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Demand and potential recovery of rare earths for a more sustainable development of electric mobility in Europe

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Summary

The European Union (EU) is developing strategies for fostering electric mobility (EM); however, there are risks that threaten the development of this emergent technology which must be considered and evaluated. In this study, we analyse the use and potential recovery of the four rare earth elements, which are used in the permanent magnets (PMs) of the electric engine by means of dynamic Substance Flow Analysis. In terms of potential recovery and recycling, we find that the "ambitious" scenario could potentially supply 40% by 2050 with current end-of-life vehicle collection rate. Overall, we explore how improving the collection rate and recycling infrastructure capacity can strategically increase potential recycled supply.

Keywords: electric vehicle, critical metal, rare earth, permanent magnet engine, recycling

1 Introduction

The private car is the most widely used mode of transportation in Europe. With the aim to reduce the environmental impacts and the dependence on fossil fuels, the EU is promoting electric mobility (EM) to replace internal combustion engine (ICE) through legislative and economic mechanisms. Due to various obstacles such as the high cost and the short-lived autonomy of the vehicles, EV sales in Europe presently are lower than expected. The market share of EVs was below 1% in most European countries in 2014, except for Norway and the Netherlands [1]. Albeit this fact, they are expected to rise to 50% to 85%, equivalent to 10 to 18 million EVs on the road, by 2030 depending on various CO_2 emissions scenarios determined by [2], [3]. By 2050, EVs are expected to have saturated the European market of passenger cars, estimated to be 23 million cars. These ambitious targets rely on an expected 80% decline in the cost of EV components by 2020 with respect to 2010, a reduction in battery weight, and significant improvement on overall efficiency [1].

Although technology limitations might be overcome and costs reduced, the development of EM is seriously threatened by the limited supply of critical metals (CMs) with unique properties that are crucial for high tech applications in EVs. The study "Resource efficiency and resource policy aspects of the electro mobility system" [4] identifies 12 priority metals for the EM system. Based on this work, we have gathered the metals which meet the following criteria: 1) the metals are identified as critical by the EU because of their high economic importance and supply risk [5], 2) they have an end-of-life (EoL) recycling rate below 1% [6], 3) there have no substitutes presently, and 4) EoL recycling is technically feasible. According to these criteria, four rare earth elements (REEs) were identified in the permanent magnets of the electric engine component (mentioned as PMs or EV PMs in this article): the light rare earths (LREEs) neodymium (Nd), praseodymium (Pr), and the heavy rare earths (HREEs) dysprosium (Dy) and terbium (Tb).

The supply of these REEs is considered risky given the low concentration in mineral ores (from 0.93% for LREEs to 0.07% for HREEs) [7], low producer diversity (China produces 85% of the global supply of REE) [8], and the expected growth of demand which is very strong (> 8%) for the HREE, and strong (4.5% - 8%) for the LREE [1].

The substitution of REEs in the EVs is limited because substitutes generally provide lower performance [4], [10], [11]. Presently, several R&D projects aim to develop rare-earth-free engines such as synchronous engines with electromagnets, asynchronous, reluctant and hybrid (combination of synchronous with PMs and reluctant) [12], [13].

We attribute the lack of REE recycling in great part to the relatively low price of the virgin REEs currently compared to the cost of collection, disassembly, and recycling [14], but high increase in future demand might make recovery more attractive. In-use stocks already offer higher concentration of REEs than the mineral ores as well as a high accumulation. For example, EV PMs contain an average of 27% by weight of Nd, while the mine deposit of Mount Weld in Australia contains only 0.85% by weight [15] - not to mention the fact that this potential source does not have the radiation issues so common in many of the REE mines.

EoL REE recycling is an important strategy for Europe to reduce dependence on virgin metal, alter the geographical distribution of supply of REEs as well as promote a circular economy [16]. EVs are expected to be one of the largest users of REEs, and hence represent the greatest potential for REEs recovery in future. They are expected to be responsible for 50% of the market share of Nd and Dy by 2030 [10]. At the present time, electric end-of-life vehicles (electric ELVs) are not yet available in large quantities due to the slow penetration of the technology and its long service lifetime of 15 years [10], [17]. However, by 2030, the stock of EVs for recycling will be around one million units in Europe [18], [19], [20], [21].

Previous studies have analyzed the criticality of REEs in different applications, and the potential stocks available for future recycling by means of Substance Flow Analysis (SFA) [17], [22], [23], [24]. In our study, we concentrate on EVs, in order to determine the potential resource constraints on the development of EM in Europe. Furthermore, we find it is important to perform the study at the European level (rather than global as most studies have been) in order to include the geopolitical aspect of CM supply. Moreover, since Europe is one of the main regions in EV sales [21] and has the most ambitious targets in terms of CO2 emissions reduction [25], its future situation as a region with one of the largest stock of ELVs and with no mining operations needs to be assessed [9], [24], [26], [27]. As opposed to previous studies that consider a more general classification of two types of EVs (hybrids and all-electric) [22], [24], we perform a more accurate estimation of the potentially recoverable REE, considering five types of EVs (HEVs, PHEVs, REEVs, BEVs, and FCEVs). In addition to this, we propose several potential scenarios of collection improvement.

