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Sustainability of emerging energy and transportation technologies is impacted by the coexistence of minerals in nature

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Wind power and electric vehicles can help reduce carbon dioxide emissions and improve air quality. However, these technologies rely on rare metals whose extraction requires large amounts of energy and water and are high in carbon emissions. Here we consider the sustainability of both technologies and the impacts of rare earth elements co-extraction. We use a global dynamic material flow-stock model and several scenarios for rare earth elements demand and supply. Cumulative carbon dioxide equivalent emissions associated with rare earth metals oversupply was between 5.5 and 6.4 times the emissions associated with dysprosium and neodymium production when dysprosium demand was increased. Carbon dioxide equivalent emissions associated with metals extraction and production were equivalent to between 10% and 29% of carbon dioxide emissions reduction through electric vehicle use. Targeting metal rich deposits and increased material efficiency and recycling reduced carbon dioxide emissions by 78%, 39% and 35%, and combined by 90%. Our findings highlight the role of resource efficiency and recycling in enhancing clean energy technologies.

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Energy and transportation are two of the main economic sectors, yet responsible for most CO₂ emissions¹ and several other environmental impacts². In addition, there are increasing concerns in the two sectors regarding the fossil fuel sources depletion and energy supply³. Wind power (WP) and electric vehicles (EVs) are seen as possible solution for the problems associated with the two sectors^{4–7}. The use of the two technologies has increased in recent years and expected to significantly increase in the future as a result of their advantages over traditional energy and transportation technologies^{8,9}. Although the two technologies are expected to reduce CO₂ emissions, improve air quality, and reduce dependency on fossil fuel^{8–11}, both rely on metals that have limited availability and production capacity, mostly produced as companion metals in few countries, and associated with large amounts of energy and water, high CO₂ emissions, and other impacts including air pollution and human health problems. For example, Neodymium (Nd) and Dysprosium (Dy) required for the two technologies are produced with other REEs mainly from other metals deposits^{12,13}. Increasing demand for technologies target metals (Nd and Dy) may result in increasing companion metals (other rare earth elements (REEs)) production with several implications on the sustainability of these technologies, especially if companion metals demand does not increase at the same level as target metals^{14–17}. Supply-demand balance problem, which is the balance between metals demand and natural presence of metals in ores^{18,19}, associated with metals required for emerging technologies is not limited to critical metals used in these technologies but also to other metals in which increasing use of technologies may result in reducing their demand. For example, Li ion batteries use for EVs is expected to replace nickel-metal hybrid (NiMH) batteries²⁰ and consequently reduce Lanthanum (La), Cerium (Ce) and other REEs demand, which could increase supply-demand balance problem related to Nd and Dy increasing demand. Similar trends are also expected as a result of light-emitting diode (LED) technology increasing use. In addition, EVs use is expected to reduce Lead (Pb) demand in conventional vehicles^{21,22}, consequently either its production from secondary sources or extraction from primary sources has to be reduced. Reducing Pb production from secondary sources would have adverse environmental impacts due to lower energy and emissions associated with secondary production compared to primary production²³, while reducing its production from primary sources would reduce the supply of its companion metals; Bismuth (Bi), Antimony (Sb), Barium (Ba), Tellurium (Te), Selenium (Se), and Indium (In)¹², some of which have been identified critical and essential for renewable technologies^{24–26}. Critical metals are defined as those that have high strategic and economic importance and have high supply risk²⁵.

REEs are among the metals that have been identified critical in most criticality assessment methodologies²⁷ and for energy and transportation sectors transition²⁸ in most studies addressing metals limited resources availability and production capacity, mainly due to limited production capacity, geographical concentration of their production, and environmental problems associated with their production^{25,29–32}. REEs production is known for being associated with high energy, water, and CO₂ emissions, permanent loss of ecosystems, soil erosion, air pollution, and human health problems, which caused the closure of several mining projects or the shift in operation location as a result of social resistance^{33–39}. However, when the environmental impacts of emerging technologies are evaluated, the impacts associated with naturally coexisting metals with those utilized in the technologies are not fully captured in life cycle analysis (LCA) models and energy system models (ESMs)⁴⁰. It is argued that the mitigation potential of energy technologies will be overestimated

unless the emissions associated with technology manufacture explicitly considered in ESMs⁴¹. Although LCA models have a detailed representation of energy infrastructure, these models include the impacts associated with materials directly utilized in the technology and mostly the bulk materials, with little attention to minor metals that may have impacts on both the supply and demand side of energy¹¹. In addition, allocation of the environmental impacts to the jointly produced outputs, which is done if not possible to avoid by either mass allocation or economic allocation, is a controversial issue in LCA⁴². Joint production, either as co-products or by-products, is challenging to assess with LCA because it introduces the methodological problem of allocation, in addition to the increased risk of price volatility for specific materials including REEs which further confound the allocation approaches⁴³. The restrictions, environmental impacts, and risk of disruption associated with REEs supply chain due to market imbalances or governmental policies increase the uncertainties related to their price and make the mass allocation is the preferred approach⁴⁴.

Several studies have addressed the impacts of metals coproduction on the criticality score of metals by including the coproduction fraction as indicator in the supply risk dimension of the criticality methodologies²⁷. In addition, several studies have addressed supply-demand balance in general or for wind power technology^{14,15,19}. However, none of these studies quantify supply-demand balance associated with naturally coexisting metals with critical metals required for energy and transportation technologies, which utilize the same metals, and their impacts on energy, water, CO₂ emissions and radioactive materials and ultimately the sustainability of emerging technologies.

This paper is aimed at analysing the global implications of utilizing a number of REEs in WP and EVs technologies on the supply of other naturally coexisting REEs and consequently the environmental impacts associated with the two technologies and their long-term sustainability. The analysis is carried out on a global level using a dynamic material flow-stock model and a number of international scenarios for REEs demand in the two technologies and several scenarios for their supply. Several options for possible mitigation of the supply-demand balance problem, on demand and supply sides of metals, have been analysed including reducing WP and EVs shares in electricity production and vehicles market, reducing REEs content in the technologies, limiting target metals supply to their rich deposits, increasing target metals recycling, producing target metals from other sources including coal, bauxite, and phosphorus, and increasing other co-produced metals demand. To the best of my knowledge, this is the first study that addresses the impacts of naturally coexisting metals on the sustainability of emerging technologies utilizing same materials, and quantifies the impacts of possible solutions for supply-demand balance problem. The multidisciplinary approach used in this analysis enhance current analysis carried out by prospective LCA and integrated assessment modelling (IAM) studies by adding detailed assessment of energy, water, CO₂ emissions and other radioactive materials associated with the oversupply of naturally coexisting metals with the metals required for emerging technologies.

Results

The results described below are based on several scenarios for the demand and supply of REEs, and energy, water, CO₂ emissions, and radioactive materials associated with their production. Two scenarios for the demand for metals utilized in WP and EVs (Nd, Dy, Pr, and Tb) have been used; low demand scenario (Low D SC) that is based on a changing material content (MC) of the two technologies, and high demand scenario (High D SC) that is

