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Review

NdFeB Permanent Magnet Uses, Projected Growth Rates and Nd Plus Dy Demands across End-Use Sectors through 2050: A Review

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Abstract: Rare earth element (REE) permanent magnets (NdFeB) are a critical element in a vast and growing number of industrial applications. In consumer electronics, a broad category encompassing computer, CD, and DVD hard drives, in addition to the ubiquitous cell phones, the nominal NdFeB magnet content may be small, but the global market share for this sector accounts for almost 30% of NdFeB demand, due to a large and continually increasing consumer base. It is estimated that wind turbines that primarily employ permanent magnets will add roughly 110 GW annually of on- and off-shore capability over the next few years. Electric vehicles (EVs) and E-bicycles (EBs) equipped with permanent magnet motors comprise the transportation contribution. Permanent magnet motors have garnered nearly 100% of the market share among EV manufacturers worldwide. Industrial, professional service, and personal robots, most using permanent magnets, are also included in the projected global need for rare earths, particularly Nd and Dy. The sector projects significant growth of approximately 10% across robotic categories. In this paper, we calculate the future demand for Nd and Dy through 2050 across these sectors using a compounded annual growth rate coupled with magnet weight and rare earth content. Uncertainties in the estimates, such as the true global production of Nd, a range of end-product scales and/or unit types in each sector, varied magnet compositions, and the variety of uses within a sector, are all considered.

Keywords: rare earth elements; permanent magnet; electric vehicles; electric bicycles; wind turbines; robotics; consumer electronics; industrial motors; non-drivetrain motors; dysprosium; neodymium; NdFeB

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1. Introduction

From 2021 to 2026, the global permanent magnet market is projected to increase at a CAGR of 9.5%, representing an increase from 34.5 to 54.1 billion USD [1]. The drivers for this growth include an increased demand from general industrial applications and the automotive sector, with Asia Pacific representing one of the largest contributing regions [2]. The industries that rely on permanent magnet use include aerospace and defense, the automotive sector, consumer electronics, the energy and environmental sectors, general industries, medical technologies, and other applications [3]. Though permanent magnets are found across the many mentioned sectors (and even extend, for example, to magnetic drive pumps, holding systems, children's toys, medical/dental products and devices, and jewelry), in this study, we focus only on sectors with the highest demand for permanent magnets, as the contributions of smaller sectors are negligible in comparison. In 2020, the end-use sectors with the highest demand for permanent magnets are shown in Figure 1, as reported by the U.S. Department of Energy (DOE).

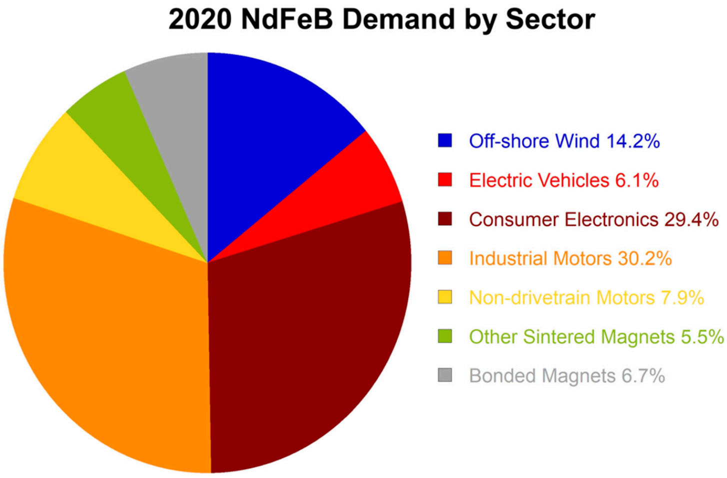

Figure 1. NdFeB demand according to end-use sector as reported by the DOE for 2020, where industrial motors and consumer electronics required more NdFeB magnets than other industries [4].

Across consumer, defense, manufacturing, and power generation sectors, rare-earth-based permanent magnets are valued for their superior coercivity. They are nominally referred to as neodymium iron boron (NdFeB) magnets, though the short acronym misses the praseodymium (Pr) and dysprosium (Dy) content and the occasional inclusion of terbium (Tb). Dy and sometimes Tb are added to improve the coercive stability at elevated temperatures during use [5]. With the exception of a few material uses for Dy (glass, ceramics, catalysts, catalytic converters, etc.), their applications are identical—underscoring their common use in NdFeB magnets.