In this study we first determine the demand of the four REEs identified, based on the historic and projected sales of the five types of EVs for the period 2005 – 2050 in Europe. Based on these sales and the amount of REEs in the products, we perform a SFA to quantify the in-use stock as well as EoL stock (based on the product lifetime) on a yearly basis in order to determine the recovery potential of these REEs. Moreover, based on the state-of-the-art of recycling technologies and collection rates, we study the potential of recycling electric ELVs, in order to analyze to which extent future REE demand for PM can be covered by ELV collection and recycling.

The article is organized as follows: 1) we first provide a description of REEs and their function in the permanent magnet engines in EVs; 2) an overview of supply and demand of the four REEs is presented; 3) the SFA methodology is briefly introduced, including system boundaries and data sources; 4) finally, the SFA is presented and the implications in terms of REE scarcity, recovery and potential recycling are discussed.

1.1 Permanent Magnet Engines

Most EVs in the market have synchronous electric engines, which use PMs to create a constant magnetic field [4], [11], [12]. The most commonly used PMs contain the four REEs analyzed in this study, namely Nd in the form of neodymium-iron-boron (Nd2Fe14B, or NdFeB) alloy, with small quantities of Pr, Tb, and especially Dy [11]. The NdFeB alloy has an energy density (calculated as an energy product of the magnetic flux density and the magnetic field) that is over 50 times greater than that of steel based magnets, which enable reducing weight and size while increasing the efficiency of the electric engine. The addition of Dy to a NdFeB magnet enhances its coercitivity (resistance against demagnetization), allowing maximum operating temperatures required by the electric engines of up to 175ºC [11]. The properties of these high-performing REEs are not matched by any other hard magnetic compounds [11].

1.2 Supply and demand of virgin material

REEs are extracted from rare earth oxides (REO), and, as can be seen in Table 1, available REO resources exceed the global demand by orders of magnitude and scarcity does not seem to be an issue for REEs at first glance [7], [28], [29]. Weng and coauthors [7] stated that current global REE mineral resources are sufficient to meet the demands for at least the next 90 years, even including significant growth in the demand for these elements. Why then are these elements considered critical and the focus of this study? The main reason is that even though they are abundant, the cost of the environmental and health impacts resulting from the extraction of these metals is too great for current market prices [30]. Only China, with less rigorous environmental policy in mining activities, has been successful and has a near monopoly with 85% of the global REE separation and production [8], [27], even though they have only 43% of the world resources [7]. Wang and coworkers [31] predicts a decrease in the long-term (from 136,000 in 2015 to 67,000 rare earth oxides tonnes in 2050) given the tendency in increasing environmental protection and depleting resources. The U.S. DOE [32] had estimated that by 2015 five new deposits (including Mountain Pass deposit in California) would be supplying more than 200,000 REO tonnes annually, but only one deposit is online in Mount Weld, Australia, given radiation and other environmental concerns. In conclusion, as Alonso et al. [33] and Habib and Wenzel [22] have estimated, the virgin supply of REEs will not be sufficient to meet the demand in the medium (2035) and long term (2050).

The situation for HREEs is more critical than for LREEs. HREEs (Dy and Tb) are likely to experience supply constraints already in the short term (2020) [9], which will continue in the medium (2035) to long term (2050) [22], [33]. Presently HREEs are solely extracted in the ion-adsorption clays deposits in southern China. Moreover, the Chinese State Council stated that these enriched-HREEs deposits will be exhausted in 15 years [34], [35]. In this study we explore the potential for recovery and recycling of the REEs from EV PMs in order to lessen the potential supply risk in the mid and long term for Europe.

Table 1: Global, European, and EV sector demand of Nd, Pr, Dy, and Tb. As an estimate, 1.20 tonnes of REO is equivalent to 1 tonne of REE.

