, the use of permanent magnets has resulted cumulatively in 32 billion tonnes CO_2-equivalent of GHG emissions globally. It shows that new approaches to decarbonization are still needed, in order to ensure sustainability of the process. The finding highlights a need to design and implement various measures intended to increase REEs reuse, recycling (currently below 1%), limit their dematerialization, increase substitution and develop new elimination technologies. Such measures would support the development of appropriate strategies for decarbonization and environmentally sustainable development of green energy technologies.

* Corresponding author.
** Correspondence to: I. Makarava, School of Engineering Science, Department of Separation Science, LUT University, FI-53850 Lappeenranta, Finland.
*** Corresponding author.
E-mail addresses: Saeed.Rahimpour.Golroudbary@lut.fi (S.R. Golroudbary), Iryna.Makarava@lut.fi (I. Makarava), Andrzej.kraslawski@lut.fi (A. Kraslawski).

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1. Introduction

Decarbonization has emerged as an important measure to keep global average temperature increase well below 2 °C above pre-industrial levels according to the goal agreed in the Paris Agreement (Waisman et al., 2019). Therefore, the transition from fossil fuels to renewable energy sources considerably accelerated in the last decade (increase by 16.4% per annum between 2007 and 2017 (Dudley et al., 2018)). However, the development of 'green energy' technologies has resulted in the growth of consumption of natural resources, e.g. growing use of 'permanent magnets', composed in 25–30% of critical materials, such as rare-earth elements (REEs). The 'permanent magnets', called Neodymium magnets (NdFeB), are used in wind turbines and direct drive motors in electric vehicles (EVs) (Fishman and Graedel, 2019).

As advocated by the Nature Reviews Materials presented in a recent series of articles (Herrington, 2021; Raw materials for a truly green future, 2021), environmentally and socially sustainable ways of sourcing raw materials needed to meet emission reduction targets must be established. We address those calls by showing that decarbonization of economy requires a much deeper analysis of environmental costs as it increases the consumption of critical materials. Our quantitative analysis provides an insight into the key question: to what extent the use of green energy is a sustainable solution.

The existed literature has highlighted methodological challenges, high uncertainty and lack of knowledge about the environmental impact of REEs production (Bailey et al., 2020; Schreiber et al., 2021). Several studies on the environmental impact of rare earth elements conducted using the life cycle assessment (LCA) are summarized in Table 1. According to the literature review, most studies have evaluated the carbon footprint of a specific stage of REEs production (mining and refining) or manufacturing of specific products (e.g. batteries or magnets production and its impact at the local scale). Unfortunately, they do not allow for a holistic analysis of environmental impacts of green energy value chain, e.g. energy and water consumption within all processes involving REEs. There are several works addressing fragmentarily the problem of environmental impact of REEs supply chain. For example, previous studies on the environmental impact of REEs life cycle assess the recycling stage only, e.g. in the case of electronic waste (Li et al., 2019; Liu and Keoleian, 2020), and electric vehicles (Jin et al., 2018; Tintelecan et al., 2019). Considering the application of REEs in wind turbines, (Arshi et al., 2018) provide the environmental assessment of REEs limited to the regional scale of mining of monazite/bastnasite deposits and ion adsorption clays from China and two manufacturing facilities located in Bayan Obo and South China. Gwenzi et al. (2018) reviewed and highlighted the lack of quantitative analysis of REEs flows from several perspectives e.g. environmental and human health risks. Bailey et al. (Bailey et al., 2020) offer a limited analysis of the mining stage by focusing only on 3 types of minerals: bastnäsite, ion adsorption clays and lateritic monazite. In contrast to the above-presented examples, this study offers a complete supply chain analysis of all REEs elements on the global scale for the years 2010–2030. Moreover, the significance of an integrated life cycle assessment and geometallurgical approach for reducing the environmental impact of the extraction of raw materials essential for the transition to a low-carbon economy has been demonstrated in the recent review analysis by Pell et al. (2021). Most of the previous studies focused only on China as the primary source of REEs ores. However, nowadays there are various mines around the world extracting those elements and their operation needs to be considered in a global sustainability assessment. It is worth mentioning that several review articles analyzing differences in mining and processing of REEs have been published recently (Pell et al., 2021; Schreiber et al., 2021). Nevertheless, there is a significant gap in the literature as none of these studies discusses historical changes in the mass flow of REEs through all the supply chain stages or estimates the dynamics of trends in the near future. Therefore, a comprehensive study of the environmental impact of all supply chain stages for green energy technologies and relevant decarbonization measures for REEs' mining and production at the global scale in a long-term perspective is still missing. The novelty of this study consists in conducting a holistic assessment of the quantitative impact of green energy technologies on other natural resources, i.e. rare earth elements and assessing their side effect and dynamic changes over time in the period 2010–2030. This work, unlike the previous publications, offers a detailed analysis of the subsequent stages of rare elements life cycle. It studies material flow in the supply chain of fifteen rare earth elements. Moreover, this study considers 16 types of ores existing in the deposits (Bastnäsite, Monazite, Xenotime, Euxenite, Apatite, Gadolinite, Loparite, Uraninite, Brannerite, Dolerite, Pyrochlore, Perovskite, Zircon, Clay, Synchysite, and Parisite) while analyses offered by other publications are limited mainly to 1 or maximum 3 types of ores (usually Bastnäsite, Monazite, or ion-adsorption clays). Several studies have been devoted to the growing global demand for REEs, e.g. (Dutta et al., 2016). Some of them (Du and Graedel, 2013; Graedel et al., 2015) suggest that supply risk can be expected for several elements such as Eu, Dy, and Er. This estimation results from the scarcity of resources. Hence, the growing global demand for these elements stemming from their importance in shifting towards a green economy, strongly encourages exploration geochemists and technology developers to conduct new research to ensure a sustainable supply of REEs. Therefore, there is a need for tracing the environmental cost of REEs consumption embodied in the global supply chains from the primary sources to their use in green energy technologies. It should help in assessing the real environmental costs of transition towards green economy. This study covers a comprehensive environmental assessment to address the discussed issues.

Using system dynamics modelling (Forrester, 1997), we quantify the key environmental concerns in mining and processing stages of fifteen REEs including yttrium (Y) and lanthanoid group (except promethium (Pm) that is radioactive, and does not have stable isotopes. In the current study, all REEs are considered in every stage of the supply chain. At the moment, no technology exists that would allow to carry out a selective recovery of selected REEs needed for specific applications. Therefore, we analyzed the life cycle of all rare earth elements in mining and processing stages, and focused on elements required for production of wind turbines and EVs in the manufacturing stage. The issues that we intended to address include: REEs deposits depletion, energy and water consumption, as well as related emissions. Energy sources used in mining and processing stages are: crude oil, bitumen, shale oil, natural gas, coal, forest residues, pet coke, hydroelectric power, nuclear energy, geothermal sources, solar and wind power. Water consumption considerations cover reservoir evaporation, cooling, mining, and processing. We assess the following emissions CO_2, CH_4, SO_x, NO_x, CO, N_2O, VOC, PM2.5, POC, BC, and PM10 at all stages of green energy supply chain.

In the production stage, we quantify the environmental impact (global warming, ecotoxicity, acidification, eutrophication, carcinogenic effects, ozone depletion, and smog emissions) of the production of permanent magnets.

We analyze trends observed in using EVs and installed wind power, price, natural resource depletion and greenhouse gas (GHG) emissions. The analysis covers years from 2010 to 2030. This period was selected to explore the trends related to rare earth elements crisis caused by China export limitations and trends emerging in REEs consumption.

2. Materials and methods

2.1. Model of the global green energy supply chain

Systematic environmental analysis of sustainability of the global supply chain of green energy technologies is still missing. Moreover, life cycle assessment of REEs is particularly sensitive to methodological differences, e.g., variations in allocation procedures can significantly change the environmental impact per kg of product. Therefore, our analysis of REEs production relies on both geology and processing route.

This study proposes a dynamics model consisting of global REEs flows, the use of respective resources, and emissions. The model consists of 1465 variables and parameters. The Anylogic software (www.anylogic.com) is

Table 1
Summary of investigation on the environmental impact of rare earth elements used in green energy technologies.