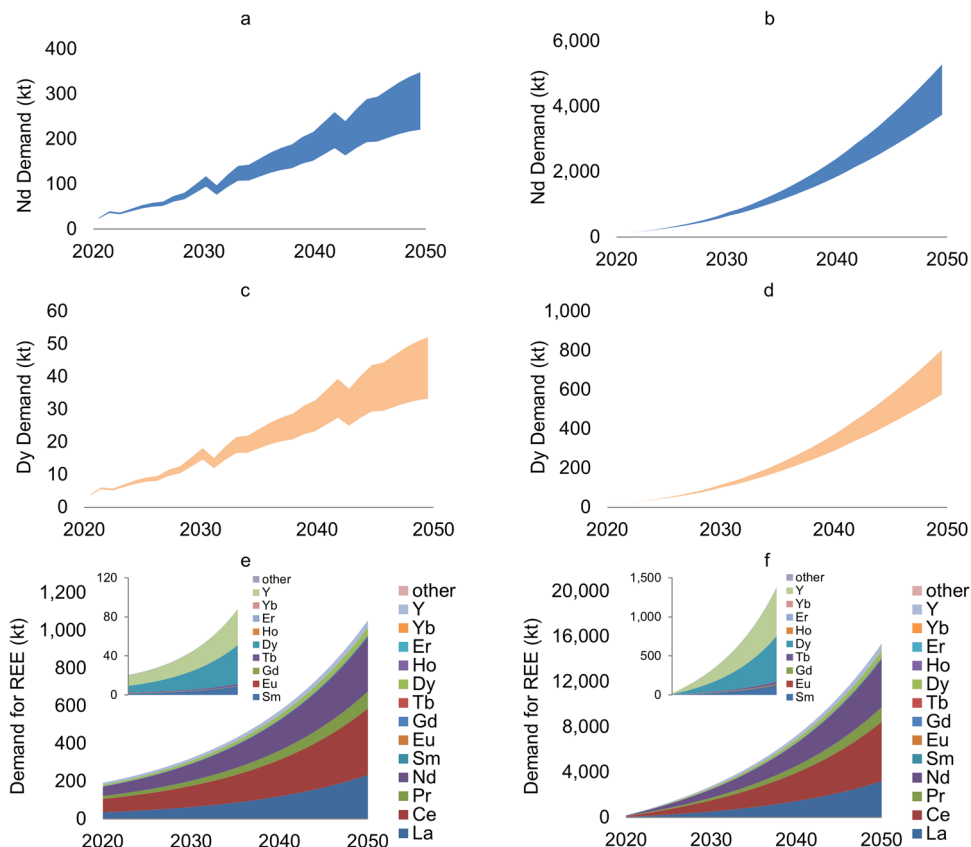


Fig. 1 REEs demand. **a** Nd annual demand; **b** Nd cumulative demand; **c** Dy annual demand; **d** Dy cumulative demand in WP and EVs in the two demand scenarios; **e** individual REEs annual demand in all applications; and **f** individual REEs cumulative demand in all applications.

based on a constant MC in the two technologies. REEs demand in all end-use applications is based on one scenario. Three scenarios for REEs supply have been used; supply from all global deposits without accounting for secondary sources supply, supply from all deposits while accounting for secondary sources supply, and supply from Dy rich deposits. Two scenarios for supply from secondary sources have been used; first recycling scenario (RSC1) assumes Dy supply is partly met by secondary sources while no recycling of other REEs and the second (RSC2) assumes Dy supply is partly met by secondary sources and there is a recycling of other REEs. Three scenarios for energy, water and CO₂ emissions associated with the REEs production have been used based on low, high, and average intensities.

REEs demand and supply. Expected annual and cumulative demand for Nd and Dy in the two demand scenarios, based on their demands in WP and EVs (Supplementary Fig. 1), and annual and cumulative global demand for all REEs (including Nd and Dy) based on their demand in end-use applications (Supplementary Fig. 1) are shown in Fig. 1. Nd annual demand in the two technologies is expected to reach 348.3 kt by 2050 in high demand scenarios (MC constant scenario), while expected to reach 219.5 kt in low demand scenario (MC changing scenario). Nd demand in WP and EVs is expected to be 8.2%, and 91.8% of Nd total demand in high demand scenario respectively, and 5.3%, and 94.7% in low demand scenario. Dy annual demand is expected to reach 52.1 kt by 2050 in high demand scenarios, while it is expected to reach 33.1 kt in low demand scenarios. Dy demand in WP and EVs is expected to be 7.7 and 92.3% of Dy total demand in the high demand scenario and expected to be 5.6 and 94.4% in the low demand scenario.

The potential supply of REEs as a result Nd, Dy, Pr, and Tb demand in WP in the two demand scenarios (Supplementary Fig. 2a) is expected to be lower than REEs current demand except the supply as a result of Tb and Dy demand in the high demand scenario. However, this supply is only the result of these metals demand in one technology. The potential annual supply of REEs as a result of Dy demand in EVs (Supplementary Fig. 2b) is expected to be higher than the supply associated with Nd demand in EVs (Supplementary Fig. 2b), and Dy and Tb demand in WP. The total supply of REEs as a result of Dy and Nd demand in EVs is higher than current REEs demand although this supply is only the result of their demand in one technology. Annual total REEs supply in 2050 (Fig. 2a) as a result of Nd demand in the two technologies is expected to be between 1388 and 2202 kt, and as a result of Dy demand between 2325 and 3660 kt in all scenarios. The highest cumulative supply of total REEs is the one associated with Dy demand in the high demand scenario (Fig. 2b). In 2050, Nd demand in the two technologies is expected to lead to the production of between 323.9 and 513.9 kt of La and between 554.2 and 879.3 kt of Ce (Fig. 2a). Nd demand is expected to lead to the production of between 19.8 and 31.4 kt of Dy, while Dy demand for WP and EVs is expected to reach between 33.1 and 52.1 kt by 2050. The amount of Dy that could be supplied as a result of Nd demand is about 60% of Dy required. This means that REE production should be increased further to meet the demand for Dy with a possible increase in all other REEs including Nd. Meanwhile, Dy demand in the two technologies is expected to reach between 33.1 and 52.1 kt by 2050 and expected to lead to the production of between 367.8 and 578.9 kt of Nd. It is clear that Dy demand is expected to lead to more REEs supply than Nd demand. It is also clear that Nd supply as a result of Dy demand is more than its demand in the two technologies. Tb

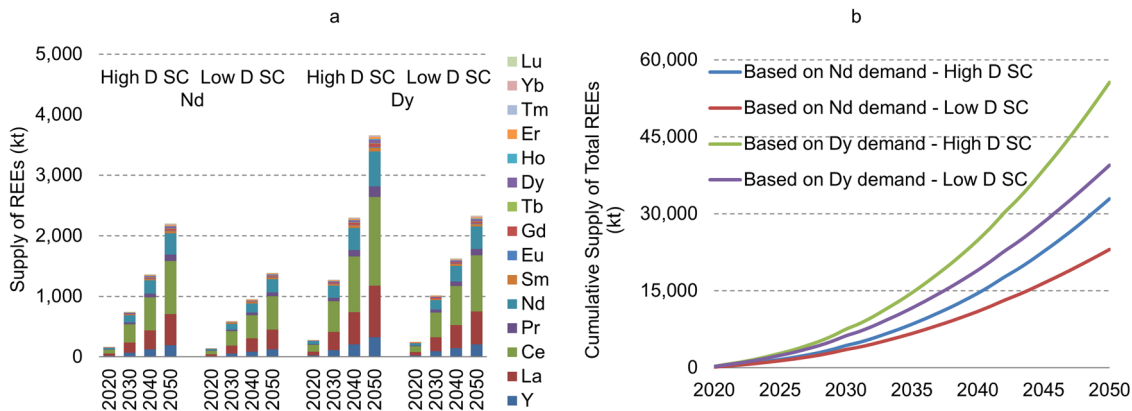


Fig. 2 REEs supply. **a** Annual supply of individual REEs; and **b** Cumulative supply of total REEs as a result of the demand for Nd and Dy in WP and EVs in the high and low demand scenarios.

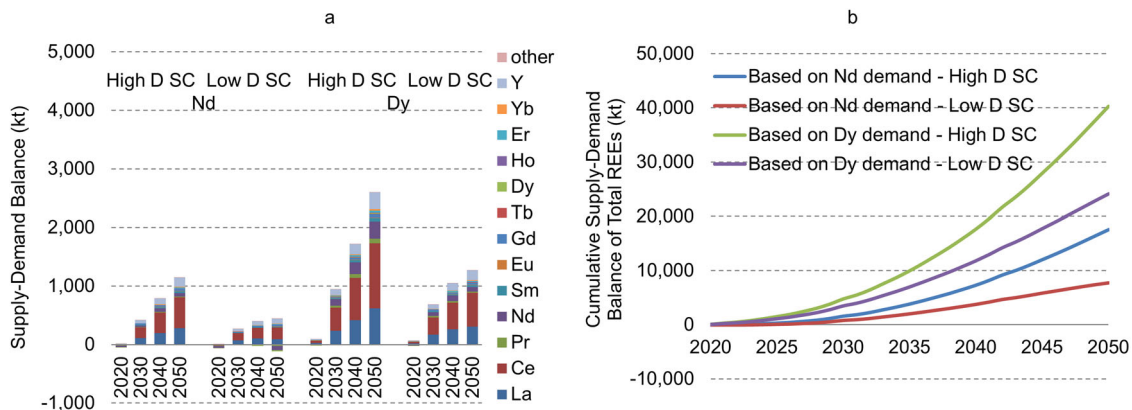


Fig. 3 REEs supply-demand balance. **a** Annual supply-demand balance of individual REEs; and **b** Cumulative supply-demand balance of total REEs as a result of Nd and Dy demand in WP and EVs in the high and low demand scenarios.

supply as a result of Dy demand and supply is expected to exceed its demand in WP technologies making Dy is main metal controlling the supply when the two technologies are considered.