	Neodymium	*Praseodymium*	*Dysprosium*	*Terbium*	*Source*
Resources (REO tonnes)	*16,700,000*	*4,800,000*	*2,980,000*	*566,104*	[36]
Global Supply in year 2012 (REO tonnes)	21,000	6,300	1,350	340	[9]
Global Demand in year 2012 (REO tonnes)	19,900	5,000	850	290	[9]
European (EU-28) Apparent Consumption in year 2013 (REE tonnes) (*)	998	not available	185	60	[37]
European (EU-28) Imports of primary material in year 2013 (REE tonnes)	178	not available	40	14	[37]
Main Global Applications in year 2012	89% Magnets 5% Cheramics 2% Autocatalysts 4% Others	73% Magnets 12% Phosphors 7% Ceramics 8% Others	98% Magnets 2% Others	71% Phosphors 24% Magnets 5% Others	[9]
Main European (EU-28) Applications in year 2013	74% Magnets 12% Batteries 3% Alloys 1% Autocatalysts 10% Others	not available	not available	54% Phosphors 46% Magnets	[37]
Global market share of magnets for EVs in Europe in year 2012 (%)	0.2	0.2	1.4	0.7	Own estimation based on [4] and [9]
Quantity in Hybrid Electric Vehicle electric engine (REE g)	150	50	90	9	[4]
Quantity in Plug-In Hybrid Electric Vehicle electric engine (REE g)	310	100	180	18	[4]
Quantity in Range Extender Electric Vehicle electric engine (REE g)	720	240	420	42	[4]
Quantity in Battery Electric Vehicle electric engine (REE g)	360	120	210	21	[4]
Quantity in Fuel Cell Electric Vehicle electric engine (REE g)	360	120	210	21	[4]

(*) Calculated as imports (which include REE as primary metal and embodied in processed materials and products) minus exports.

As can be seen in the table, the demand of REEs in pure form in Europe is rather low compared to the rest of the world, varying from one to six percent [26], [38], because most PM manufacture takes place in China. Nd, Pr, and Dy are mostly used in magnets, while a significant amount of Tb is employed in phosphorus applications. Currently, European EV magnets account for only 0.2 to 1.4% of total global use of REEs, but as we will show in this study, the demand will increase exponentially for EV PMs.

2 Methodology

2.1 Substance Flow Analysis

This study analyses the demand of Nd, Pr, Dy and Tb that will be required by different EV sales scenarios to meet future European EM targets. By "Europe" we mean the EU-28 and European Free Trade association countries (EFTA) such as Norway and Switzerland. The potential stocks of the REEs at the EoL of EVs are estimated in order to determine potential recovery with current collection and recycling rates. In order to do that, substance flow analysis (SFA) is applied for each of the REEs considered for the EM system defined.

According to the principles of SFA [39], the law of mass conservation is applied to the entire metal cycle, composed of four principal stages or processes: production, fabrication and manufacturing (F&M), use, and waste management and recycling (WM&R). In this study, the SFA is limited to analyse the use and WM&R stages of Nd, Pr, Dy, Tb embodied in EVs in Europe. Since the focus of the work is on the potential of recovery and recycling from ELVs, the previous stages of production and F&M are not included. The extraction and refining stages of REE have been previously analysed by Talens and Villalba [40].

The system boundaries considered for the present SFA are illustrated in Fig. 1, which include use and EoL management stages of collection, dismantling, and recycling of Nd, Pr, Dy, and Tb taking place in Europe for the years 2005-2050. In the use phase, the amount of REEs embodied in the PMs depends on the degree of hybridization of the electric engines used in each type of EV. Based on several studies [10], [17], the lifetime of EVs is determined to be 15 years. Because EVs have been in the market for less than 20 years and sales have been low, we assume that up to the present time there is no significant amount of electric ELVs. Presently, authorized treatment facilities do not recover and recycle REEs [41], [42], [43]. In this article, we consider that the state-of-the-art recycling technologies, which are presently developed at pilot scale [10], [44], are deployed at the industrial scale.

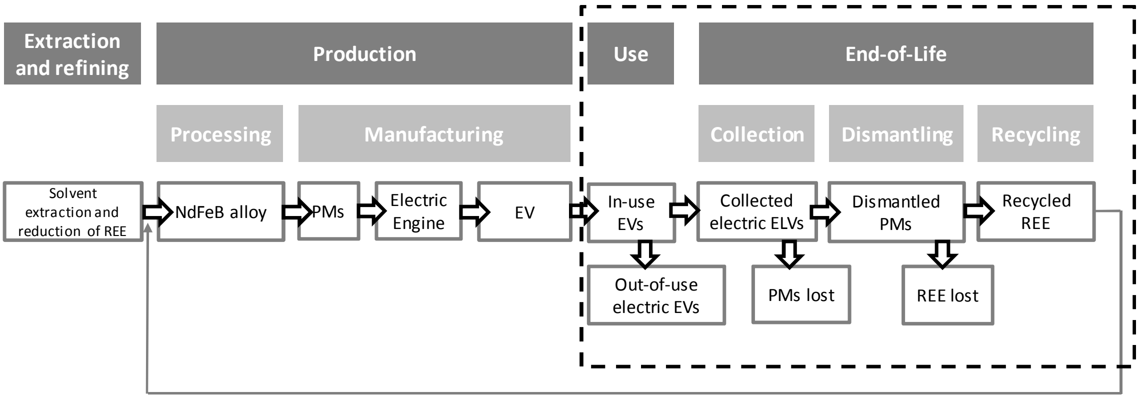

Figure 1: System boundaries of EVs in Europe (in dotted line)