Reference	Objective of study	Methodology	Supply chain scope			Environmental Impact				Geographical scope
			Mining	Processing	Manufacturing	Recycling	Energy	Water	Emissions	
(Arshi et al., 2018)	To assess the environmental footprint of rare earth products	LCA	✓	✓	✓				✓	Local: China
(Lee and Wen, 2018)	To analyze the environmental impact of the supply of rare earth elements in China	LCA and scenario building	✓	✓					✓	Local: China
(Jin et al., 2018)	To compare Neodymium-Iron-Boron magnet-to-magnet recycling for electric vehicle motors	LCA			✓	✓			✓	Local: Case of manufacturing
(Bailey et al., 2020)	To assess life cycle of REEs to provide information about data gap	LCA	✓	✓					✓	Local: Australia
(Zaimes et al., 2015)	To evaluate the environmental impacts and resource intensity of producing rare earth oxides	LCA	✓	✓			✓		✓	Local: China
(Vahidi et al., 2016)	Life cycle assessment on mixed rare earth oxides production from ion adsorption clay	LCA	✓	✓					✓	Local: China
(Deng and Kendall, 2019)	Life cycle assessment of heavy rare earth oxides from ion-adsorption clays	LCA	✓	✓					✓	Local: China
Current study	Global environmental impact of rare earth elements used in green energy technologies	System dynamics modelling integrated with LCA and geometallurgical approach	✓	✓	✓		✓	✓	✓	Global

used for simulation. The main variables including flow, stock and auxiliary variables are presented in Table S1 and parameters together with all data required to run the model are available in Table S2 and Data S1 (#2, #4, #5 and #6). Fig. S4 provides details of the dynamic model and used data sources. We divided the variables of the dynamic model into two groups including endogenous and exogenous variables to specify the model boundary. Endogenous variables affect and, at the same time, are affected by other system components and parameters, while exogenous variables are not directly affected by the system. Groups and types of all variables are presented in Table S1.

The model is composed of two main parts: (i) extractive stage which includes mining and processing of REEs and (ii) production stage of manufacturing permanent magnets applied in wind turbines and EVs. It examines environmental impact of each process including energy consumption, water use, CO_2, CH_4, SO_x, NO_x, CO, VOC, PM2.5, N_2O, POC, BC, and PM10 emissions.

In the first stage, REEs containing minerals are extracted, then separated, processed and transformed into chemicals. It should be noted that the various types of deposits have particular characteristics of size and grade. For example, carbonatites tend to be medium to large tonnage and high grade, whereas alkaline rock deposits are generally larger tonnage but lower grade, tending to have higher proportions of heavy REE. Mineral sands are low grade and REE minerals are by-products; ion adsorption deposits are small and low grade but relatively rich in heavy REE (Goodenough et al., 2016). Also, multiple stages are used for separation of the individual REE, e.g., selective oxidation can be used for Ce, and also for Pr and Tb, which have a potential +4 oxidation state, whilst selective reduction works for Eu, Sm and Yb because they have a potential +2 valency (McNeice and Ghahreman, 2018; Strauss et al., 2019). In processing, for example, the bastnäsite will be dissolved in acid and then subjected to counter-current solvent extraction using immiscible organic and acid solvents (Xie et al., 2014). The selective oxidation/reduction, fractional crystallization, fractional precipitation, ion exchange or solvent extraction are used for REEs purification (Kavun et al., 2021; Laatikainen et al., 2022; Makarova et al., 2020). The exact steps of separation process depend on the composition of the initial REE concentrate as well as the desired products. The exact steps of separation process depend on the composition of the initial REE concentrate as well as the desired products. Historical data for the global mine production of rare earth oxide (REO) are available for the period between 1996 and 2020 from the United States Geological Survey (USGS) data sources (Gambogi, 2021). Therefore, the model covers two periods: the historical (1996–2020) and the future one (2020 − 2030). Growth rate of the estimated primary production of REEs is based on future demand by 2030 (Hagelüken, 2014; Wang et al., 2020a).

The second stage of the model comprises all manufacturing streams where REEs are applied. The focus of environmental analysis in this phase is on production of permanent magnets for wind turbines and EVs applications.

2.2. Mathematical formulation

The model consists of two types of equations (state and rate) for quantifying the stocks and flows in given systems. Results from the model are next used as inputs to geographical distribution equations.

Stocks (state equations) in the mass flows of the model can be used to analyze the environmental performance of countries involved in mining and processing stages, as well as global green energy production over time. Flows (rate equations) correspond to the production of REEs, manufacturing of products, energy consumption, water use, and related emissions.

Eq. (1) corresponds to the global stock of REO ($GR_s(t)$) over the period "t_0-t" where "t_0" is the initial year and "t" is the final year. $TM_{a-i}(t)$ represents the annual production rate of REO from mining by country "i" (where $i = 1,2, \ldots,12$) including Australia, Brazil, Myanmar, Burundi, China, India, Madagascar, Malaysia, Russia, Thailand, US, and Vietnam; $REE_{a-ji}(t)$ stands for annual production of element "j" (where $j = 1,2, \ldots,15$) including Cerium, Dysprosium, Erbium, Europium, Gadolinium, Holmium, Lanthanum, Lutetium, Neodymium, Praseodymium, Samarium, Terbium, Thulium, Ytterbium, and Yttrium, in country "i" (Eq. (2)).

$$GR_s(t) = \int_{t_0}^{t} \left(\sum_{i=1}^{12} TM_{a-i}(t) - \sum_{j=1}^{15} \sum_{i=1}^{12} REE_{a-ji}(t) \right) dt + GR_s(t_0) \quad (1)$$

$$REE_{a-ji}(t) = \beta_{ji} * TR_{s-i}(t) \quad (2)$$

where β_{ji} is a coefficient of element "j" processing by country "i" and $TR_{s-i}(t)$ is the total REO stock in country "i" in year "t".

Eq. (3) describes the global stock of rare earth element "j" in country "i" ($REE_{s-ji}(t)$) in the time period "t_0-t" by a time integral of $REE_{a-ji}(t)$ as annual production of element "j" in country "i" minus $REE_{a-jk}(t)$ (Eq. (4))

gives the annual rate of element *“j”* used in global manufacturing output *“k”* (where $k=1,2,\ldots,10$) including magnets, battery alloys, metal alloys, catalysts, petroleum, polishing powders, glass additives, phosphors, ceramics, and other products. α_{jk} is coefficient of element *“j”* used for production *“k”*.

$$REE_{s-ji}(t)=\int_{t_0}^{t}\left(REE_{a-ij}(t)-REE_{a-jk}(t)\right)dt+REE_{s-ji}(t_0) \quad (3)$$

$$REE_{a-jk}(t)=\alpha_{jk}*REE_{s-ji}(t) \quad (4)$$

Eq. (5) describes the global stock of product *“l”* ($GP_l(t)$) in the time period *“t_0-t”* by a time integral of $REE_{a-jk}(t)$ as the annual rate of element *“j”* used in the global manufacturing output *“k”* minus $REE_{a-jl}(t)$ (Eq. (6)) representing the annual rate of element *“j”* used in product *“l”* (where $l=1,2,\ldots,20$) including magnets for wind turbines and electric vehicles, NiMH batteries, metallurgical alloys, catalysts for fluid cracking, automobile catalytic converters, glass altering, glass colorizing or decolorizing, glass absorbing ultraviolet light, yttrium aluminum garnet laser, cathode ray tube displays, fluorescent lamps, other color light applications, electronic applications, ceramic glazes for color control, ferrites for oxygen sensors, chemicals containing REEs, military weapons, delivery systems, and satellite systems. δ_l is coefficient of element *“j”* used in product *“l”* and $D_{jl}(t)$ is global demand of element *“j”* for using in product *“l”*.