Nd, Dy, and Pr demand in WP (Supplementary Fig. 3a) is not expected to lead to an oversupply of most REEs, while Tb demand is expected to lead to an oversupply of most REEs especially in high demand scenario. Nd demand in EVs (Supplementary Fig. 3b) is expected to lead to an oversupply of most REEs except Dy, Nd, and Pr in low demand scenario and Dy in high demand scenario, while Dy demand in EVs is expected to lead to a substantial oversupply for all REEs. Nd demand in the two technologies is expected to lead to an oversupply of all REEs except Dy, Pr, and Nd in low demand scenario indicating that the supply of the remaining demand for Nd, Dy, and Pr on a global level, may still lead to more oversupply of other metals, while it is expected to lead to substantial amounts of oversupply of all metals except Dy in high demand scenario (Fig. 3a). Dy demand is expected to lead to substantial amounts of oversupply of all REEs in the two demand scenarios (Fig. 3a). Potential cumulative total REEs supply-demand balance as a result of Nd and Dy demand in WP and EVs is shown in Fig. 3b. It is clear that the highest demand scenario is expected to lead to a substantial amount of oversupply of REEs especially Dy demand.

Energy, water, and CO₂ emissions. As shown in the previous section, the highest oversupply of all REEs is expected as a result of Dy demand in the two technologies and the other three REEs (Nd, Pr, and Tb) demand is expected to be covered by Dy supply. Cumulative energy, water, and CO₂-eq emissions (E-W-CO₂)

associated with oversupplied REEs in high demand scenario as a result of Dy demand based on lower, higher, and average energy, water, and CO₂ intensities are shown in Fig. 4. Cumulative E-W-CO₂ associated with oversupplied REEs as a result of Dy in the three intensities values and high demand scenario are expected to be between 28,124 and 55,975 PJ, 24,518 and 62,056 million m³, and 1881 and 3530 Mt. These are huge numbers considering the savings in E-W-CO₂ emissions by using emerging technologies compared to traditional technologies⁹.

Cumulative E-W-CO₂ associated with Nd and Dy production required for the two technologies compared to those associated with oversupplied REEs as a result of Dy demand in the two demand scenarios, based on average values of energy, water and CO₂ emissions intensities, are shown in Fig. 5. Cumulative E-W-CO₂ associated with Nd and Dy production required for the two technologies are expected to be between 4380 and 6230 PJ, 4966 and 7060 million m³, 287 and 408 Mt. Cumulative amounts of E-W-CO₂ associated with oversupplied REEs as a result of Dy are expected to be between 24,000 and 39,600 PJ, 27,180 and 44,410 million m³, 1580 and 2615 Mt, which are between 5.5 and 6.4 times the actual cumulative amounts associated with the production of Nd and Dy. These results indicate that when emerging technologies are analysed using LCA, energy, water, CO₂ emissions and other impacts associated with the materials required for these technologies are underestimated because LCA studies only consider the materials that actually utilized in these technologies without considering their impacts on naturally coexistent materials.

Annual E-W-CO₂ associated with the production of oversupplied REEs by 2050 in the two demand scenarios are expected

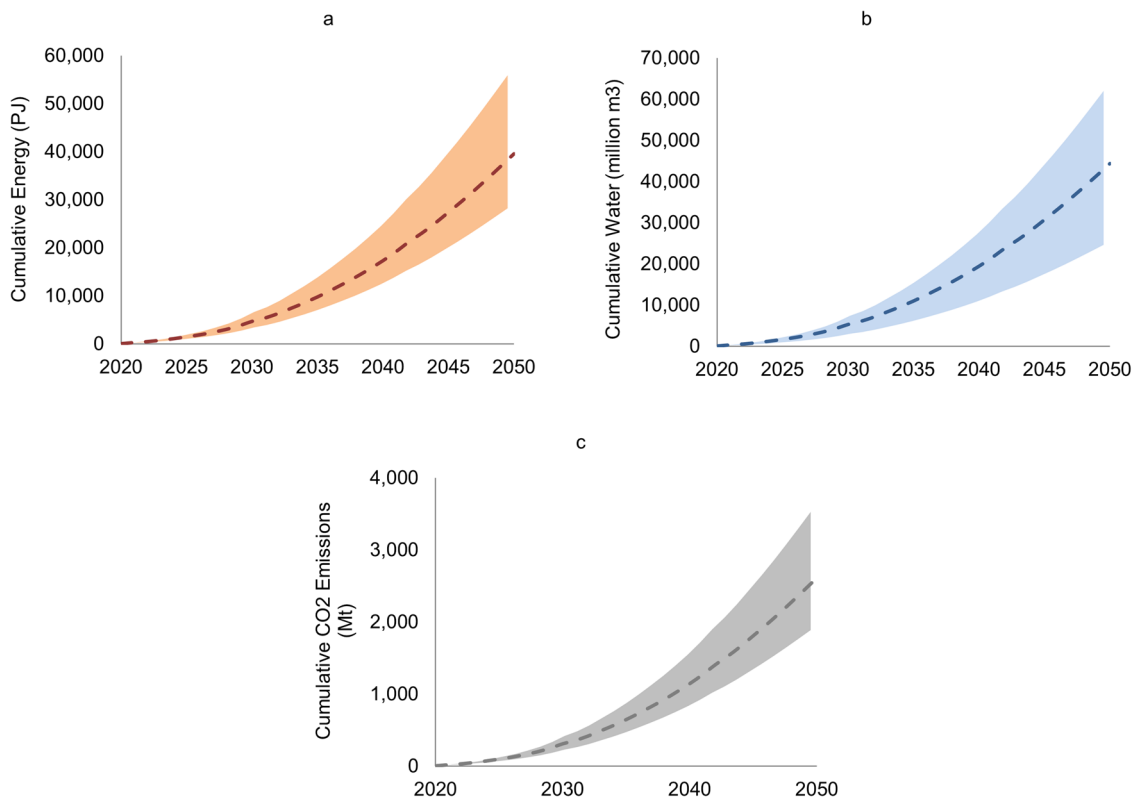


Fig. 4 Energy, water, and CO₂ emissions associated with oversupplied REEs in high demand scenarios. Cumulative **a** energy, **b** water, and **c** CO₂ emissions associated with the oversupplied REEs in the high demand scenarios as a result of Dy demand based on the lower, higher, and average intensities.

to be between 1277 and 2565 PJ, 1461 and 2883 million m³, and 84.1 and 169.3 Mt. Annual E-W-CO₂ associated with Dy and Nd production by 2050 in the two demand scenarios are expected to be between 262.1 and 415.1 PJ, 297 and 470 million m³, and 17.2 and 27.2 Mt. E-W-CO₂ associated with the oversupply is expected to be between 4.9 and 6.2 times those associated with Dy and Nd production. Annual CO₂ emissions as a result of Nd and Dy demand by 2030 is expected to be between 7.3 and 9.2 Mt while CO₂ emissions associated with the oversupply of REEs is expected to be between 45 and 61.5 Mt. The reduction of CO₂ emissions in the IEA EV30@30 scenario⁹ as a result of EVs use is expected to be 241 Mt without any change in the electricity mix, while additional 273 Mt reduction of CO₂ emissions in the IEA EV30@30⁹ scenario could be reached considering the sustainable development scenario for power generation. CO₂ associated with REEs demand and oversupply obtained in this study is expected to be between 22 and 29% of CO₂ emissions reduction expected in the IEA EV30@30 scenario due to EVs use without changing the electricity mix, between 19 and 26% of CO₂ emissions reduction due to power grid decarbonisation, and between 10 and 14% of CO₂ emissions reduction expected in the IEA EV30@30⁹ scenario due to EVs use and power grid decarbonisation.

Other environmental impacts. There are several other impacts associated with the production of REEs in addition to CO₂ emissions, however, the radioactivity of some ores and management strategies for dealing with radioactive waste materials is the most important impact^{34–39}. Annual ThO₂ production from all deposits as a result of Dy demand (Supplementary Fig. 4) is expected to reach between 43.14 and 67.5 kt by 2050 in the two demand scenarios, mainly from Nolans in Australia (42% of the total production), Steenkampskraal in South Africa (16%),

Chavara in India (9.2%), Bayan Obo in China (7.5%), Strange Lake in Canada (6.7%), and Others (18.6%). Thorium has a very limited demand and almost the entire amount produced with REEs, which is significantly more than the current production, would either be disposed of as low-level radioactive waste or stored⁴⁵. Annual U₃O₈ production from all deposits as a result of Dy demand is expected to be between 9.4 and 14.78 kt by 2050 in the two demand scenarios, mainly from Kvanefjeld in Greenland (59.3%), Nolans in Australia (14%), Strange Lake in Canada (10.2%), Dubbo in Australia (7%), Zandkopsdrift in South Africa (4%), and Others (5.5%). Cumulative production of thorium and uranium from all deposits as a result of Dy demand is shown in Fig. 6.