2.2 Data sources and scenarios

EV sales from 2005 to 2016 are gathered from literature reviews [18], [19], [20], [21], and EV future sales from 2020 to 2050 are based on two reports by McKinsey & Company [2], [3] that describe three potential sale scenarios depending on different transport CO2 reduction goals: 1) moderate EV sales or "Below 100" (B100), 2) medium EV sales or "Below 40" (B40) and 3) ambitious EV sales or "Below 10" (B10) [2], [3]. The B100 scenario assumes a conservative development of EVs, reducing well-to-wheel CO2 emissions to 95 g/km by 2050 (currently 130 g/km); the B40 reflects increasingly restrictive emission standards, with a CO2 emission reduction to 40 g/km by 2050; while the B10 scenario assumes a very dynamic development of EVs, coupled with rapid development of the electrical charging infrastructure, reducing well-to-wheel CO2 emissions to 10 g/km by 2050. It is important to point out, that for the period from 2030 to 2050 no forecasts are available for Europe in the McKinsey reports, and instead sales past 2030 are based on forecasted global sales of each type of EV.

The historic and projected EV sales data used in the study are summarized in Fig. 2 for each of the three scenarios B100, B40, and B10. In the Supporting Information (SI1) EV sales are broken down into each type of EV. Sales in 2015 reached close to half a million EVs, and are expected to increase by factor of 25, 35, and 45 by 2030 for scenarios B100, B40 and B10, respectively, and more than 50-fold in all scenarios by 2050, reaching close to 23 millions of units (equivalent to all cars expected to be sold in Europe that year). Presently HEVs dominate the market, but it is expected to be more diversified with the introduction of REEVs and more BEVs by 2020. Over time, EVs with higher electrification will replace HEVs and PHEVs in B40 and B10 scenarios, while HEVs will remain the dominant EV in B100 scenario reaching a market share of 60% by 2050.

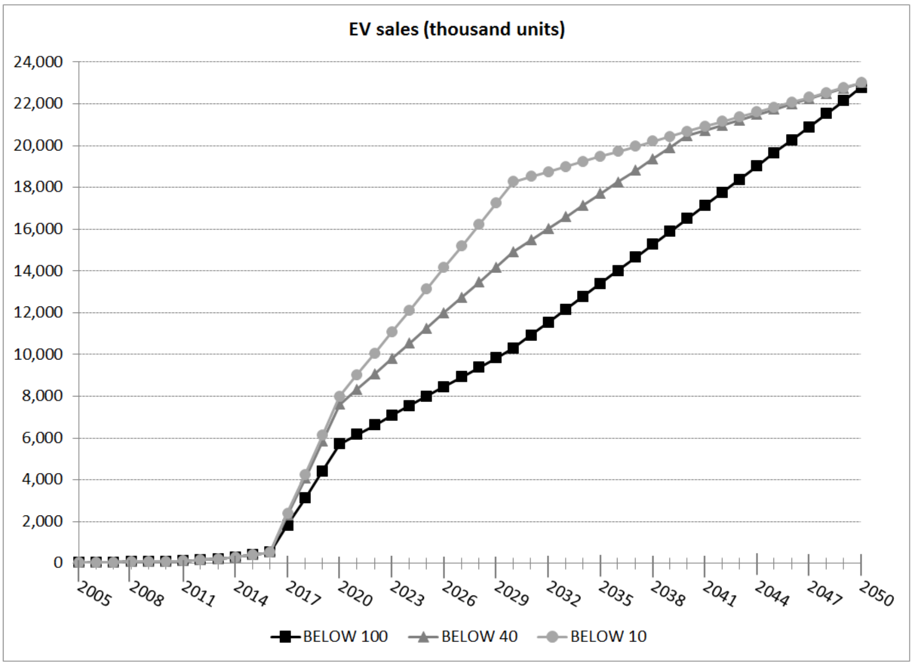

Figure 2: Historic and projected EV sales in Europe (thousand units) (ACEA 2016a, 2017; ICCT 2015; IEA 2016; McKinsey & Company 2011, 2014).

The amount of REEs contained in the different kinds of EVs for a given year can be calculated according to the following equation:

$$S_{i,j} = P_{k,j} \times w_{i,k} \qquad (1)$$

Where Si,j is the in-use stock of the REE i in year j (in tonnes) and Pk,j is the number of units of EVs produced with different degree of hybridization k in year j. wi,k is the amount of mass of REE i for each type of electric engine k (in tonnes), given in the last five rows of Table 1. An HEV is assigned a small electric engine (<50 kW) requiring about half of the REEs of a large electric engine (>50 kW); the PHEV has a combination of 75% large engine and 25% small engine; the BEV and the FCEV have large electric engines; and the REEV has two large electric engines.