The supply of neodymium (Nd) is limited in the US, which has little domestic production of rare earths and even smaller permanent magnet manufacture. Figure 2 below summarizes REE production from 2016 through 2022 with figures reported by the U.S. Geological Survey (USGS) [6–14]. Increasingly, China dominates the annual REE production, of which Nd, Pr, Dy, and Tb collectively account for a quarter (by volume) [15]. Of the approximately 130,000 t of NdFeB magnets produced worldwide in 2019, representing a 6.5 billion USD market volume, approximately 93% were sourced and produced in China [16]. Increasingly, NdFeB magnets are imported as a preassembled component of the final product (i.e., the entire motor) [17]. Hence, imports in the form of the rare earth oxide (REO), magnets, and integrated end products are essential to fulfilling demand across the globe and especially within the US. This article relates permanent magnet consumption to the specific rare earth quantities required across major usage sectors.

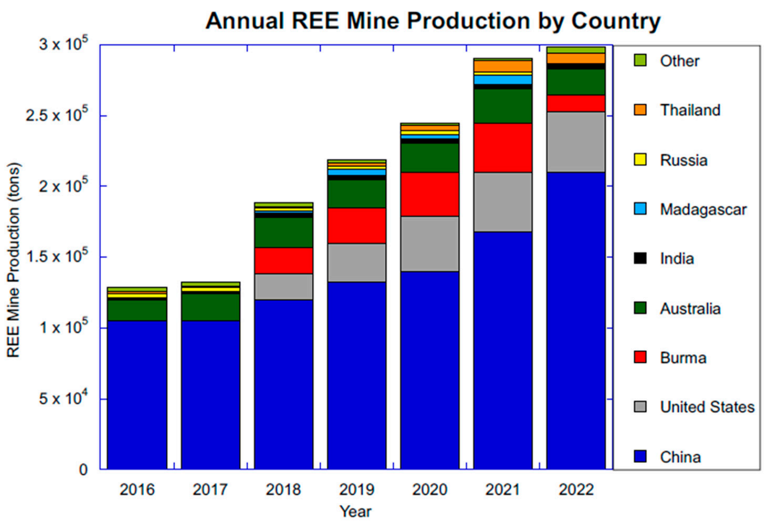

Figure 2. Annual mine production by largest contributing countries as adapted from USGS data [6–14].

2. NdFeB Permanent Magnets

NdFeB magnets (also called rare earth, REE, NIB, Neo or just neodymium magnets) are permanent magnets produced using rare earth alloys [1]. They possess stronger magnetic fields than other available permanent magnets, for example ferrite (Fe) or aluminum nickel cobalt (AlNiCo) magnets [1]. An REE magnet is made from an alloy of Nd, Fe, and B. The name reflects the major elements but is not inclusive, as Dy (dysprosium) and sometimes Tb or Gd are added to retain coercivity at high temperatures. Table 1 summarizes the relative compositions of these magnets, which are used to calculate the demands of Nd and Dy in this study. A summary of the factors involved is presented in Table A1, which gives Nd and Dy percentages in different applications and shows that they comprise roughly one third of NdFeB magnets.

Table 1. NdFeB magnet content by element with REEs highlighted, reflecting relative composition utilized in this study, data adapted from Peak Resources [18].

NdFeB Elements	Weight Percent
Iron (Fe)	64.2%–68.5%
Neodymium and Praseodymium (NdPr)	29%–32%
Boron (B)	1%–1.2%
Dysprosium (Dy)	0.8%–1.2%
Niobium (Nb)	0.5%–1%

NdFeB permanent magnets were independently and simultaneously discovered in 1984 by both General Motors (melt-spun nanocrystalline $Nd_2Fe_{14}B$) and Sumitomo Special Metals (full-density sintered $Nd_2Fe_{14}B$) [19]. The high raw material acquisition cost of their predecessor (samarium cobalt (SmCo) permanent magnets) was the driver for the research [19]. NdFeB magnets continue to be the strongest commercially available permanent magnets. Their maximum energy product is very high relative to Fe, AlNiCo, or SmCo permanent magnets [20]. The maximum energy product is a measure of the magnetic energy that can be stored per unit volume of a magnetic material [20,21]. Specifically, it is calculated as the maximum product of the material's residual magnetic flux density (or degree of magnetization) and its coercivity (its ability to resist heat and demagnification after it is magnetized) [20]. The high power-to-volume ratio increases efficiency, allowing for the miniaturization of NdFeB magnets while retaining a much better performance than the Fe or SmCo species [22]. Furthermore, these properties make it possible to miniaturize high-capacity motors. A myriad of industrial and consumer products that depend on the superlative performance of NdFeB magnets include actuators, anti-lock braking systems and other automotive parts, audio equipment, communication systems, frictionless bearings, magnetic storage disks, magnetic resonance imaging (MRI), robotics, and more [22–24]. NeFeB batteries are used in National Defense systems, including guided missile actuators and ship propulsion systems and infrastructure [25]. These magnets are employed in electric and hybrid vehicles and, increasingly, in wind turbines. Due to the increasing demand across a multitude of sectors, the NdFeB magnet market is expected to see significant growth [1].