REEs supply options. To analyse other possible supply options, Dy and other REEs supply from secondary sources have been used based on two recycling scenarios (RSC1 and RSC2) to cover part of the supply of required Dy in the two demand scenario and other REEs. Annual E-W-CO₂ associated with the oversupplied REEs is expected to reach between 1277 and 2565 PJ, 84 and 169 Mt, and 1461 and 2883 million m³ when there is no recycling. Annual E-W-CO₂ associated with the oversupplied REEs is expected to reach between 422 and 1268 PJ, 27.6 and 83.5 Mt, and 516 and 1451 million m³ when Dy is partly supplied from secondary sources while there is no recycling for other REEs (RSC1). Annual E-W-CO₂ associated with the oversupplied REEs is expected to reach between 605 and 1558 PJ, 40 and 103 Mt, and 704 and 1756 million m³ when Dy is partly supplied from secondary sources while there is a recycling for other REEs (RSC2). Cumulative E-W-CO₂ associated with the oversupplied REEs (Fig. 7) are expected to be reduced by 35 and 45% in the high and low demand scenarios as a result of the first recycling scenario,

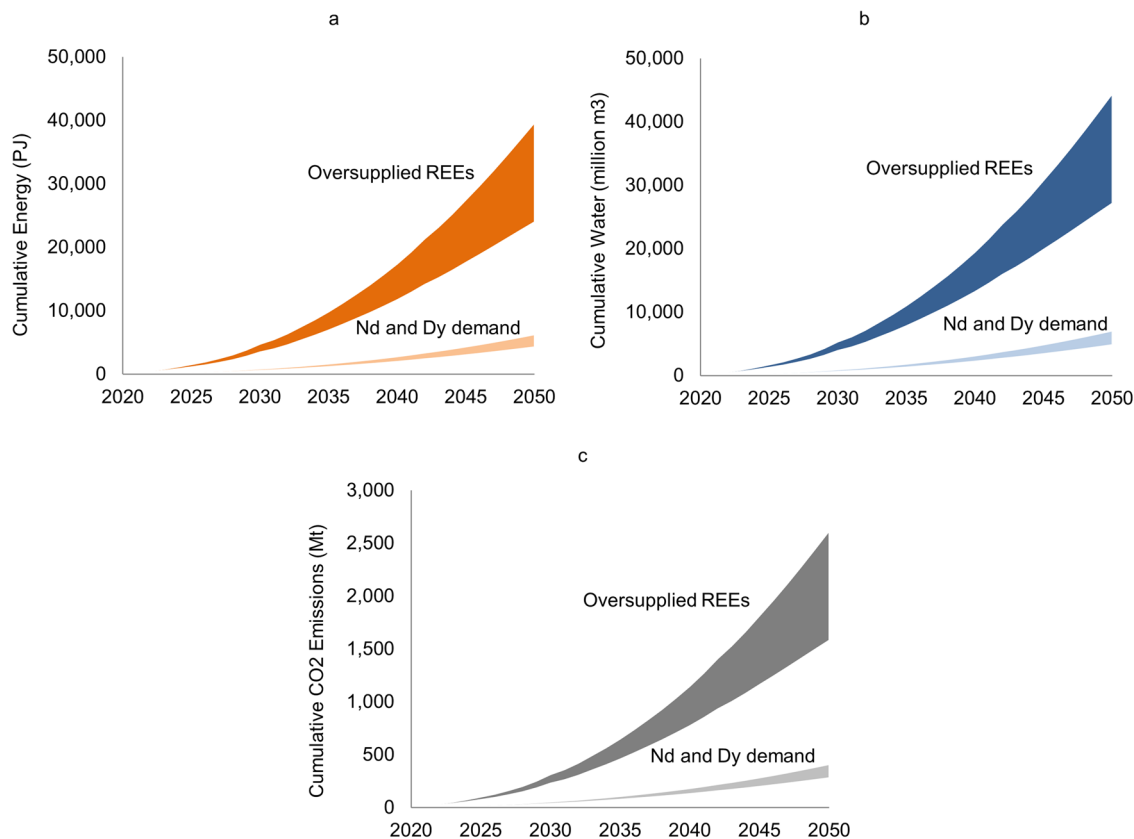


Fig. 5 Energy, water, and CO₂ emissions associated with Nd and Dy production and oversupplied REEs. Cumulative **a** energy, **b** water, and **c** CO₂ emissions associated with the production of Nd and Dy required for the two technologies and the oversupplied REEs in the high and low demand scenarios as a result of Dy demand based on the average E-W-CO₂ intensities.

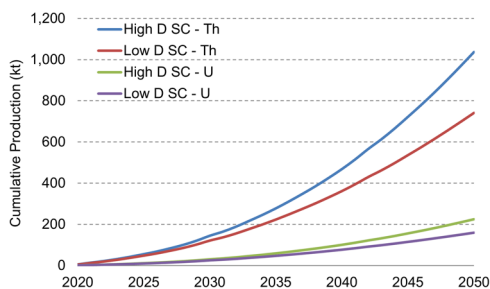


Fig. 6 Thorium and uranium production. Cumulative production of the coproduced metals thorium and uranium in the high and low demand scenarios.

while expected to be reduced by 24 and 28% in the second recycling scenario.

To analyse another possible primary supply options, the supply of REEs from Dy rich deposits only (SSC2) has been used for required Dy in the two demand scenario. There is some difference between E-W-CO₂ associated with oversupplied REEs and those with Dy and Nd demand when the supply is coming from Dy rich or all deposits (Fig. 8). The highest amount of E-W-CO₂ associated with oversupplied REEs is associated with high demand and all deposits supply scenario, followed by low demand and all deposits supply scenario, high demand and Dy rich deposits supply scenario, and low demand and Dy rich deposits supply scenario. However, the highest amount of energy, and CO₂ associated with Dy and Nd demand are associated with high demand and Dy rich deposits supply scenario, followed by

high demand and all deposits supply scenario, low demand and Dy rich deposits supply scenario, and low demand and all deposits supply scenario. The highest amount of water associated with Dy and Nd demand is associated with high demand and Dy rich deposits supply scenario, followed by low demand and Dy rich deposits supply scenario, high demand and all deposits supply scenario, and low demand and all deposits supply scenario. This indicates that Dy supply from Dy-rich deposits would reduce E-W-CO₂ associated with oversupplied REEs, while increase those associated with Dy and Nd demand. This is mainly due to the high E-W-CO₂ allocated to Dy when produced from its rich deposits. In addition to the possibility of underestimating the impacts associated with REEs used in emerging technologies using LCA, the results of the impacts of shifting Dy supply to Dy-rich deposits would also be different compared to LCA results. LCA studies are considering materials that are utilized in technologies only. The impacts associated with Nd and Dy production when Dy is supplied from Dy rich deposits would be higher than the impacts when Dy is supplied from all deposits. However, when oversupplied REEs is taken into account, overall impacts when Dy is supplied from Dy-rich deposits are lower than supplying Dy from all deposits.

Cumulative E-W-CO₂ associated with oversupplied REEs as a result of Dy demand in addition to those associated with Dy and Nd production in the two demand scenarios and based on the supply from all global deposits and Dy rich deposits are shown in Fig. 9. The highest amount of E-W-CO₂ associated with oversupplied REEs and Nd and Dy demand is associated with high demand and all deposits supply scenario, followed by low demand and all deposits supply scenario, high demand and Dy rich deposits supply scenario, and low demand and Dy rich