To calculate the EoL stock we use the average collection rate of 55%, calculated by the Öko-Institut as the ratio between the number of reported ELVs and the total estimated ELVs for a single year [45], [46]. The total estimated ELVs expected for one year is determined based on mass balance as the sum of new cars registered, imported cars, and the increase of car stock compared to the previous year. For example, in 2013, 13.4 million ELVs were expected, of which only 6.3 million units were collected and reported as ELVs for proper waste management. The difference is considered "lost" to recycling within Europe, of which 80% have unknown destiny and 20% are exported, mainly to Africa [47].

When the ELVs arrive to the authorized treatment facilities (ATFs), they are processed in three main phases: depollution, dismantling, and shredding. As a first step, the vehicle is drained of all operating liquids [48], [49], [50], followed by the dismantling phase which consists of the removal of spare parts and materials (i.e. glass, bumpers) for reuse and recycling as prescribed in the Directive 2000/53/CE [51]. After that, in the shredding process, automobile hulks are fed into a large rotating hammer mill, where they are broken into small pieces. Mechanical and magnetic separation processes are used to produce separated streams of ferrous and nonferrous metals, which are sold for recycling, and a waste stream known as automotive shredder residue (ASR) consisting of a heavy and a light fraction. ASR is a very heterogeneous mixture, which is often disposed of in a landfill [48], [49], [50], [52], [53].

Presently the REEs are “lost” in the shredder light fraction of ASR because there is no market incentive to recover them [41], [42], [43]. In order to quantify the potential recovery and recycling of REEs from PMs, we consider the disassembly process of electric engines described by Schulze and Buchert [17], which estimates a 90% disassembly rate of PMs from electric ELVs. The 10% losses are attributed to deeply embedded PMs in the electric engines that cannot be easily extracted.

Neither Umicore, the largest European company in processing metals, nor Solvay, which has recently opened two rare earth recycling units in France, have disclosed any information about the REE recycling process [54], [55]. We therefore base our potential recycling yield on the most promising recycling technologies that have been publically described [10], [56]. In a recycling process designed by the project MoRe [10], the PMs are disassembled, demagnetized, washed and broken into particles during the mechanical preprocessing. Then, via a hydrometallurgical treatment, the alloy in form of powder is dissolved in hydrochloric acid, in order to separate the metals iron and cobalt. After this stage, the recovery of the REEs is performed by solvent extraction resembling virgin metal extraction with a high purity > 99% with a process yield of 90% [10], [40]. It is expected that this recycling process can be implemented between 2030 and 2040. For this purpose, several obstacles must be overcome, such as the standardization and automation of the disassembly, as well as the scale-up and cost optimization of the hydrometallurgical treatment [10].

The EoL Recycling Rate (EoL-RR) is 45% and is calculated as described by Graedel [6], as the factor of collection rate (55%), disassembly rate (90%), and recycling yield (90%). In order to quantify total potential REE recovery (or the EoL stock) given best available technologies in both disassembly and recycling, we also consider a 100% collection rate which results in an EoL-RR of 80%. We analyse the potential recovery of Nd, Pr, Dy and Tb by applying the EoL-RR to the three scenarios B100, B40 and B10 of future EV sales using the following equation (2):

$$R_{i,j} = S_{\ i,j-15} \times EoL - RR \qquad (2)$$

where Rij is the quantity of REE i available for second use in year j (in tonnes), and Si,j-15 is the in-use stock of REE i in the year j-15 when it is put in the market (in tonnes).

To gauge the significance of the forecasted EoL stock as a potential future supply we use the “potential recycling supply ratio” (PRSR) defined by Hagelüken et al. [24] and Rademaker and Yang [57], which in our case is the ratio between the amount of REE collected at EoL and the demand for REE for PMs for new EVs for a given year.

3 Results and discussion

The SFA for each REE has been determined based on the projected sales of EVs according to the three scenarios B100, B40, and B10, as well as the metal composition, collection, disassembly and recycling rates as described in the methodology section. Here we present the estimated quantity of electric ELVs arriving at the ATFs, and we compare the forecasted future demand with the potential supply of recycled Nd, Pr, Dy, and Tb from EV PMs in Europe.

The number of electric ELVs expected from 2020 to 2050 is shown in Fig. 3. Based on the 55% ELV collection rate, we expect that ATFs will see the number of collected electric ELVs arriving at their facilities increase 15 to 20 fold in five years: from 200,000 in 2030 to 4.5 million electric ELVs in 2035. This trend will continue until 2050, except for the most ambitious scenario B10 which stabilizes in 2045, due to a faster saturation of the market in the previous 15 years. By 2050 we can expect the number of collected electric ELVs to range between 7 million for scenario B100, to 10 million for B40 and B10. If we consider B100, results indicate that most of the EVs collected will be HEVs. However, for B40 and B10, the majority of the electric ELVs are expected to be REEVs and BEVs, respectively (a more detailed description by EV type is given in the Supporting Information SI4).