In this article, we focus on the current generation of NdFeB permanent magnets, which feature a combination of light and heavy REEs, NdPr, and Dy, respectively. All of these are considered critical REEs; Dy in particular is in short supply. Substitutions and recycling across industries are briefly discussed as a critical component to the future viability of REE (or REO) industrial applications.

3. Motivation

The projections of REE demand require as inputs (a) material intensities, (b) an accounting for variations in technology or type of manufactured article, and (c) estimated growth rates.

The estimates for growth rates may be based on historical trends, climate goals, estimated market economics, or optimistic predictions. Notably, these approaches may or may not be based on the present manufacturing capacity or available resources. Depending on the application scale (e.g., wind turbines), technology class, and manufacturer, material intensities vary and can evolve over time. Often, secondary references are given in the literature articles.

Projection growth formulas or rates can be unclear. Few studies illustrate bandwidths for projected demand but rather choose a set value. However, small percentage differences in a compounded annual growth rate, $CAGR = \left(\frac{EV}{BV}\right)^{\frac{1}{T}} - 1$, can lead to significant differences in projections over just a few decades. For example, in a 30-year growth projection study for wind turbines, the initial capacity of on-shore turbines used for the year 2020 is 75 GW. Assuming a growth rate of 6.1%, the annual capacity in the year 2050 would be 443 GW. However, if that fixed CAGR were instead given a range of $\pm$0.5%, the 5.6% rate would yield a 2050 capacity of 385 GW, whereas 6.6% growth would result in a 510 GW capacity. The difference is not trivial.

Here, we (a) explicitly list the material intensities; (b) provide the growth rate values, references, and where possible, include uncertainty estimates; and (c) account for changing end product technologies or note dependences on scale of the end product unit. In the case of multiple technologies or market segmentation by different technologies, percentage allocations are stated and sourced. These factors are summarized in Appendix A, Table A1.

4. Permanent Magnet (PM) Uses

Clean energy, electrification, automation, and electronic devices are critically dependent on rare earth permanent magnets and, hence, the elements Nd and Dy, as well as Tb and samarium (Sm) [23]. The major categories driving NdFeB magnet growth are EVs, wind turbines, robots, and consumer electronics. The present usage and projected growth are included in a CAGR, along with the material intensities for estimating future Nd and Dy demand through 2050.

4.1. Wind

Wind turbines vary in generating capacity, drive mechanism, and generator type. For those using direct-drive gearing with a permanent magnet generator, large-, medium-, and small-scale versions contain 650 kg, 160 kg, and 80 kg of NdFeB, respectively [26]. The total rare earth content is ~30% as the reduced metal [5,27]. Conversion to the oxide requires a stoichiometric factor, along with an estimated 20% loss in conversion from oxide to metal, not including the metal loss during magnet fabrication [23]. Dy is included for high temperature stability and improved coercivity [5,28]. Though percentages greater than 6%–10% are desirable, cost and availability have pushed the Dy content to ~4%, with advanced manufacturing methods striving for an even lower content overall [28,29]. Notably, not all wind turbines use permanent magnet generators, but the market share of those that do is increasing due to the higher conversion efficiency and reduced maintenance, a desirable pairing for off-shore wind turbines operating at low speeds [30,31].