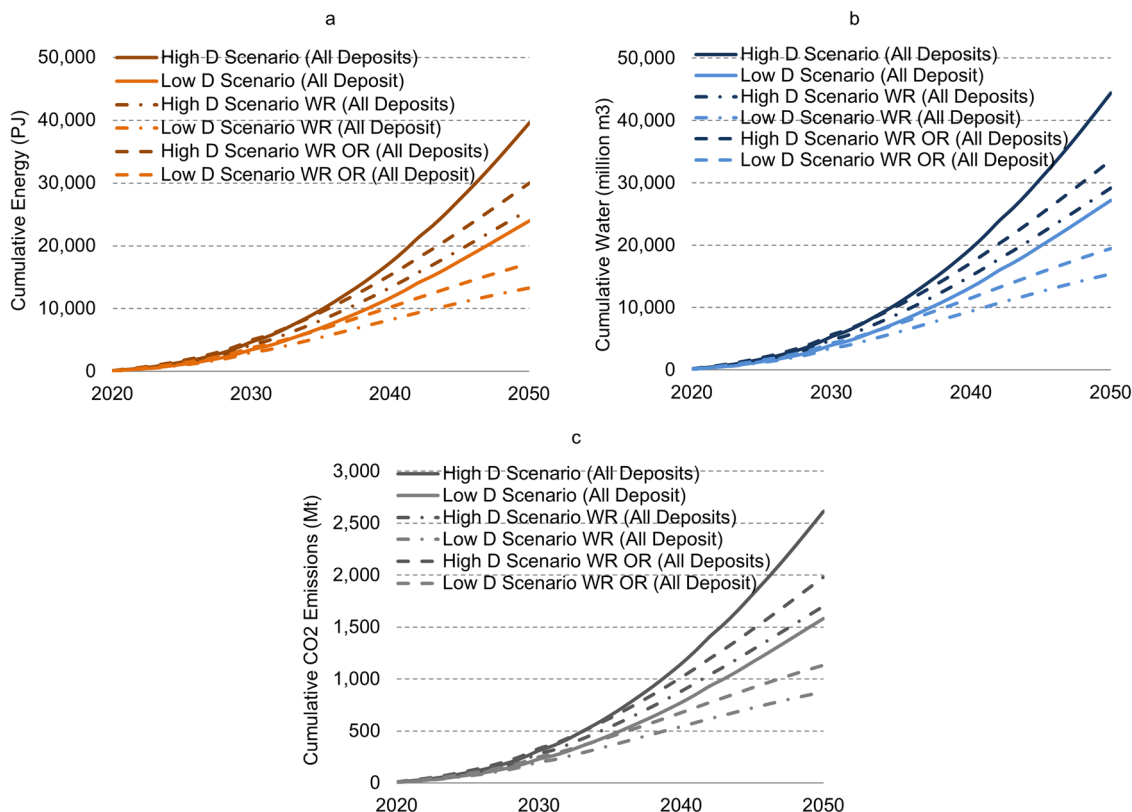


Fig. 7 Energy, water, and CO₂ emissions associated with oversupplied REEs in two demand scenarios and two secondary supply scenarios. Cumulative **a** energy, **b** water, and **c** CO₂ emissions associated with the oversupplied REEs in the two demand scenarios and the two secondary supply scenarios; High D Scenario (All deposits) combines the high demand scenario, no recycling, and supply from all deposits; Low D Scenario (All deposits) combines the low demand scenario, no recycling, and supply from all deposits; High D Scenario WR (All deposits) combines the high demand scenario, Dy recycling, and supply from all deposits; Low D WR Scenario (All deposits) combines the low demand scenario, Dy recycling, and supply from all deposits; High D Scenario WR OR (All deposits) combines the high demand scenario, Dy and other REEs recycling, and supply from all deposits; Low D WR Scenario (All deposits) combines the low demand scenario, Dy and other REEs recycling, and supply from all deposits.

deposits supply scenario. This is mainly due to the higher impacts associated with oversupplied REEs compared to Dy and Nd demand which made the trend in the different scenarios for overall impacts are similar to those of oversupplied REEs impacts. Resource efficiency increase is expected to reduce energy, CO₂ emissions, and water by 38, 38.2, and 37.5%, supply from Dy rich deposits is expected to reduce them by 64.4, 66, and 44%, and the two measures are expected to reduce them by 75.6, 76.7, and 61.6%.

When Dy supply comes mainly from Dy rich deposits, annual ThO₂ production as a result of Dy demand is expected to reach between 7.39 and 11.63 kt by 2050 in the two demand scenarios, mainly from Strange Lake in Canada (48%), Dubbo in Australia (41%), and Lahat in Malaysia (11%) (Supplementary Fig. 4). Annual U₃O₈ production as a result of Dy demand is expected to be between 2.11 and 3.32 kt by 2050 in the two demand scenarios, mainly from Strange Lake in Canada (56%), Dubbo in Australia (42%), and Lahat in Malaysia (2%) (Supplementary Fig. 4). Cumulative ThO₂ production is expected to be reduced by 485% when Dy is supplied from Dy-rich deposits compared to the supply from all deposits, while U₃O₈ cumulative production is expected to be reduced by 320%.

Although the impacts associated with oversupplied REEs as a result of Dy demand are significant, reducing the demand by using less Dy per technology (MC changing scenario), increasing Dy recycling (Dy recycling scenario) and supplying Dy from its rich deposit (Dy rich scenario) have the potential to reduce these impacts. Cumulative energy, water, and CO₂ are expected to be

reduced by about 39% in MC changing scenario, 35% in the recycling scenario, and (77% energy), (78% CO₂), and (64% water) in Dy rich scenario.

Cumulative energy, water, and CO₂ are expected to be reduced by about 83.4, 74.4, and 84.3% if recycling and Dy rich scenarios are combined, while expected to be reduced by 90, 84, and 90% if recycling, Dy rich, and MC scenarios are combined.

Supply from other sources compared to traditional global deposits. Several other sources have been identified for REEs supply including coal, bauxite, and phosphate gypsum. REEs concentrations in these sources are relatively low although available in large quantities⁴⁶. REEs production from these sources could diversify REEs supply and probably reduce the geographical concentration of production and some of the impacts associated with the production from traditional deposits. The environmental impacts of producing REEs from these sources are not well known, however, it is possible to analyse the supply-demand balance associated with the production of Dy from these sources.

In terms of supply-demand balance, not all these sources have a clear advantage over traditional deposits (Supplementary Table 1). Producing one kg of Dy from all traditional deposits would lead to the production of 69 kg of other REEs, while producing one kg of Dy from coal, phosphate gypsum, and bauxite would lead to the production of 31.6, 118.9, and 44.5 kg of other REEs (Fig. 10). In general coal and bauxite have lower ratios

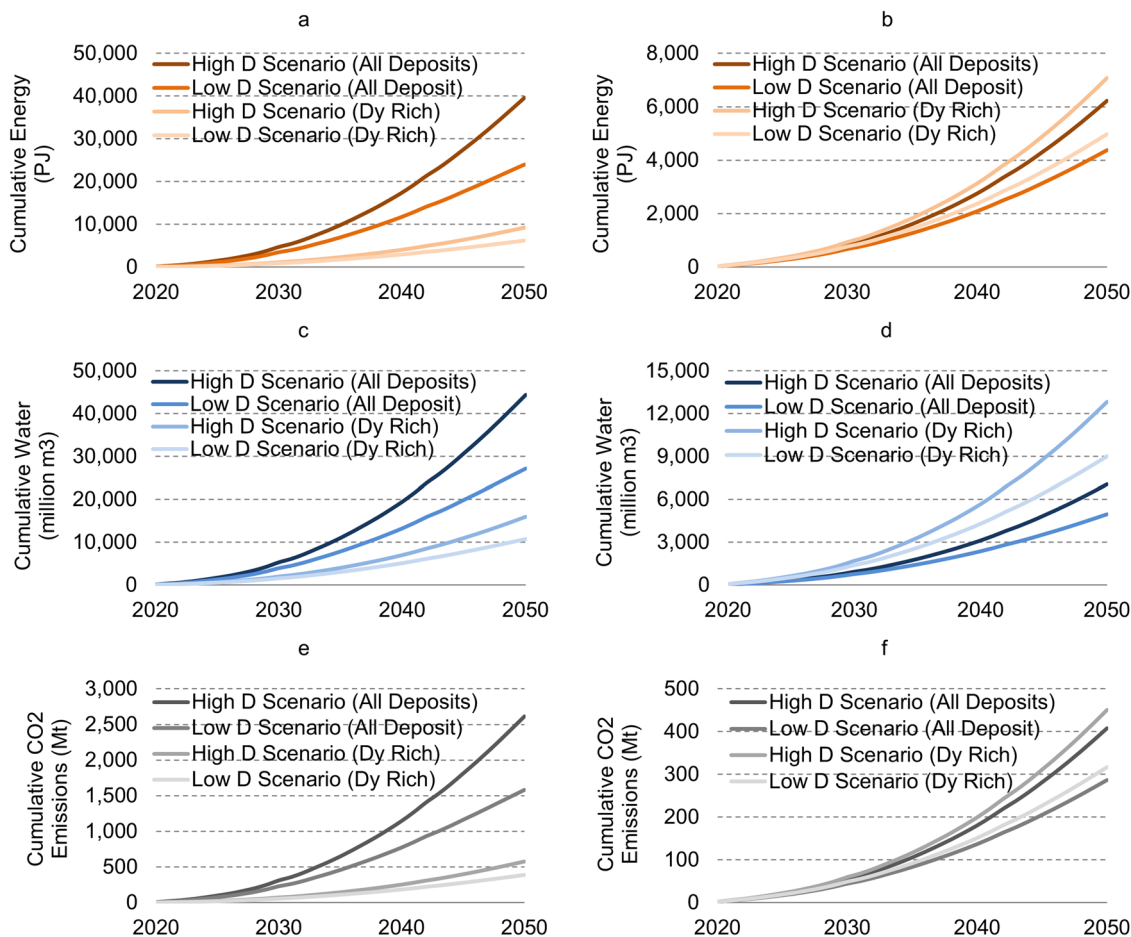


Fig. 8 Energy, water, and CO₂ emissions associated with oversupplied REEs and Dy and Nd demand in two demand scenarios and two primary supply scenarios. **a, c, e** Cumulative energy, water and CO₂ emissions associated with oversupplied REEs; and **b, d, f** cumulative energy, water and CO₂ emissions associated with Dy and Nd demand, in the high and low demand scenarios and two primary Dy supply scenarios.