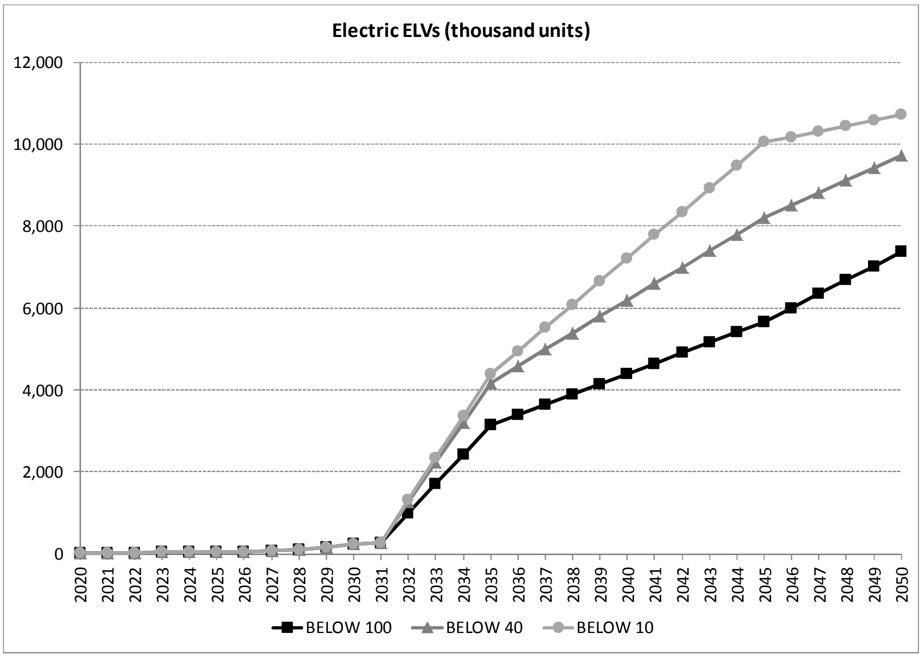

Figure 3: Estimated electric ELVs in Europe (thousand units) for the three scenarios B100, B40, and B10.

The forecasted demand and potential recycling of the four REEs in EV PMs in Europe according to the three scenarios are presented in Fig. 4 (a)-(d). In general, B10 presents the highest demand of all four metals until 2035, at which point B40 is expected to require more REEs than B10, due to the predominance of REEVs, which have the highest amount of REEs. The European demand for the four REEs for EVs in 2035 will increase by factor of 40 (by scenario B100) to 80 (by scenarios B40 and B10) from 2015 levels. In the long term, however, the most ambitious CO2 reduction scenario represented by B10 equals the least ambitious B100 in terms of REE demand at 17,000 tonnes and, surprisingly, is 25% lower than B40 demand. This is due to the fact that the B10 scenario includes a much larger proportion of BEVs and FCEVs, which contain a lower amount of REEs than REEVs. This can be seen in the slight dip in REE demand in Fig. 4 (a)-(d) for scenario B10 in 2040, during which REEV sales are expected to be replaced by BEV and FCEV sales. The other two scenarios B40 and B100, although they have less EVs in total, have more REEVs, which require more REEs as can be seen in Table 1.

According to the results shown in Fig. 4(a), the sale forecast of EVs in Europe is expected to increase Nd demand from 100 tonnes in 2015 to 4,000 (B100) and 8,000 tonnes (B40 and B10) in 2035, and up to 8,500 (B100 and B10), and 12,000 tonnes (B40) in 2050. This increase in demand replaces EV PM Nd market share from a 0.2% in 2012 to 50% (B100 and B10) or 60% (B40) by 2050 (based on the 2012 total global supply presented in Table 1 and increases EU apparent consumption up to 12 times.

The demand for Pr in EV PMs in Europe is expected to grow from 35 tonnes in 2015 to around 1,500 tonnes (B100) or 2,600 tonnes (B40 and B10) in 2035, and 2,800 tonnes (B100 and B10) or 4,000 tonnes (B40) in 2050, as is shown in Fig. 4(b). These numbers are alarming when we consider the fact that current virgin supply is 6,300 REO tonnes worldwide [9]. In terms of global demand, Pr demand for EV PMs in Europe can be expected to shift from 0.2% in 2012 to 50% (B100 and B10) and 70% (B40) by 2050 (based on 2012 total global supply).

Our results show that Dy is the most critical REE in terms of demand. As shown by Fig. 4(c), Dy demand for EVs in Europe will increase from 60 tonnes in 2015 to around 2,500 - 4,500 tonnes by 2035 and up to 7,000 tonnes by 2050. Considering a 2012 global supply of 1,350 REO tonnes of Dy , we estimate that demand for Dy in EV PMs in Europe is likely to increase from 1.4% from total global REE supply in 2012 (as shown in Table 1) to up to 600% by 2050 (based in 2012 total global supply).