Wind turbines have a wide variety of systems for operation, mostly consisting of geared/gearless transmission accompanied by either electromagnet or permanent magnet (PM) generators, where gearless transmission is direct-drive (DD) [32]. Low-speed generators, usually associated with DD, often utilize electromagnet or PM generators. Notably, the magnet mass in these generators depends on their speed, with the increasingly preferred low-speed generators often requiring larger quantities of PMs [32]. Surveying across four manufacturers, Moss et al. (2013) reported an average range of 0.625–0.85 tons/MW [32]. However, this range was reported for low-speed PM generators. For our analysis, we use an average of 0.5 t of magnet per MW, taking into account the aforementioned analyses and ranges in addition to a recent study determining the average among all turbines to be around 0.5 t [33]. At this material intensity and with a REE content of around 30%, the Nd and Dy contents for this study are taken to be 29% (145.5 kg/MW) Nd and 1%

(4.5 kg/MW) Dy, representing mid-range estimates [32]. For geared-EM systems, which can use either PM or EM to start the generator, an equal share between the two is assumed.

Wind turbine installation has seen considerable growth throughout the past few years, with China's share at 46% overall in 2015, 56% on-shore and 50% off-shore in 2020, 42% on-shore and 80% off-shore in 2021, and 47% on-shore and 58% off-shore in 2022, as reported by the global wind energy council (GWEC) [34,35]. While China dominates the off-shore installations, countries within Europe are also increasing theirs, with the Netherlands accounting for between 4 and 25% of off-shore installations throughout the years [34]. The United States, on the other hand, has held steady at between 15 and 18% of the total with on-shore installations only [34,35]. Growth within the wind turbine energy industry has been record-setting in recent years and continues to show substantial CAGRs for the next several years. Annual on-shore installations have contributed between 35 and 87 GW of additional capacity per year over the past 10 years, with 2020 showing an almost 62% growth from the previous year [34]. The off-shore installation rate remained steady through most of the past decade, ranging from 1.6 to 6.9 GW per year through 2020, but in 2021, the additional capacity installed was 21.1 GW, a nearly 200% growth [34]. For additional information on other market growth predictions within wind energy, see Appendix B.

After some record-setting years, wind turbine growth is predicted to remain steady at a somewhat lower rate over the next decade. The GWEC predicts an on-shore growth rate of 6.1% and an off-shore rate of 8.3% [34]. Starting in 2020, with 837 GW on-shore and 57 GW off-shore capacity, the GWEC estimates annual capacity increases of 75 GW on-shore and 6 GW off-shore through 2026 [34].

These projections form the basis for calculating PM demand and the required amount of REO, presented in this study as the baseline demand. However, the market share of turbines using PM generators is expected to change through 2050; it is generally expected to increase for on-shore turbines and decrease for off-shore turbines, mostly due to optimization and implementation [36]. JRC predicts low and high growth scenarios for both turbine types, where low demand results in an increased market share for on-shore and decreased for off-shore [36]. A high-demand scenario suggests that the off-shore share will remain the same while on-shore demand will nearly double. For comparison, the baseline study assumes a 50% market share to demonstrate an average value between possible scenarios. Wind energy on/off-shore growth is summarized in Figure 3, broken down into Nd and Dy content over three demand scenarios based on the market share.

The JRC Science for Policy Report, which covers low- and high-demand scenarios, explains that these market shares were based on GHG emissions limitation goals predicated on the Paris Agreement, as well as innovations in the industry for low demand, while high demand is based on lower maximum temperature goals than the Paris Agreement [36]. Low-demand estimates expect on-shore turbines to increase from 32% to 40% by 2050, while off-shore decreases from 76% to 41% [36]. Their high-demand scenario predicts that on-shore increases from 32% in 2020 to 68% in 2050 and off-shore maintains an industry permanent magnet market share of 76% through 2050 [36]. As these are some of the primary factors driving the wind turbine market to increase, further analysis is presented through other predictions. The IEA lays out more aggressive growth in many industries, including wind turbines, within the next decade to achieve the NZE by 2050 goals. To reach these goals, the IEA suggests a total wind power capacity of over 3000 GW in 2030, resulting in a CAGR between 18 and 19% for the industry, which translates to a needed annual installation growth two to three times greater than the current predictions [37]. Figure 4 compares the resulting Nd_2O_3 and Dy_2O_3 demand between these two growth scenarios with the baseline analysis. As shown below, these goals have the potential to create substantial REE demand increases through 2030, should rare earth content and market share remain consistent.