of other REEs to Dy production compared to traditional deposits, while phosphate gypsum has higher ratios.

Other impacts of naturally coexisting metals associated with EVs. Minerals coproduction issues related to the energy and transportation sector is not limited to REEs but also to other metals including indium, tellurium, cobalt, platinum, palladium, and lead. Impacts of EVs development are different for each one of these metals. EVs development may increase Co demand^{47,48}, which is mainly produced with copper and nickel¹², and In and Te, which is mostly produced with zinc and copper¹². EVs development is expected to reduce Pd and Pt use, which would make Pt available for fuel cells but could have negative impacts on Pd. Although Pd is produced mainly as companion metal to Pt and Ni, reducing its demand may reduce the profitability of mining operations in which Pd contribution is considerable such as mining platinum group metals (PGMs) in Canada and USA¹². The use of EVs is also expected to reduce the demand for Pb^{21,22}. Several metals are coproduced from Pb deposits, and reducing its demand will either reduce their supply from primary sources or reduce Pb recycling to keep supply from primary sources. To illustrate the impacts of EVs on other metals, Pb is taken as example. Complete analysis of Pb dynamic material flow analysis can be found in the SI (Supplementary Fig. 5a–e). Pb demand is expected to increase by 110% between 2020 and 2050. Annual supply from secondary resources by 2050 is expected to cover 58% of total demand and the remaining 42% is expected to be

covered by primary sources. The increase in the recycling rate (RR) is expected to reduce primary supply by 29%, replacement of traditional vehicles by EVs is expected to reduce primary supply by 12% (Supplementary Fig. 5f), while the combined impact of the two is expected to reduce primary supply by 36%. These reductions in primary supply may lead to a reduction in the supply of Pb companion metals. If primary supply is assumed to grow at the same level of past 20 years to maintain supply of its companion metals and EVs has replaced traditional vehicles, RR will be reduced from 80 to 63%.

Discussion

The analysis presented in this paper shows that demand for REEs required for emerging technologies; WP and EVs, is expected to substantially increase in the future. Consequently, the supply of these REEs from traditional sources could lead to a substantial oversupply of other REEs that are naturally coexisting with them. When WP and EVs are analysed separately, Tb demand in WP is the only metal that could lead to oversupply of other REEs, while Dy demand is the main cause of oversupply in EVs case. When the two technologies are analysed together, Dy is the metal that could lead to oversupply (Tb demand is covered as a result of Dy supply). Energy, water, CO₂ emissions and radioactive materials associated with the oversupplied REEs are several times more than those associated with metals utilized in the two technologies; Dy and Nd, and combined should be allocated to the two technologies. Therefore the sustainability of emerging technologies is

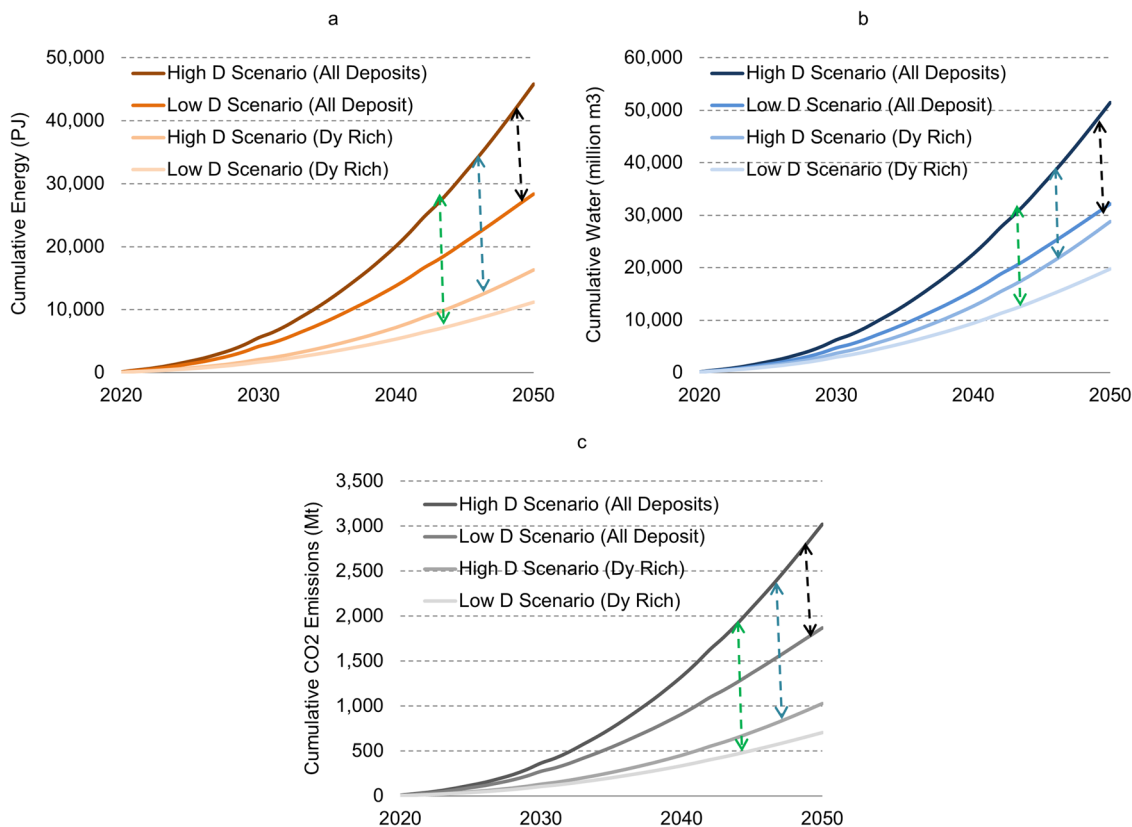


Fig. 9 Total energy, water, and CO₂ emissions associated with both oversupplied REEs and Dy and Nd production in two demand scenarios and two primary supply scenarios. Cumulative **a** energy, **b** water, and **c** CO₂ emissions associated with the oversupplied REEs and the production of Dy and Nd in the high and low demand scenarios and two primary supply scenarios. The black dotted line represents the reduction due to resource use efficiency (MC changing scenario compared to MC constant scenario), the blue dotted line represents the reduction due to the supply from Dy rich deposits instead of the supply from all deposits, and the green dotted line represents the reduction due to both resource use efficiency and the supply from Dy rich deposits.

not only determined by the impacts of materials used in these technologies but also by other oversupplied materials that are naturally coexisting with them. To analyse emerging technologies sustainability, it is necessary to include all metals coexisting in nature together even if only one of them is utilized in these technologies to determine whether an oversupply occurs or not. In addition, it is necessary to analyse technologies together especially those using the same metals, since the demand for one metal in specific technology could lead to an oversupply of its companion metals, while this metal demand could be covered as a result of the demand for one of its companion metal used in other technology.

Several options could reduce supply-demand balance problem including reducing metals demand, increasing other coproduced metals demand, increasing supply from target metals rich deposits, supply of REE from ores with different REEs distribution, increasing metals recycling, and others such as reuse and remanufacturing.