The growth of the rare earth metals market is driven by the growing use of products intended to mitigate the climate change and global warming., e.g. hybrid cars, electric car batteries, and wind turbines. Therefore, our projection scenarios for REEs rely on the compound annual growth rate of REEs demand until 2030.

$$GP_l(t)=\int_{t_0}^{t}\left(REE_{a-jk}(t)-REE_{a-jl}(t)\right)dt+GP_l(t_0) \quad (5)$$

$$REE_{a-jl}(t)=\delta_l*D_{jl}(t) \quad (6)$$

Considering all mass flows over time, the environmental assessment (energy, water and emissions) is given in an identical form in the model. Every stage in the REEs supply chain consumes energy obtained from different sources. There are three initial steps for mineral processing: mining, beneficiation, and separation of an element. After separation, metals are produced by molten salt electrolysis and metallothermic reduction methods. During the mining of REEs, energy consumption is mainly associated with the use of mining machines and equipment. The industrial processes used are complex and require large amounts of electricity. Although all rare earth minerals are generally open-pit mined, energy requirement for crushing and grinding varies depending on (i) their hardness and the gangue minerals associated and (ii) the chemical form that they extract (Peiró and Méndez, 2013). In the production stage, the manufacturing of permanent magnets containing REEs is analyzed separately. Total cumulative and the annual amount of energy consumed in each stage are calculated using Eqs. (7) and (8).

$$TE_{Sn-i}(t)=\int_{t_0}^{t}TE_{an-i}(t)\mathrm{d}t+TE_{Sn-i}(t_0) \quad (7)$$

$$TE_{an-i}(t)=REE_{a-ji}(t)\times\sum_{m=1}^{8}\varphi_{n,m} \quad (8)$$

In Eq. (7), $TE_{Sn-i}(t)$ corresponds to the total cumulative amount of energy consumption in country *“i”* in year *“t”* for the period 2010–2030, $n=1,2,3$ represent mining, processing and production stages of the green energy supply chain and $TE_{an-i}(t)$ is annual energy consumption in stage *“n”* in country *“i”* in year *“t”*. In Eq. (8), $REE_{a-ji}(t)$ is the amount of mass of element *“j”* in country *“i”* in year *“t”*, and $\varphi_{n,m}$ is the energy required per 1 T of REEs flow in stage *“n”* from each energy source $m=1,2,\ldots,8$ which represent all sources of energy: fossil fuel, natural gas, petroleum, coal, non-fossil fuel, nuclear, renewables, and biomass.

The total cumulative and annual amount of water consumed in stage *“n”* of REEs supply chain can be given by Eqs. (9) and (10).

$$TW_{Sn-i}(t)=\int_{t_0}^{t}TW_{an-i}(t)\mathrm{d}t+TW_{Sn-i}(t_0) \quad (9)$$

$$TW_{an-i}(t)=REE_{a-ji}(t)\times\sum_{w=1}^{4}\upsilon_{n,w} \quad (10)$$

where, the cumulative amount of water directly linked to the mining or processing of REEs ($n=1,2$) in country *“i”* in year *“t”* is shown by $TW_{Sn-i}(t)$. $TW_{an-i}(t)$ is annual water use for REEs mining in country *“i”* which is calculated based on $REE_{a-ji}(t)$ and water sources used for procedure *“w”* ($w=1,2,3,4$ including water cooling, water mining, water process, and water reservoir) in stage *“n”*.

The life-cycles of emission rates from energy sources are adapted from the GREET model (Wang et al., 2020b) and previous studies (Jin et al., 2018). GHG intensities are calculated by using IPCC AR5 100-year Global Warming Potential values (Stocker et al., 2013) of 1 (CO_2), 36 (CH_4), and 298 (N_2O). We applied Eqs. (11) and (12) to estimate the total and annual emissions of each life cycle stage of the green energy supply chain.

In Eq. (11), $TG_{Sn-i}(t)$ is the cumulative emission *“g”* ($g=1,2,3,\ldots,11$ including CO_2, CH_4, SO_x, NO_x, CO, VOC, PM2.5, N_2O, POC, BC, and PM10) in stage *“n”* in year *“t”* and $TG_{an-i}(t)$ corresponds to the annual emission *“g”* in stage *“n”* in country *“i”* in year *“t”*. In Eq. (12), $\varrho_{g,n}(t)$ is the rate of emission generated in stage *“n”* in year *“t”*.

$$TG_{Sn-i}(t)=\int_{t_0}^{t}TG_{an-i}(t)\mathrm{d}t+TG_{Sn-i}(t_0) \quad (11)$$

$$TG_{an-i}(t)=\left(REE_{a-ji}(t)+REE_{a-jk}(t)\right)\times\varrho_{g,n}(t) \quad (12)$$

3. Results and discussion

3.1. Trends in REEs production

Annual growth rate of REEs global consumption is expected to reach 4.4% between 2016 and 2026 (Wang et al., 2020a). Fig. S1 presents geographical distribution of REEs global reserves for top suppliers and by type of deposits in 2020 – about 120 mt. More than 250 mineral species are identified to contain REEs. However, few of those are considered economically exploitable, e.g. silicates, fluorocarbonates, oxides and phosphates. The highest proportion of the global REE reserves (95%) has been identified for Bastnäsite, Monazite, Xenotime or Ion-adsorption clay deposits in China. We focus only on minerals with the highest concentration of REEs (information on quantities and type of minerals for each country is presented in Data S1 (#1 and #2)). The results shown in Fig. S1 suggest that the US and Russia have the most diversified spectrum of REE-containing minerals. US ranks 7th in reserves and 2nd in mining while Russia occupies 4th place in reserves and 7th in mining.

Fig. 1 presents geographical distribution of cumulative primary production in 2010–2020 of five the most significant REEs used in the production of permanent magnets, i.e., Nd, Dy, Tb, Pr, and Gd. Fig. S2 shows geographical distribution of cumulative primary production of other REEs including Yb, Ce, Y, Tm, Ho, Sm, Lu, La, Er, and Eu in the given period. The results illustrate an increase in primary production of all elements between 2010 and 2020 – light rare-earth elements (Ce: 1.5 times, Er: 4.3 times, Ho: 3.4 times, La: 12.1 times, Nd: 1.6 times, Pr: 1.6 times, Tm: 9.3 times, and Y: 4.1 times) and heavy rare-earth elements (Dy: 2.6 times, Eu: 4.4 times, Gd: 2.3 times, Lu: 2.1 times, Tb: 1.4 times, Sm: 1.8 times, and Yb: 1.3 times). REEs never occur individually and they are accompanied by other elements in various minerals.

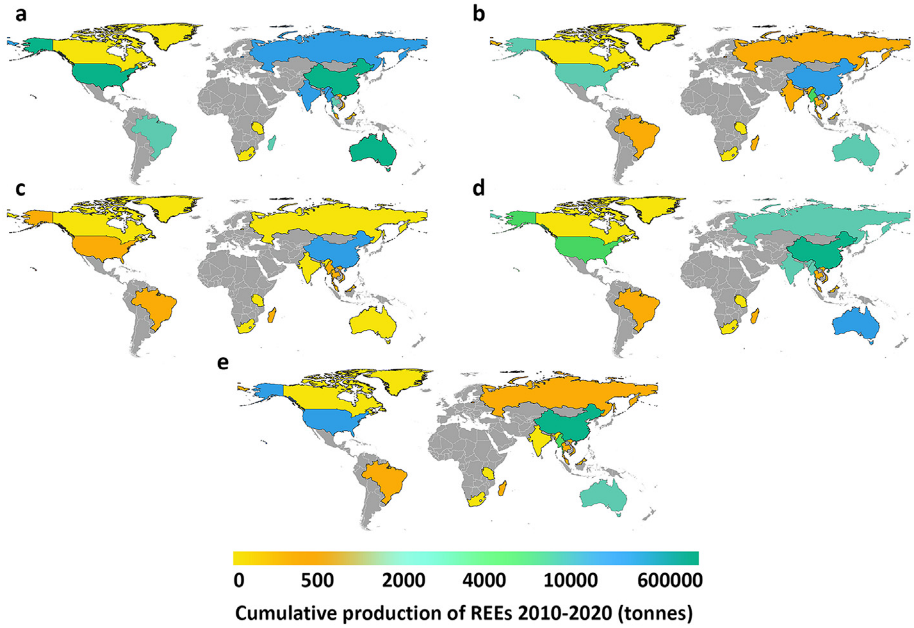


Fig. 1. Global cumulative primary production of rare earth elements by country in the period 2010–2020. a, Neodymium. b, Dysprosium. c, Terbium. d, Praseodymium. e, Gadolinium.