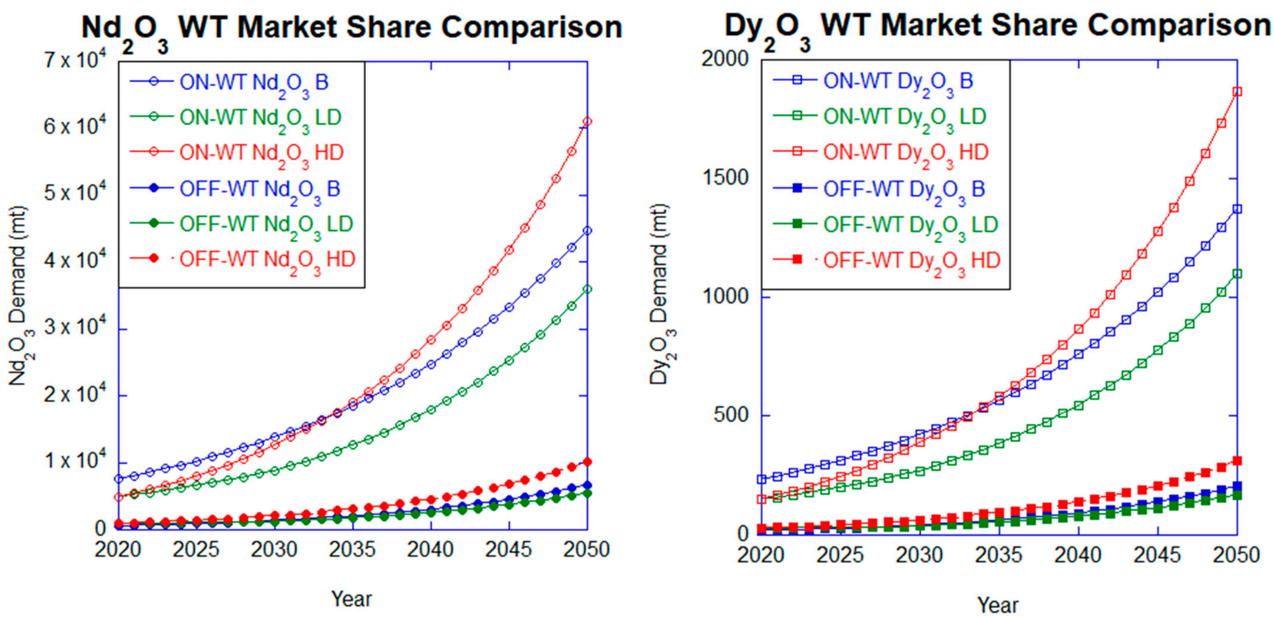

Figure 3. Nd_2O_3 and Dy_2O_3 demand through 2050 for on- and off-shore turbines with differing market share scenarios. B is this study's findings as a baseline scenario; LD and HD are low and high demands adapted from JRC [36], where LD shows increasing need for PMGs in on-shore and decreasing need for off-shore, and HD demonstrates a greater increase for on-shore and a maintained high market share for off-shore.