Metals demand estimates in this analysis are based on two scenarios for future development in WP and EVs developed by the IEA, which are lower than most other international scenarios^{49,50}. Scenarios that include more potential for WP and EVs would lead to higher demand for required metals and therefore the oversupply of naturally coexisting metals. Several other factors may have impacts on metals demand including sub-technologies MS, MC, and LT. The values used for these factors in this analysis are either taken directly from the original scenarios or assumed to cover the wide range of assumptions in literature. Although the MS of sub-technologies has direct impact on Nd and Dy demand, the assumption on WP technologies utilizing

permanent magnet generator (PMG) in the analysis, which is assumed to increase reaching a maximum of 50% by 2050, is not expected to have a major impact on the results as the main demand for the two metals is a result of EVs. MC has major impacts on reducing Nd, Dy, Tb, and Pr demand as illustrated in MC changing scenario. Detailed discussion on the two factors can be found in^{51,52}. Technologies LT is taken as an average value among assumed values in literature. Lower LT is expected to increase Nd and Dy demand and consequently increase other REEs oversupply, while higher LT is expected to lower Nd and Dy demand but increase demand for other metals used for the battery system such as Li and Co with several consequences⁴⁷. Another option that could reduce Nd and Dy demand includes the substitution on element or component levels. It is indicated that Tb could replace Dy however its use has been limited due to its higher price⁵³. In terms of supply-demand balance, Tb is expected to lead to higher oversupply of other REEs compared to Dy due to its lower concentration in the deposits, which leads to higher other REEs production to Tb production ratios (see Supplementary Table 3 and Supplementary Data 1). Although Sm-Co could be used instead of Nd₂Fe₁₄B, this option is not practical due to the low energy product of SmCo₅ magnets and the high price of Sm and Co as well as their limited availability⁵³. In terms of coproduction, both Sm demand would lead to oversupply of other REEs as a result of its lower concentration in the deposits, and Co demand is expected to increase as a result of increasing use of Li ion batteries, while its supply is connected to Ni and Cu production.

Increasing other REEs demand is an option but not always possible. For example, Sm-Co magnet could not only decrease Dy

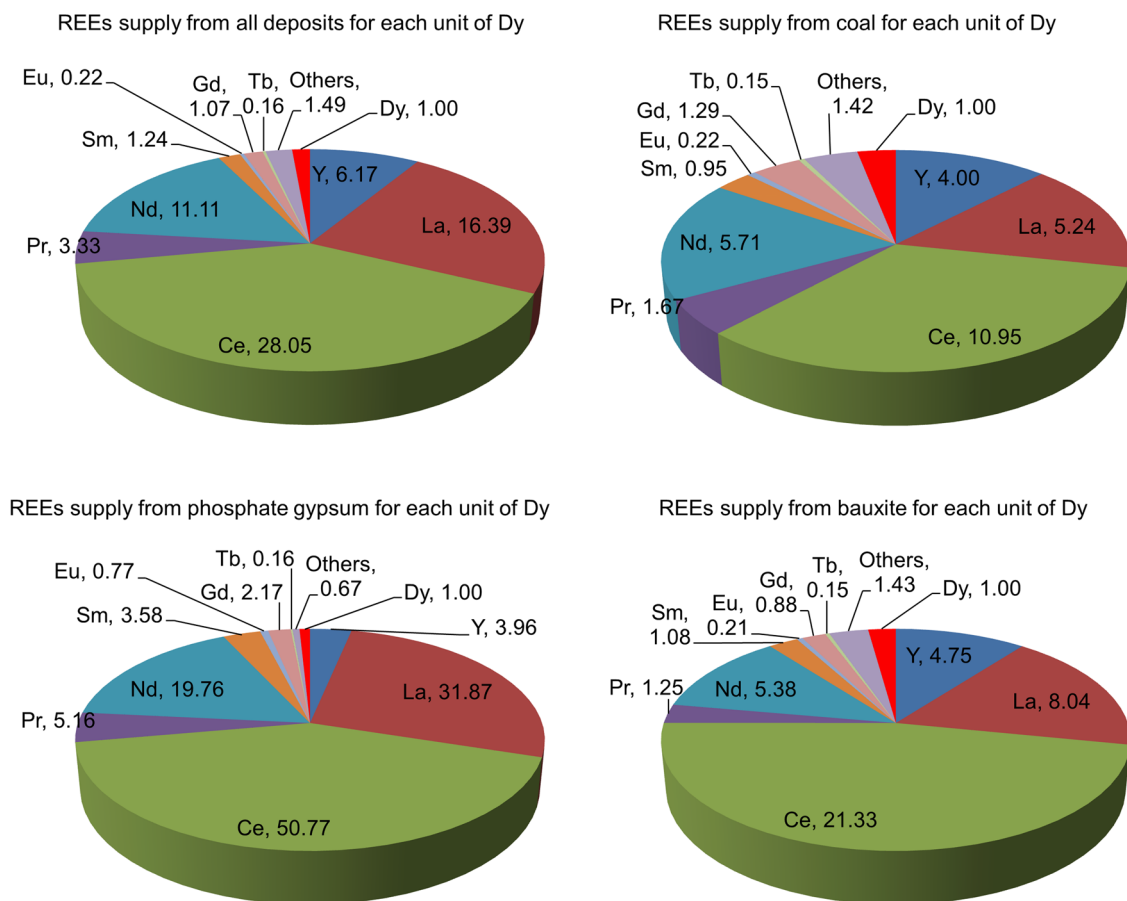


Fig. 10 Ratios of Dy production to other REEs production. Ratios of Dy production to other REEs production from coal, bauxite, phosphate gypsum and all traditional deposits (data on REE concentration in coal, phosphate gypsum, and bauxite, and for all deposits are taken from several sources^{46,72–78,85}).

and Nd demand but also increase Sm demand, however, there is a problem with Sm and Co demand and supply since both are companion metals with low concentrations compared to their host metals as mentioned before. La market was in balance largely due to its use in NiMH batteries however in the future the use of these batteries could be phased out²⁰ due to the use of Li batteries for EVs. However, the possibility of finding new applications for the oversupplied REEs or expanding their current use applications remains an option that could potentially reduce the balance problem. The scenario used in the analysis for the growth of other REEs demand in other applications⁵⁴ assumes low demand growth for REEs in catalyst, glass, and other applications, including agricultural applications⁵⁵, in which Ce and La are the most used ones. The alternative scenario proposed also in Alonso et al.⁵⁴ with slightly higher demand growth in these applications could minimize the balance problem.

The supply of metals is based on the production of REOs from currently operating and planned projects. Currently, China provides 84% of total REOs supply⁵⁵ and Australia 11%, while based on the scenario used for current and expected REOs production in this analysis (See the “Method” section), China is expected to provide 45% of the total REOs supply, Australia 16%, Canada 9%, Greenland 8% and the remaining (more than 20%) from other countries. Producing REEs from Chinese deposits has higher impacts compared to the production in other projects in most impact categories including global warming addressed in this analysis⁵⁶. Therefore the assumed scenario in the analysis would lead to lower impacts compared to the possibility of a continuation of the current trend of Chinese dominant REEs production and should be seen as an optimistic scenario. Dy supply

from its rich deposits would increase the impacts associated with its production but reduce the impacts associated with the over-supply of other REEs and consequently reduce the overall impacts as illustrated by the second supply scenario. Recycling of Dy and Nd would reduce their extraction from primary sources but not necessarily reduce supply-demand balance problem. Recycling of Dy, and Nd would reduce the amounts required from primary sources on the long term and consequently the supply of other naturally existing REEs with them. If the recycling of other REEs has increased, the supply-demand balance problem will not disappear. Otherwise, if the primary sources of other REEs are used, recycling would decrease, with possible increase in environmental impacts.

Energy, water, and emissions intensities are based on data mainly for the production of REEs from Chinese deposits with possible reduction in the impacts related to production from other regions. It is important to note that energy, water, and emissions intensities are dynamic by nature and determined by the development in ore grade, energy efficiency, and energy mix^{57,58}, which all dynamic and may change in the next 30 years. Several scenario studies have addressed these aspects for major metals^{59–62}, however, work still needs to be done for most metals especially minor metals.

Methods

A number of REEs are used in WP and EVs including Nd, Dy, Pr, and Tb. Other REEs, in addition to the four metals, are used in several applications including magnet, metal alloys, catalyst, polishing, glass, phosphors, ceramics, and others. The following sections describe REEs demand and supply and the energy, water, and CO₂ emissions associated with their production.