Based on reports of 48 exporters and 75 importers in the United Nations Commodity Trade Database (UNCOMTRADE), Fig. S3 shows the distribution of REEs suppliers and the position of countries in international trade. Detailed information on quantity and value of exports and imports of REEs is presented in Table S3. The result shows that in 2020 exports and imports of REEs reached around 131 kt (USD 1.22 billion) and 118 kt (USD 1.53 billion), respectively.

3.2. Use of REEs in green energy technologies

Fig. 2 shows geographical distribution of wind turbines (Fig. 2a) and different types of EVs (Fig. 2b) in 2020. BP Statistical Review of World Energy revealed that 1590.19 terawatt-hours of global electricity was generated by wind turbines in 2020 (Looney, 2020). The installed wind power capacity has been increasing by more than 50 GW each year and the cumulative installed wind power capacity amounted to 651 GW at the end of 2019 (Jung and Schindler, 2020).

REEs play an important role in the production of wind turbines, due to the increasing power per tower with turbines that have become taller, larger, and lighter, and the application of preferred more efficient configurations of magnet-based technologies, such as gearbox or direct-drive permanent magnet synchronous generators. Although, several technologies are currently being developed that intend to reduce the use of REEs in permanent magnets, according to the IEA they will remain far from being competitive with the existing wind technologies even until the next decade (Bobba et al., 2020). Therefore, we focus on magnet-based technologies in this study.

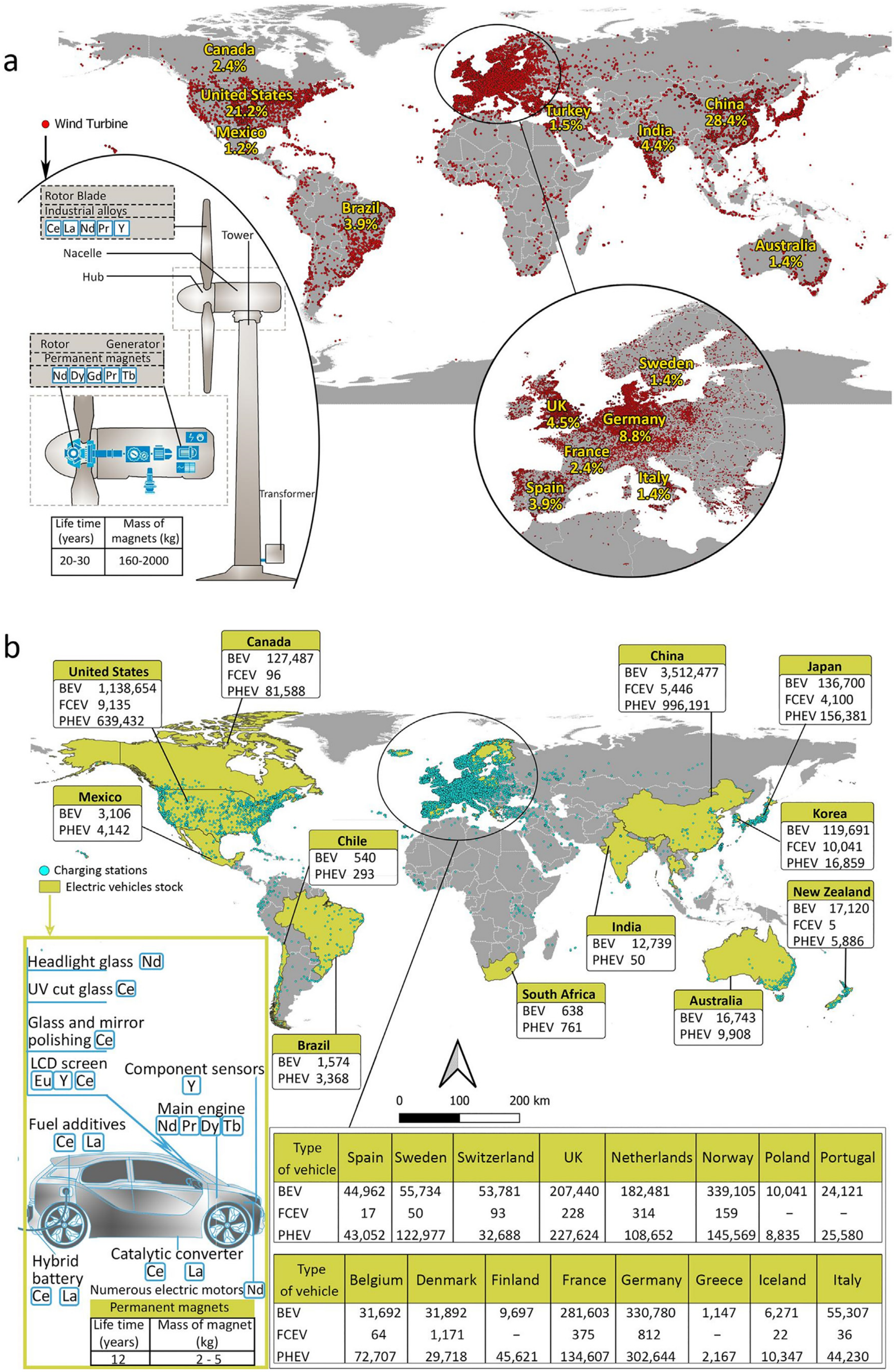
Wind power corresponds to 4.1% of electricity generation (coal 39%; natural gas 27%; nuclear 19%; hydropower 7%; biomass 1.5%; petroleum and gaseous hydrocarbons 1% and geothermal, solar and other <1%) (Lampert et al., 2015). Fig. 2a shows that the biggest fraction of wind turbines can be found in China (28.4% with cumulative installed capacity of wind power 237 thousand megawatts) and the United States (21.2%, with 105 thousand megawatts).

Global sales of EVs rose by 43% in 2020 in comparison to 2019. It is estimated that in 20 years there will be around 500 million EVs. (Raw materials for a truly green future, 2021) To meet this demand, we will need more critical raw materials such as REEs. Fig. 2b shows the distribution of charging stations and the stock of battery electric vehicles (BEV), fuel cell electric vehicles (FCEV) and plug-in hybrid electric vehicles (PHEV) in 2020. The installation of public electric vehicle charging stations has been increasing exponentially from 30 thousands in 2011 to 1.2 million in 2020. The number of BEV, FCEV, and PHEV globally is about to reach 8.2 million, 35.2 thousands and 4.4 million, respectively. China dominates with around 36% share of the market of EVs followed by Europe (20%), the United States (ca. 14%), and other countries (ca. 30%) in 2020. It is estimated that until 2027 EVs production will increase to 44% and 29% in China and Europe respectively. Detailed analysis of mass flows shows that the annual growth rate of permanent magnets will grow to 6–9.5% between 2020 and 2030 (Keilhacker and Minner, 2017; Trench and Sykes, 2020). The results indicate that the amount of primary REEs available for the global production of permanent magnets is about 24 thousand tonnes (kt) in 2020 and will reach around 50 kt in 2030. However, the estimates obtained from our model suggest that there is a need for 83 kt of those elements based on demand for magnets production in 2030. So the primary production of REEs fails to meet the demand. The findings highlight that the contribution of other supply sources, such as extraction from waste and recycling can be very important. However, recycling alone cannot bridge the gap in the supply of critical materials needed for the development of the above discussed technologies. Therefore, we should consider recycling as one of the core principles of circular economy (Rahimpour Golroudbary et al., 2020). It will be essential to develop an effective recycling system, invest in the development of recycling technologies and dedicated infrastructure for collecting, dismantling, and separating products containing rare earth elements. Moreover, we need to consider other complementary solutions such as substituting materials, introduction of new technologies, and more efficient use of materials.