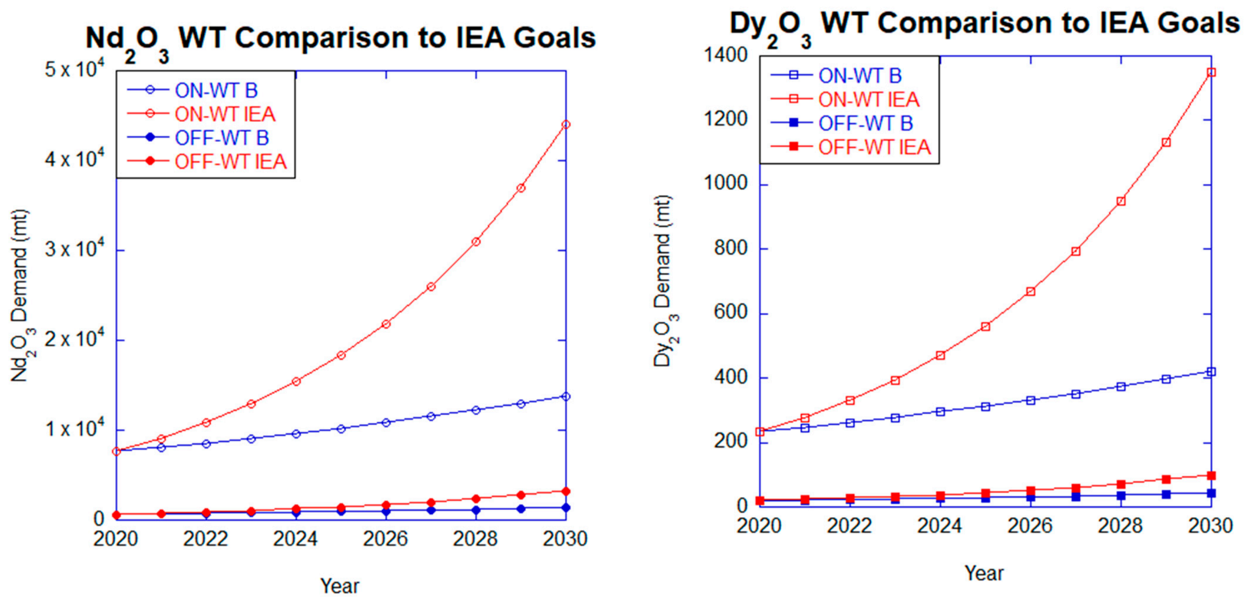

Figure 4. Nd_2O_3 and Dy_2O_3 metal demand for wind turbines through 2030, considering IEA predictions to reach NZE by 2050 goals.

4.2. Electric Vehicles

The existing market share among all automotive manufacturers illustrates the superiority of permanent magnet motors. Tesla, for instance, shifted from using alternating current (AC) induction motors to direct current (DC) permanent magnet motors for their drive trains in 2017 [18,38]. In 2022, Tesla was responsible for 2%–3% of the worldwide NdFeB magnet demand (excluding micromotors, sensors, and speakers) [39]. Other manufacturers are continuing to expand their electrification plans. In 2020, 90% of new EV registrations came from the top 20 global manufacturers, of which 18 have begun to widen their portfolios while scaling up production of light-duty EVs [40]. There were over twice as many light-duty EV models available in 2022 (500 models) than in 2018 [41]. Currently, NdPr motor technology is utilized in ~99% of all passenger EVs, representing a ~99% market share for NdPr permanent magnet motor solutions, a trend that should continue for the foreseeable future [18]. The availability of heavy-duty EVs is also broadening, with four major truck manufacturers indicating an all-electric future, according to the IEA in 2022 [42]. Collectively, the top three markets (China, Europe, US) have 500, 120, and 170 commercial bus and truck models available, respectively [41]. Supporting these plans, global consumer spending on EVs peaked at 383 billion USD in 2022, with governments contributing nearly 43 billion, bringing the total spending to ~425 billion USD. This was a 50% increase in total spending relative to 2021 [41].

EV sales increased significantly in 2020. Europe saw the highest growth, bringing their total to 3.2 million EVs, although China's EV fleet is still larger, totaling 4.5 million [42]. EV sales in the United States have continued to break records over the past few years compared to 2018, which represents the onset of increased demand for EVs [43]. For instance, 2021 sales in the United States exceeded 600,000 units, an estimated 75% increase from 2018 [44].

The global EV stock hit 10 million in 2020, which was a marked 43% increase from the previous year [44]. Two thirds of the new EV registrations and stock were battery electric vehicles (BEVs) [42]. As EVs become more popular, they can compete on a total cost-of-ownership basis in certain countries. Moreover, fiscal incentives, offered by some countries, have buffered EV purchases from the downturn in car markets [42]. These represent just a few of the many factors contributing to the huge uptick in EV sales in 2020. In 2022, new EV sales alone exceeded 10 million and are projected to increase an additional 36% in 2023, bringing the year-end sales total to 14 million EVs [41]. Three markets continue to dominate the EV market (in order of sales): China, Europe, and the United States [41]. Notably, China accounts for 60% of new EV sales and has over half of the EVs on the road today [41]. Europe saw a 15% growth in 2022, translating to a 20% EV market share, and the United States experienced 55% growth, or 8% of the market share [41]. Sales in India, Thailand, and Indonesia experienced 300% growth collectively, largely due to incentives and policy support schemes to encourage EV adoption by the public [41]. Sales through 2022 are broken down into these markets with the rest portrayed as "other" in Figure 5 (adapted from the IEA) [45].