REEs demand and supply. Global demand for Nd, Dy, Pr, and Tb in WP and EVs in the analysis is estimated using a dynamic material flow-stock model⁶³ and based on two scenarios developed by the International Energy Agency (IEA) for global WP and EVs future developments^{8,9}, combined with several scenarios for the technologies market share (MS), material content (MC), life time (LT), and materials recycling rates (RR). Supplementary Figs. 6a and b show WP installed capacity (stock) and EVs on the road (stock) scenarios used in this analysis. WP installed capacity and EVs stocks in the IEA scenarios are given until 2040 and 2030 respectively. Data given in the IEA scenario are extrapolated until 2050 and the total numbers of EVs are comparable to other scenarios⁴⁸. The MS of WP technologies utilizing PMG in the WP market is assumed to increase reaching a maximum of 50% by 2050^{30,64}. Stocks of PHEV and BEVs are given directly in the IEA scenario and the stock of HEVs is assumed to be similar to PHEVs. The sales (inflows) of WP technologies and EVs are estimated based on the installed capacity given in the scenarios, historical inflows of these technologies^{8,9} and their LTs, which are assumed 20 years for WP^{65,66} and 12 years for EVs as an average value among different values given in literature^{49,67}. Two scenarios have been used for the MC of WP and EVs. The first assumes a constant MC based on data given in Elshkaki and Graedel²⁹ for WP and in Moss et al.²⁰ for EVs. The second assumes a changing MC with a reduction in MC of WP (based on the magnet size, a reduction in the PM by 45% and an increase in the manufacturing efficiency by 20%) by 55% for Nd and Dy by 2050 based on a scenario constructed in Elshkaki and Shen⁶⁴, and a reduction in MC of EVs by 35% for Nd and Dy based on a scenario constructed in Harvey⁶⁸. Demand for individual REEs in all applications is estimated based on their global demand in 2017 in each end-use sector (magnets, alloys, catalysts, polishing, glass, phosphors, and ceramics) (Supplementary Table 2)⁶⁹, a scenario which assumes an annual growth rate of their demand in each end-use sector⁵⁴ (Supplementary Table 2), and the fraction of each REE in these sectors (Supplementary Table 3)^{14,70}.

Supply of REEs could be met by primary sources and secondary sources. Currently REEs supply from secondary sources is <1%^{66,71}. Two scenarios for REEs recycling have been used in the analysis. The first (RSC1) assumes Dy supply is partly met by secondary sources while no recycling of other REEs and the second (RSC2) assumes Dy supply is partly met by secondary sources and there is a recycling of other REEs. Dy supply from secondary sources is estimated based on its outflow, which is estimated by the dynamic material flow-stock model, and assuming Dy recycling rate of 90% in WP and 70% in EVs³⁰. Dy supply from secondary sources is expected to cover between 27 and 39% of Dy total demand in WP and between 43 and 48% of Dy total demand in EVs by 2050 in the two MC scenarios. Supply from secondary sources is assumed to cover 30% of other REEs total demand in the second recycling scenario.

Two scenarios for the supply of REEs required for WP and EVs from primary sources have been developed. The first assumes primary Nd, Dy, Pr, and Tb is produced from all global deposits (supply scenario 1 (SSC1)). The second is based on the argument that future demand of specific REEs should be met targeting suitable deposits with high ore grade^{15,33}, and assumes the supply of these metals is mainly from Dy rich deposits (supply scenario 2 (SSC2)). The supply of the four metals from each deposit is estimated based on the demand for these metals and the share of each deposit in their production. On a global level, the supply of the four metals is assumed to be their demand. The supply of other REEs is estimated based on the supply of the four metals and the ratios of Nd, Dy, Pr, Tb production to other REEs production in each deposit as given by Eq. 1.

$$P_i(t) = R_{ix}(t) \times D_x(t) \quad (1)$$

P_i is the supply of metals (other REEs), R_{ix} is the ratio of metal i (other REEs) to metal x (one of the four metals), D_x is the demand for metal x (one of the four metals).

The ratios of Nd, Dy, Pr, Tb production to other individual REE production in each deposit (Supplementary Data 1) is estimated based on the production of each metal from each deposit to the production of these four metals from the same deposit as given by Eq. 2 or on a global level as given by Eq. 3. The global ratios of individual REEs production to the four metals production, if the supply is based on the production from all global deposits (scenario 1 of the supply), are given in Supplementary Table 4a and if the supply is based on the production from Dy rich deposits (scenario 2 of the supply), are given in Supplementary Table 4b.

$$R_{ixj}(t) = \frac{P_{ij}(t)}{P_{xy}(t)} \quad (2)$$

R_{ixj} is the ratio of metal i to metal x in deposit j

$$R_{ix}(t) = \frac{P_i(t)}{P_x(t)} \quad (3)$$

Global production of each REE in each deposit from all deposits (Supplementary Fig. 7a) and from Dy rich deposits (Supplementary Fig. 7b) are estimated based on their concentrations in the deposit, the expected production of REOs from the deposit, and conversion factor to convert REO to REE as given by Eq. 4. Data on the concentration of each REO in deposits are obtained from different sources^{72–78} (Supplementary Fig. 7c) and data on expected production of REOs from each deposit are taken from Elshkaki and Graedel¹⁵ and updated based on information provided in several sources^{79,80}. The total global production of each

REE is given by Eq. 5.

$$P_{ij}(t) = C_{ij}(t) \times P_{Mj}(t) \times \alpha_{Mi} \quad (4)$$

$$P_i(t) = \sum_{j=1}^n P_{ij}(t) \quad (5)$$

i refers to REEs; j refers to deposits; M refers to REO; P is the production; α is the conversion factor from rare earth oxides to metals; n is the number of deposits

Supply-demand balance is estimated as the difference between amounts of REEs supplied as a result of Dy, Nd, Pr, and Tb demand in WP and EVs and global demand for REEs. Companion metals production including thorium and uranium as a result of Dy demand is estimated based on Dy demand in the two technologies, supply of Dy from each deposit, either from all deposits (supply scenario 1) or Dy rich deposit (supply scenario 2), ratios of companion metals production to total REO production in each deposit, and the ratio of Dy production to total REE production in each deposit. The supply of Dy from each deposit, either from all deposits or Dy-rich deposits, is estimated based on the total production in each deposit and the concentration of Dy in the deposit. The ratio of companion metals production to total REO production is obtained from Elshkaki and Graedel¹⁵, and the ratio of Dy production to total REE production in each deposit is estimated as described before (Supplementary Data 1). The ratios of thorium and uranium production to Dy production in each deposit (Supplementary Table 5) have been estimated based on the ratios of thorium and uranium production to total REO production and the ratios of Dy production to total REO production in each deposit. The ratios of thorium and uranium production to total REO production in each deposit, which is estimated based on the concentration of REO and the companion metals in the ores, have been obtained from Elshkaki and Graedel¹⁵.

Energy, water, and CO₂ emissions. The amounts of energy and water required for the production of Nd and Dy and associated CO₂-eq emissions are estimated based on the amount of Nd and Dy required for WP and EVs and the energy, water and CO₂-eq emissions intensities of producing one unit of the metal. Energy, water and CO₂-eq emissions associated with the production of the oversupplied quantities of each REE are estimated based on the oversupplied amount of each of the REEs and energy, water and CO₂-eq intensities of producing one unit of these metals.

Different energy and CO₂-eq emissions intensity of producing REEs have been reported in literature mainly determined by the analysed deposits and the allocation methodology^{23,81,82}. Chinese deposits data for energy, water and CO₂-eq emissions intensities of cradle-to-gate REEs production based on mass allocation given by Lee and Wen⁸¹ have been used in the analysis (details on the used methodology can be found in the SI). It was difficult to find detailed LCA data for the production of REEs from all world deposits, therefore energy, water, and CO₂-eq emissions intensities of producing REEs in other world deposits have been estimated based on the data provided by Lee and Wen⁸¹ for the Chinese deposits and reduced based on information and assumptions on the impacts of producing REEs from other world deposits compared to Chinese deposits given in several sources^{23,40,56,83,84}. Although including detailed LCA data for other world deposits could improve the estimates in this study, the assumed values in this study are not expected to have a major impact on the overall results as most REEs production is located in China. Lee and Wen⁸¹ provides data for the lower, average and higher amount of energy, water, and CO₂-eq emissions for three types of Chinese deposits. Average values have been used in the analysis and minimum and maximum values have been used for the sensitivity analysis. Global low, average, and high energy, water, and CO₂-eq emissions intensities of producing REEs are estimated based on the low, average, and high intensities of each REE in each deposit and either the production of each REE from all deposits (Supplementary Fig. 8a–c), or the production of each REEs from Dy rich deposits (Supplementary Fig. 8d–f).

Data availability

The data used in the analysis are either available in the supplementary information or in the referenced sources.

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A.E. designed research, processed the data, analysed the results, and wrote the paper.

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The author declares no competing interests.

Additional information


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