After 2030, it is expected that the amount of spent magnet-based products for EVs will considerably increase and after 2040 the same phenomena will consider wind turbines. Therefore, there is a growing gap between available recycled magnets and steadily growing demand for REEs. Hence, mining remains necessary to meet the demand for minerals needed in decarbonization process.

3.3. Trends in environmental impacts of REEs mining

In this study, the dynamic model is used to evaluate REEs global flows and their environmental impact in 2010–2030. The total annual energy



Type of vehicle	Spain	Sweden	Switzerland	UK	Netherlands	Norway	Poland	Portugal
BEV	44,962	55,734	53,781	207,440	182,481	339,105	10,041	24,121
FCEV	17	50	93	228	314	159	–	–
PHEV	43,052	122,977	32,688	227,624	108,652	145,569	8,835	25,580

Type of vehicle	Belgium	Denmark	Finland	France	Germany	Greece	Iceland	Italy
BEV	31,692	31,892	9,697	281,603	330,780	1,147	6,271	55,307
FCEV	64	1,171	–	375	812	–	22	36
PHEV	72,707	29,718	45,621	134,607	302,644	2,167	10,347	44,230

Fig. 2. Geographical distribution of green energy technology including wind turbines for energy supply and electric vehicles as consumers in 2020. a, Distribution of wind turbines and leading countries based on wind energy capacity. b, Distribution of charging stations and stock of battery electric vehicles (BEV), fuel cell electric vehicles (FCEV) and plug-in hybrid electric vehicles (PHEV).

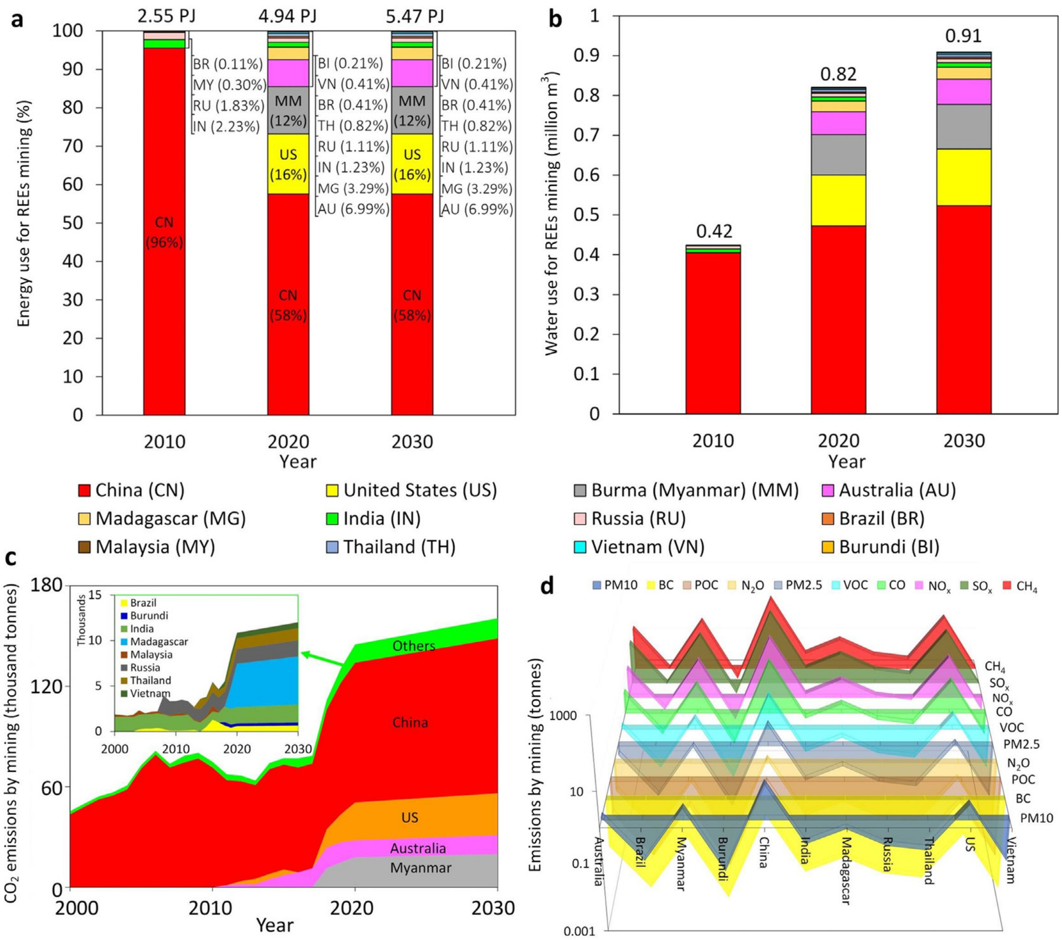


Fig. 3. Environmental performance of primary production of rare-earth elements in the mining stage between 2010 and 2030. a, Global energy consumption, in petajoules (PJ). b, Global water consumption, in million cubic meters. c, Annual global carbon dioxide (CO_2) emission by country, in thousands tonnes CO_2. d, Global methane (CH_4), sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), particulate matter with sizes smaller than 2.5 μm (PM2.5), nitrous oxide (N_2O), particulate organic carbon (POC), black carbon (BC), and airborne particulate matter with sizes smaller than 10 μm (PM10) emissions through mining of REEs in 2020, in tonnes.

and water consumption, as well as the trend in emissions related to the REEs global primary production are given in Fig. 3.

Results presented in Fig. 3a indicate an increase in global energy consumption for the primary production of REEs from 2.55 petajoules (PJ) in 2010 to 5.47 PJ in 2030, which corresponds approximately to a 2.14-times growth within 20 years. An identical trend can be seen in Fig. 3b for water consumption in the primary production of REEs. It starts from 0.42 million cubic meters (m^3) in 2010 to reach 0.91 million m^3 in 2030. The results highlight the issues raised in the Carbon Disclosure Project (CDP)(CDP, 2013) on criticality of sustainable water management.

The results show that energy consumption is growing in all REEs producers. For example, in China it increased from about 2.4 gigajoules (GJ) in 2010 to 2.8 GJ in 2020 and is estimated to reach 3.2 GJ in 2030, and in the United States from 60.9 megajoules (MJ) in 2012 to 771.1 MJ in 2020 and is expected to reach 854.4 MJ in 2030. The same trend can be observed for the use of water, e.g., China water consumption grew from about 0.40 million m^3 in 2010 to 0.47 million m^3 in 2020 and is estimated to reach 0.52 million m^3 in 2030, and in the United States water consumption increased from 0.01 million m^3 in 2012 to 0.12 million m^3 in 2020 and is expected to reach 0.14 million m^3 in 2030.

Fig. 3c shows annual CO_2 emissions generated by mining of REEs. In Fig. 3d, there are presented the emissions (CH_4, SO_x, NO_x, CO, VOC, PM2.5, N_2O, POC, BC, and PM10) generated by the mining of REEs in 2020. In particular, it is estimated that CO_2 emissions from REEs mining will grow in China by the factor of 1.3, from 71.5 kt CO_2 in 2010 to 92.5 thousand t CO_2 in 2030. Detailed calculations show that China, being the major polluter among the REEs mining countries, releases 138.9 t of CH_4, 132.6 t of SO_x, 60.8 t of NO_x, 33.2 t of CO, 9.8 t of VOC, 4.2 t of PM2.5, 1.3 t of N_2O, 0.9 t of POC, 0.4 t of BC, and 9.9 t of PM10.

The analysis shows that global GHG in carbon dioxide equivalent (CO_2 eq) emitted by REEs mining has increased by 94% (152.97 kt CO_2 eq) in 2020 compared to 79.01 kt CO_2 eq in 2010 and it is estimated to reach 169.49 kt CO_2 eq in 2030. China emitted 88.06 kt CO_2 eq, followed by the U.S. 23.90 kt CO_2 eq, Myanmar 18.87 kt CO_2 eq, Australia 10.69 kt CO_2 eq, and other countries 11.44 kt CO_2 eq. China has the highest share of GHG emissions in REEs supply chain due to its the largest share of primary production. To keep global average temperature increase well below 2 °C above pre-industrial levels, many regions in China are establishing carbon neutrality targets, but this trend is the most noticeable in the power and transport sectors or industries that heavily contribute to GHG emissions e.g., magnesium production. However, it does not concern the REEs industry itself yet (Liu et al., 2021; Rahimpour Golroudbary et al., 2022).