As can be seen in Fig. 4(d), the demand of Tb for EVs in Europe is likely to grow from 6 tonnes in 2015 to around 250 - 450 tonnes by 2035, and 500 - 700 tonnes (B40) by 2050. Considering the global Tb market in 2012, the demand of Tb for EV PMs in Europe is expected to increase from 0.7% in 2012 to 200% (B100, B40 and B10) in 2050 (based in 2012 total global supply as show in Table 1). Or said differently, EU apparent consumption can be expected to increase from 60 tonnes to over 600 tonnes by 2050.

In general, our results show that the potential recycled supply meets less than 40% of the demand for EV PMs for any single year under study. As can be seen in the Fig. 4(a)-(d), REE recycled supply will remain relatively small and insignificant until 2035, at which point the Potential Recycling Supply Ratio (PRSR) of the four metals will grow to 12% (B100), 14% (B40) or 15% (B10). Even though the PRSR is estimated to be very similar regardless of the CO2 reduction scenario chosen, the B10 scenario requires double the amount of REEs (2,270 tonnes) than the B100 scenario (1,040 tonnes). However, in the long run, the PRSR of B10 is expected to reach 40%, significantly higher than B100 (23%). This study seems to point that the most ambitious CO2 reduction strategy for EM is also the most favorable in the long run in terms of critical resource recovery and recycling. Furthermore, alternatives for REE-free electric engines are most likely to be applied in BEVs rather than in PHEVs or REEVs, due to space in the vehicle [17], [23], which would further increase the PRSR of scenario B10. A comprehensive environmental evaluation such as life cycle assessment is needed in order to account for environmental impacts, such as those incurred from extraction and mining, but is out of the scope of this study.

The results of this study show that a more or less ambitious deployment of EV sales will depend on the available virgin supply, especially in the short term up until 2035. Resource constraints are already expected in the short term (2020) for HREEs, which jeopardizes the ambitious deployment of B10 scenario. On the other hand, given that supply constraints will be even more significant in the long term [22], the substantial PRSR reached by scenario B10 makes it attractive. It is also important to point out that the relatively low REE demand for European processing industries (shown in the row of “imports of primary material” in Table 1 could be met by recycled REEs from EV PMs by all scenarios before 2035.

Albeit significant PRSR values in the long term lead us to believe that an important part of demand can be met by recycling, the demand of the four REEs studied is expected to increase tremendously globally. According to [22], by 2050 future global demand (for all uses) of Nd could range from 100,000 to 250,000 tonnes and demand of Dy could vary between 10,000 and 30,000 tonnes. Other fast-growing applications (such as PMs for wind turbines), and large consuming regions (China), will be competing with EVs for the use of REEs. This accentuates the need for reducing material use as well as the need to find non-critical substitutes.