3.4. Trends in environmental impact of REEs processing

We use a dynamic model to evaluate the global environmental impact of processing of 15 REEs (Fig. 1 and Fig. S2) in 2010–2030. Energy and water used in processing of each element, as well as emissions generated along the process are presented in Fig. 4.

The result indicates that global energy and water consumption during the processing of REEs is 22 times higher than that in mining. The results presented for energy consumption, Fig. 4a, and water analysis in Fig. 4b show an increase (81%) of the consumed energy and water for processing of REEs in 2020 when compared to 2010. The estimates for 2030 show consumption of energy and water as 121.89 PJ and 20.24 million m^3 respectively. According to Fig. 4b in 2010, the highest consumption of energy and water in the processing stage is attributed to Ce (30.81 PJ and 5.12 million m^3) and Nd (12.22 PJ and 2.03 million m^3). In 2020, annual trend shows that in addition to Ce (46.8 PJ and 7.76 million m^3) and Nd (19.40 PJ and 3.22 million m^3), also La (8.31 PJ and 1.38 million m^3) and Y (6.97 PJ and 1.16 million m^3) are considered the highest consumers of energy and water in the processing stage. When comparing 2030 and 2010, it is estimated that energy and water consumption will increase for Ce by 1.8-times, for Er by 6.2-times, and for La by 15.5-times.

Fig. 4c presents the annual trend of CO_2 emissions from the processing of REEs in years 2010–2030. The results show that CO_2 emitted during the processing of Ce, Nd, Pr, and totally for other elements (La, Sm, Eu, Gd, Tb, Dy, Y, Er, Ho, Tm, Yb, and Lu) increases from 0.91, 0.36, 0.09, 0.27 to 1.64, 0.69, 0.18, 1.07 mt CO_2 in years 2010–2030, respectively. Fig. 4d illustrates the global amount of emissions (CH_4, SO_x, NO_x, CO, VOC, PM2.5, N_2O, POC, BC, and PM10) generated by the processing of REEs in 2020. Detailed calculations show that the global Ce processing corresponds to the highest amount of emissions (47% of total emissions in the processing stage) – 2286.8 t of CH_4, 2180.5 t of SO_x, 1001.6 t of NO_x, 546.0 t of CO, 162.2 t of VOC, 72.6 t of PM2.5, 21.4 t of N_2O, 15.2 t of POC, 6.4 t of BC, and 0.2 t of PM10. We can also learn that global GHG emissions from the processing stage of REEs in 2020 amounted to around 3.08 mt.

The results of simulation of environmental emissions from the mining and processing of REEs for 5 years interval between 2010 and 2030 are available in Data S1 (#7 and #8).

It is important to note that there exist several routes of bio-accumulation of REE in plants, animals, and humans resulting from mining or processing of REEs. Several activities in the primary production of REEs such as cutting, drilling, blasting, transportation, stockpiling, and processing can create dust containing REE, other toxic metals and chemicals. Therefore, environmental degradation (air, soil and water) may occur together with negative impact on human health of hazards encountered in waste disposal areas. Moreover, REE mining poses a serious challenge due to the considerable amount of radioactive elements in minerals, such as thorium and uranium (García et al., 2020). It shows that the mining and processing of rare earth elements, if not carefully controlled, can create serious environmental hazards. For example, during the production of one ton of rare earth oxides it is necessary to treat 1.4 tons of radioactive wastes in solid, liquid, or gaseous form (Talan and Huang, 2022). The problem of the radioactive waste is one of the reasons why new policies addressing safety of mining activities of rare earth elements are urgently needed.

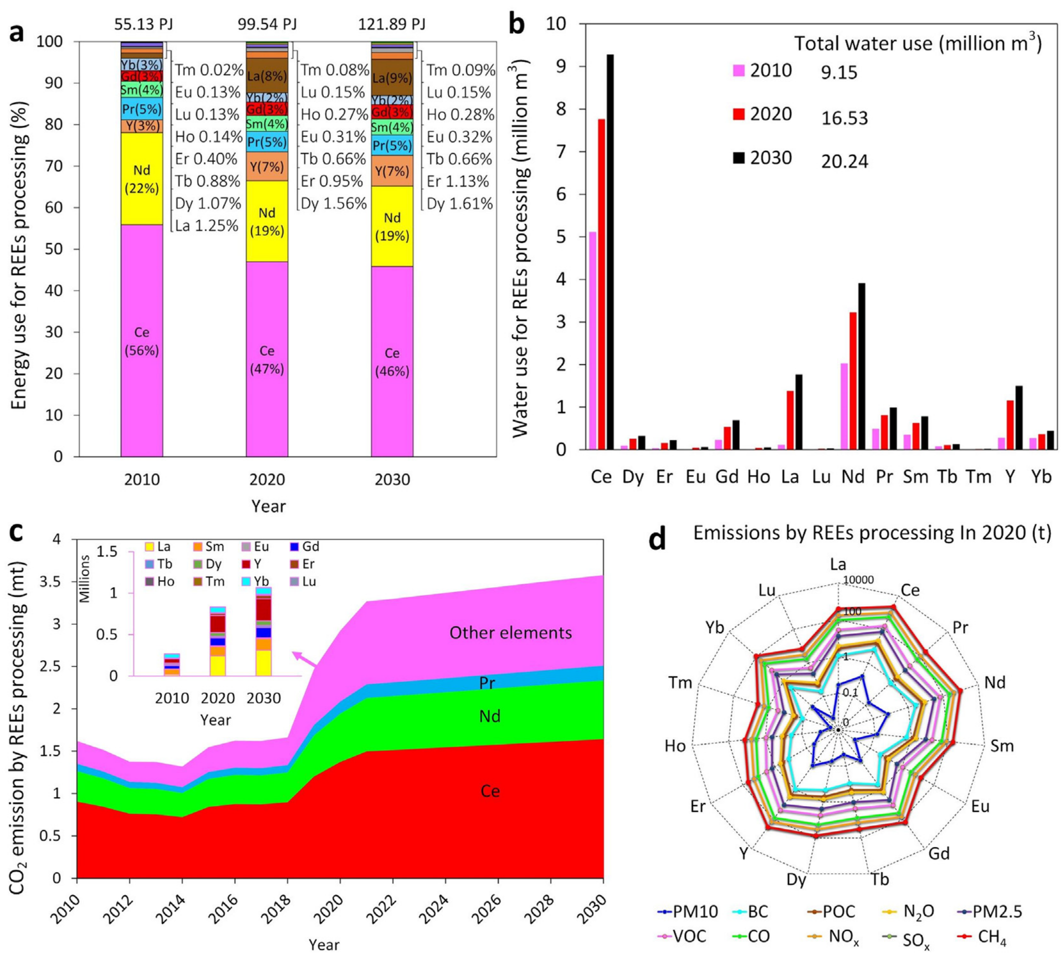


Fig. 4. Environmental impact of processing rare-earth elements between 2010 and 2030. a, Global energy consumption, in petajoules (PJ). b, Global water consumption, in million cubic meters (m^3). c, Annual global carbon dioxide (CO_2) emission by element, in million tonnes CO_2. d, Global methane (CH_4), sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), particulate matter with sizes smaller than 2.5 μm (PM2.5), nitrous oxide (N_2O), particulate organic carbon (POC), black carbon (BC), and airborne particulate matter with sizes smaller than 10 μm (PM10) emissions through processing of REEs in 2020, in tonnes.

3.5. Trends in environmental impacts of magnets production

In this section, a detailed analysis is presented of emissions related to the production of permanent magnets in years 2010–2030. Production process comprises strip casting, hydrogen decrepitation, jet milling, and electroplating. As shown in Fig. 5a, pollution related to global warming and ecotoxicity is increasing rapidly by taking into account the production of magnets for wind turbines and EVs. The environmental analysis of manufacturing magnets shows an increase of GHG emissions from 2.4 billion CO_2 eq in 2010 to 5.4 billion CO_2 eq in 2030 for the transportation sector and from 499.6 million CO_2 eq in 2010 to 1.1 billion CO_2 eq in 2030 for energy generation. The ecotoxicity of magnets' manufacturing is estimated to grow from 16.9 billion Comparative Toxic Unit equivalent (CTUe) in 2010 to 37.4 billion CTUe in 2030 in EVs manufacturing and from 3.5 billion CTUe in 2010 to 7.7 billion CTUe in 2030 in wind turbines production. Subsequently, Fig. 5b shows the impact of magnet production on water acidification and eutrophication. The results indicate that permanent magnets production in EVs manufacturing emitted 18.7 mt SO_x in 2010 and is estimated to reach 41.6 mt SO_x in 2030 while in wind turbine manufacturing the amount of sulfur oxides emitted grows from 3.8 to 8.5 mt SO_x in 2010 and 2030, respectively. The same trend is observed for eutrophication, in the unit of nitrogen equivalent (N eq), which increased from 26.3 to 58.2 million N eq in EVs manufacturing and 5.4 to 11.9 million N eq in wind turbine manufacturing. Fig. 5c represents the projected emissions of carcinogenic and non-carcinogenic components in the unit of human toxicity impacts (CTUh) and CH_4 and NO_x emissions as a result of the global production of permanent magnets between 2010 and 2030.

The results of simulation for 5 years interval between 2010 and 2030 are available in Data S1 (#9).

3.6. Rebound effect of green energy

A bi-directional positive reinforcing causal relationship between renewable energy consumption and economic growth has been demonstrated in previous research studies (Pirlogea and Cicea, 2012; Zafar et al., 2020). We discovered that the rapid development of green energy technologies causes a rebound effect as shown in Fig. 6. On the one hand, the number of produced EVs and installed wind power capacity have increased between 2010 and 2020 (Fig. 6a) triggering technological progress and production diversification. As a result, REEs prices (except Lu) have decreased sharply in 2020 compared to 2011 (e.g. by 53% for Yb, 76% for Tb, 78% for Pr, and 82% for Dy), reducing the price of wind power by 71% in 2010 (Fig. 6b and Data S1 (#3)). On the other hand, lower prices of REEs elements led to the increase of demand for them for EVs (from 8 kt in 2010 to 18.5 kt in 2020) and wind turbine production (from 1 kt in 2010 to 7 kt in 2020), as shown in Fig. 6c. The results given in Fig. 6d show annual GHG emissions from mining and processing stages of REEs, as well as the production of magnets applied in wind turbines and EVs. The calculations indicate that every 1% increase of green energy production causes roughly a 0.18% depletion of rare-earth elements reserves and 0.90% increase of CO_2 eq. It means, cumulatively 32 billion t CO_2 eq of greenhouse gas emissions in the period 2010–2020, globally.

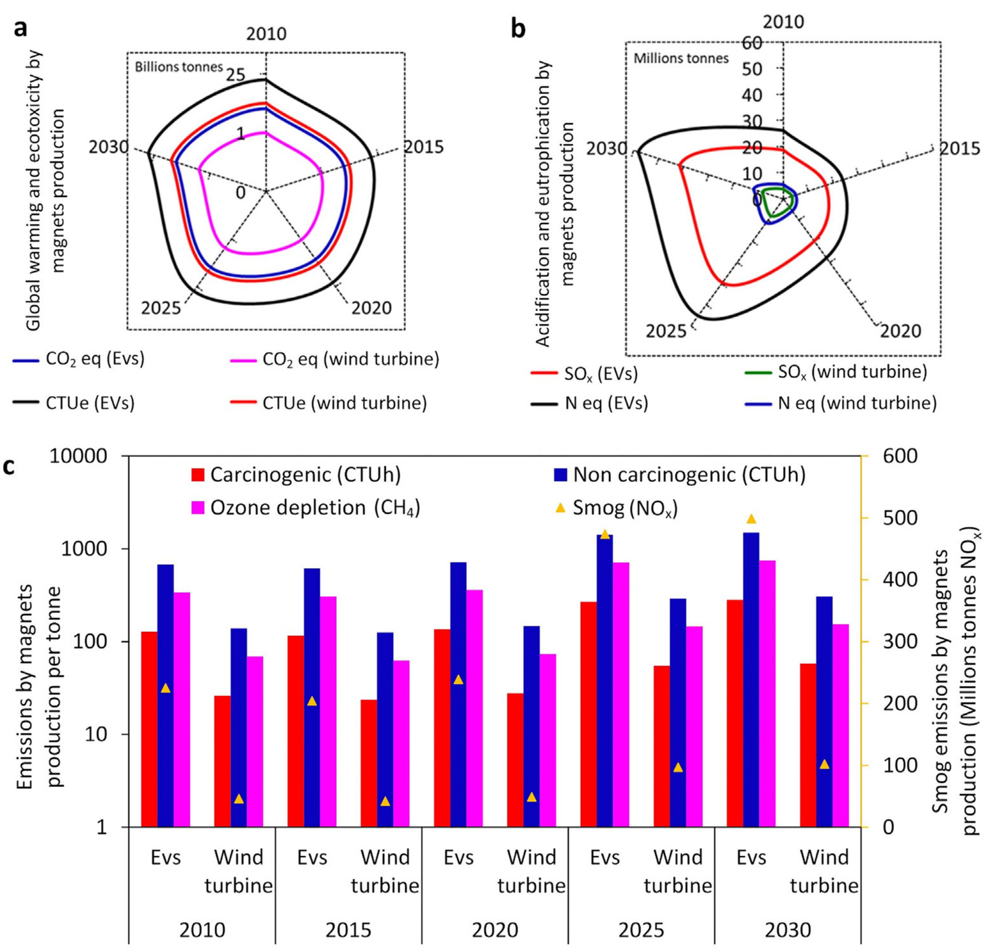


Fig. 5. Environmental effects of the production of permanent magnets applied in electric vehicles and wind turbines between 2010 and 2030. a, Global warming and ecotoxicity b, Acidification and eutrification c, Carcinogenic and non-carcinogenic component emissions, ozone depletion and smog pollution.