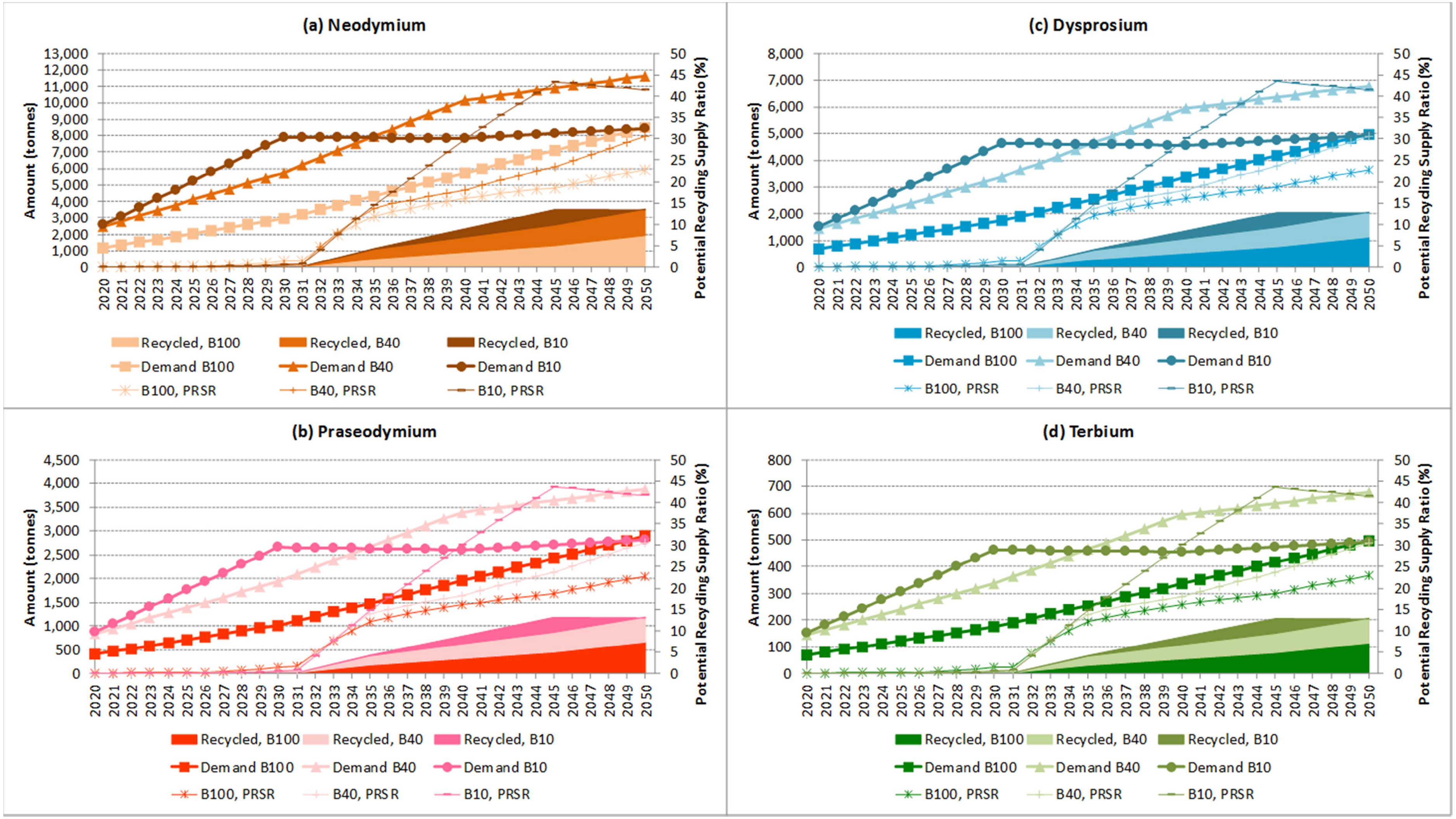

Figure 4: Demand and secondary supply of (a) Nd, (b) Pr, (c) Dy, and (d) Tb from EV PMs in Europe (tonnes). Total demand of REEs: 282,670 (B100), 476,805 (B40), and 439,320 (B10) tonnes, whereas recycling will amount to 38,990 (B100), 74,940 (B40), and 89,470 (B10) tonnes.

4 Conclusions

This study shows that based on current ELV collection rates and feasible disassembly and recycling technologies, a partial circular economy of REEs for use in EVs is possible. The potential recycled supply of Nd, Pr, Dy and Tb from EV PMs is significant in the more ambitious CO2 reduction scenarios, reaching a PRSR value of 15% for scenario B10 by 2035. After 2035, PRSR continues to grow steadily until reaching values, ranging from 23% (for scenario B100) to 40% (for scenario B10) in 2050, which is equivalent to 3,845 to 6,920 tonnes of REEs. Between 2020 and 2050 the total estimated potential supply of REEs from EVs for the study is 38,990, 74,940, and 89,470 tonnes for scenarios B100, B40, and B10 respectively.

Additionally, we have estimated that REE demand for EV PMs will increase from 200 tonnes in 2015 to a total of 9,000 to 16,000 tonnes by 2035, and 17,000 to 23,000 tonnes by 2050. Presently EV PMs only account for approximately 1% of the global market share of REEs, and will soon be competing with other fast-growing technologies with similar increasing REE demand. Constraints in REE demand are foreseen, especially for Dy, for which demand for EV PMs in Europe from 2020 onwards can be expected to exceed current global supply (1,350 REO tonnes) [9].

With respect to the collection system of vehicles in the EU, it is estimated that 45% of ELVs are “lost”, of which most are considered to have an “unknown destiny”, including illegal shipment, illegal disposal or kept in garages [47]. Measures should be implemented in order to improve the collection rate of ELVs, such as only allowing deregistration of the car when it is disposed of properly, or obtaining a refund when correct disposal takes place [47].

Other ways to reduce the gap between demand and potential recycled supply of REE are to implement substitutes and material reduction strategies. Presently, substitution results in loss of performance, but there are ongoing research efforts in asynchronous and reluctant electric engines without PMs [12], [13]. The Japanese government is currently supporting research on how to reduce Dy in PMs from 5% to 1%, and shows a promising alternative before the substitution is viable [58]. Another strategy consists of reducing resource demand by means of servitization. In a future context of collaborative economy where mobility services will be provided for the customers, instead of selling cars, a decrease of vehicles on the road is expected.

In conclusion, the development of the EM is a challenge for Europe, especially in terms of guaranteeing the necessary supply of REEs required for the electric engines. Although a significant part of the future REE demand of the EM sector can potentially be met by recycled REE from electric ELVs, we show that recycled supply is not enough, and it is in Europe´s best interest to implement an intelligent resource strategy not only in terms of improving collection and recycling rates, but also reducing and optimizing REE use.

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