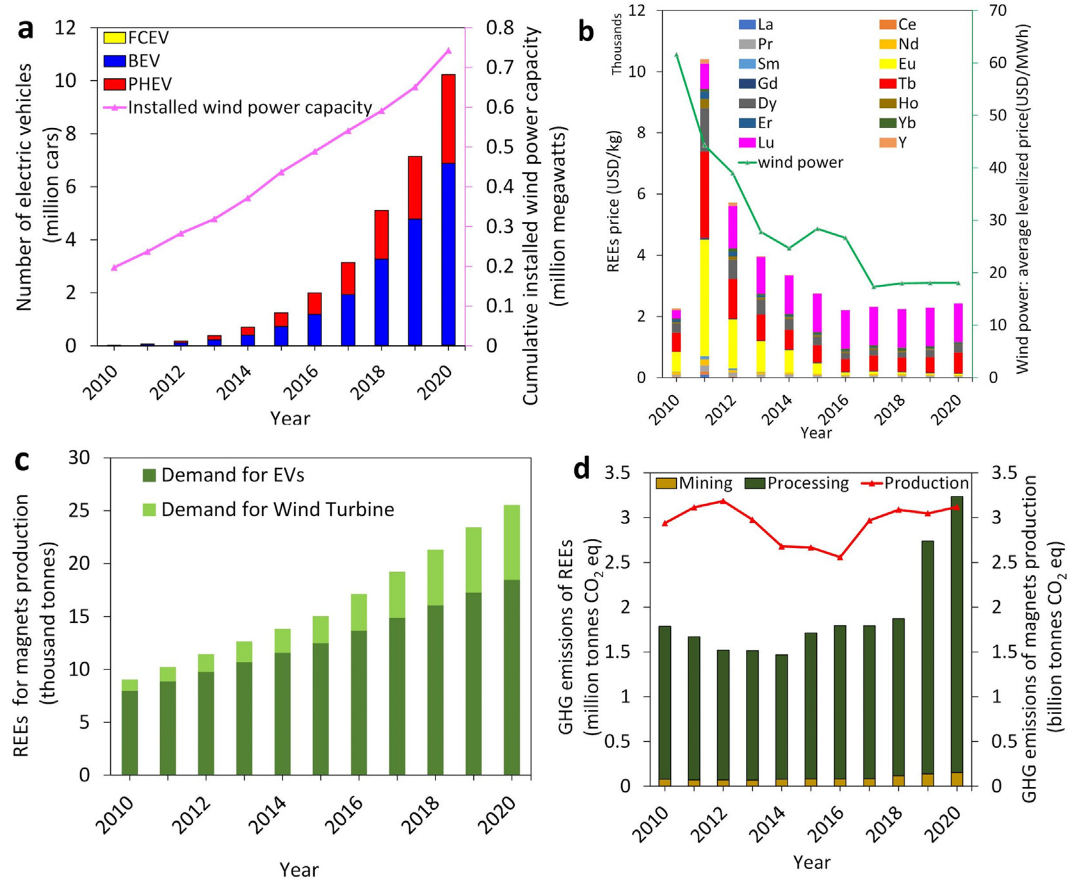


Fig. 6. Rebound effect of the transition to green energy based on the use of critical materials and their environmental impact between 2010 and 2020. a, Annual green energy production. b, Annual price of rare-earth elements and wind power (the price for thulium is not available). c, Consumption of rare-earth elements applied in green energy technology. d, Global greenhouse gas emissions from mining and processing of rare-earth elements and from the production of magnets.

3.7. Discussion

One of key elements in the development of green energy technologies is utilization of wind power generators and electric vehicles. The use of REEs in those applications is hardly substitutable due to their physical and chemical properties. According to the IEA, achieving net-zero emissions globally by 2050 would require 6 times higher mineral input (3–7 times more REEs) in 2040 than today. Building wind farms and manufacturing EVs generally require more minerals (6–9 times) than their fossil fuel-based counterparts. The results of our simulations show that critical materials could be a bottleneck in the propagation of green energy technologies. Our findings reveal a rebound effect of the current decarbonization activities aimed at ensuring sustainable development.

It is generally accepted that wind energy generators emit no pollution to air or water, require no mining or drilling for fuel, use no water in electricity generation, and create no hazardous or radioactive wastes that would require a permanent storage. Also, it is estimated that wind power has the potential to cumulatively avoid one-third of global annual carbon emissions until 2050 — a 2 MW wind turbine containing around 350 kg REEs can reduce up to 42 kt of CO_2 eq over its life time (Change, 2014; Nugent and Sovacool, 2014). However, those benefits are limited only to the system exploitation phase. They are considerably limited in the raw material extraction and equipment production phases. Therefore, a complete life cycle analysis of the system should be considered. For EVs, it is estimated that total GHG emissions associated with EV-related handling operations (e.g., charging, and driving) are typically lower than those of a conventional gasoline vehicle, particularly when electricity is generated from renewable energy sources, e.g. wind. However, as demonstrated in this paper, energy and water consumption and emissions generated in the manufacturing of permanent magnets remain substantial. It is worth noting that the energy required in mining and processing of minerals usually comes from fossil fuels and not from wind or solar power stations. Therefore, mining and processing are one of the global top GHG emitting industries.

Energy production sector accounts for 72% and transportation corresponds to 15% of global GHG emissions including CO_2, CH_4 (16%), N_2O (6%), and fluorinated gases (2%) (Ritchie and Roser, 2020). Also, statistics shows that global GHG emissions from the use of energy in the manufacturing sector corresponds to 24.2% of the total GHG emissions (49.4 billion t CO_2 eq in 2016) (Ritchie and Roser, 2019) and our results show the share of REEs mining, processing and manufacturing of permanent magnets for wind turbines and EVs to be 0.05%. Considering total GHG emissions from the energy sector of the REEs producing countries (Australia, Brazil, China, India, Russia, United States and others), the obtained results show that mining and processing account for 0.12% and 0.19% of CO_2 eq emitted by this sector in 2010 and 2020, respectively. The detailed calculation shows that an increase by 1% of green energy production represents roughly a 0.90% increase of GHG emissions in exploitation phase including mining, processing, and production stages. Moreover, the results show that 1% of green energy production leads to 0.18% REEs resource depletion.

Moreover, our analysis shows that China, the US and Australia are the top suppliers of raw materials demanded by the green energy sector and their production has the highest environmental impact. Focusing on the case of China, the eco-cost analysis of 19 development pathways for REEs mining industry has provided us with the net cost ranging between 14.8 and 16 US$ billion reported for 2015 and 2025, respectively (Lee and Wen, 2018). In the longer perspective, diversification of supplies to meet the actual demand for REEs from the existing technologies, leaving aside the sustainability issues, shifts environmental problems from one place to another and moves them forward into the future while no attempts are made to mitigate the most urgent issues. This finding highlights the need to design and put in place various measures intended to increase REEs reuse, recycling (the current rate is less than 1%), limit dematerialization, increase substitution and develop new elimination technologies (e.g. an engine without permanent magnets). Such actions would support an environmentally sustainable development of green energy technologies.

4. Conclusions

This paper contributes to the enhanced understanding of environmental impact of green energy technologies and supports energy policy makers in developing appropriate strategies for decarbonization. Contrary to the previously published works on REEs focused on local scale analysis, this publication, for the first time, presents a global scale analysis of environmental cost of using REEs in green energy technologies. It has been performed using system dynamics modelling integrated with life cycle assessment and geometallurgical approach. The obtained results confirm the existence of a rebound effect - rapid development of existing green energy technologies leads to unsustainable consumption of rare earth elements. In the longer perspective, it could trigger shifting environmental problems from one location to another and pushing them forward into the future if any relevant attempts would be made to mitigate the core issues. Therefore, it is necessary to propose strategies aimed to develop new technologies required to substitute rare earth elements used for green energy generation. Another approach would be to develop efficient recycling policies to increase the circularity of rare earth elements. For example, large scale implementation of closed loop supply chain of permanent magnets used in wind turbines and electric vehicles.

It is important to switch to more sustainable energy sources. However, the considerable environmental cost of implementing green energy technologies and its rebound effect at a global scale cannot be overlooked. The insight offered by this study should facilitate the analysis of real environmental costs of transition to green energy technologies. Our findings will hopefully help in developing adequate policies aimed at the implementation of sustainable decarbonization measures. These polices should carefully consider ways to increase the share of non-fossil fuels, the implementation of negative GHG emission technologies, or creating a basis for economically viable processes for capturing/storing CO_2 or its use as a raw material.

The most critical parameters that influence the results are: volatility of rare earth markets caused by the political situation and substitution of NdFeB technology by another one requiring smaller amount of REEs. However, data on the social impacts of using rare earth elements for green energy generation are still missing. Therefore, a comprehensive assessment of sustainability of green energy issues still needs to be considered. The activities aimed at the reduction of rare earth elements consumption in green energy generation will be an important factor contributing to the enhancement of environmental sustainability of renewable energy technologies.

The closed-loop supply chain of green technology, which differs significantly from the forward supply chain in many aspects, is not considered in the analysis. Therefore, the limitation of this study is the exclusion of the potential circularity of REEs originating from end-of-life wind turbines and electric vehicles. Another limitation are missing data on life cycle assessment of all stages of the REEs supply chain.

CRediT authorship contribution statement

Saeed Rahimpour Golroudbary: Conceptualization, Data curation, Methodology, Verification and validation, Formal analysis, Investigation, Visualization, Writing—original draft preparation, Writing—review and editing. **Iryna Makarava:** Data curation, Methodology, Formal analysis, Investigation, Visualization, Writing—original draft preparation, Writing—review and editing. **Andrzej Kraslawski:** Conceptualization, Verification and validation, supervision, Writing—original draft preparation, Writing—review and editing. **Eveliina Repo:** Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Data and materials availability

The authors declare that all data supporting the findings of this study can be found in the article and/or its Supplementary Information files.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.155022.

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