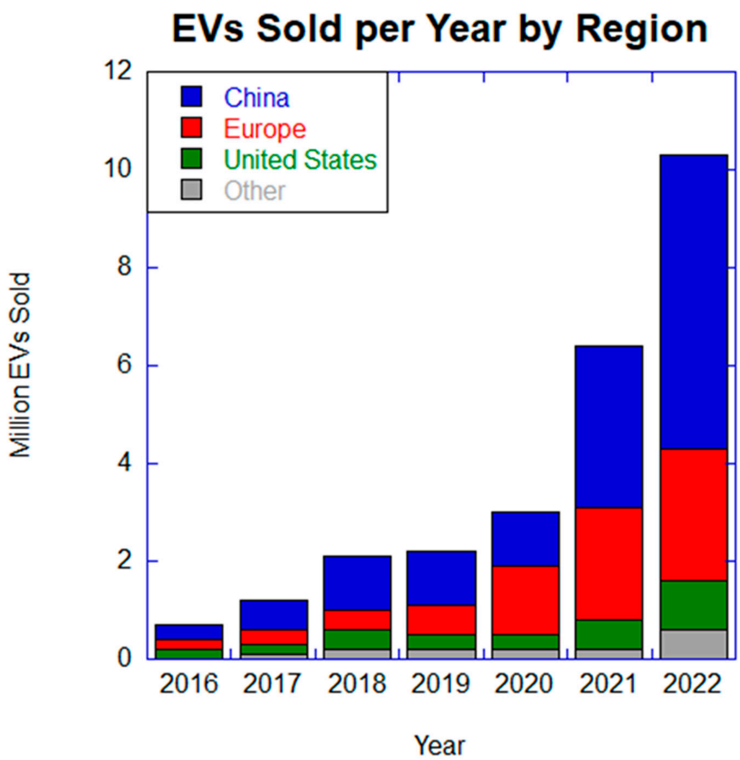

Figure 5. EVs sold per year as adapted from the IEA data [46], under Creative Commons license 4.0.

The baseline growth scenario in this analysis takes into account the aforementioned historical growth, along with other factors, including overall economic growth and climate incentives, in addition to EV turnover rates and the availability of REOs based on recent mining production. A vehicle turnover rate of 12 years gives a CAGR of 6%. Given the recent market data and predictions, this is unrealistically low. REO production from 2015 to 2022 (as reported by the USGS) saw annual growth varying from 2% to 20%, with a significant production increase of over 40% from 2017 to 2018; that same year also saw a substantial EV sales increase of over 60% [6–14]. Thus far, REO production has kept up with the overall REO demand across sectors; however, because of the projected growth in both the implementation of these technologies and in public demand, it is likely, according to Adamas Intelligence [47,48], that demand will overtake supply by as soon as 2030. Notably, the recent boost in EV sales (more than doubling from ~3 million in 2020 to ~6.5 million in 2021 and increasing over 50% from 2021 to 2022, with over 10 million units sold), makes the EV market a significant contributor to future REO shortages [45]. However, prior to this substantial increase, EV sales growth throughout the next decade was projected at anywhere between 4.5% and 24.7% [4,22]. Factoring in the replacement rate, recent sales, and REO availability, this study, therefore, sets the baseline CAGR at 9%.

The use of permanent magnets in vehicles is not limited to EVs. Today's light gasoline-powered vehicles already use rare earth permanent magnets for power steering, power door locks, power window lifts, cruise control, automatic mirror positioning, fluid pumps and sensors, electric brake actuators, and power seats, among many other uses. One study found that mid-class internal combustion engine vehicles utilize permanent magnets in over 30 separate applications [18], while other studies have found over 100 of these applications [22,49]. Some reference all of these PMs as NdFeB magnets, while others, based on a detailed analysis of four selected vehicles, list only a few functions (e.g., speakers) that incorporate NdFeB magnets, while the others use Fe or SmCo magnets [18,50]. As most of these (now standard) "accessories" are likely to carry over into EVs, their contribution to PM demand is effectively constant as declining gasoline/diesel passenger vehicles are offset by the corresponding increases in EV sales. In the former, the named applications represent a total NdFeB magnet mass of ~0.6 kg, aside from the engine [18]. The few select functions identified, namely, speakers, by a more detailed analysis were found to be as high as 0.114 kg [50]. However, the traction motor of a battery-powered EV contains an additional ~1.5 to 2.5 kg of NdFeB magnet. This number varies. It is sometimes difficult to discern whether the mass listed refers to PM or rare earth mass. Using the upper values, (including oxide-to-metal conversion and magnet manufacturing losses) the approximate demand for pure NdPr oxide is calculated at 40% of the final NdFeB magnet weight. Each new EV, thus, translates into a 1 kg increment to NdPr oxide demand [18,46,50,51]. Using an overall PM demand per vehicle of 2 kg results in a Dy oxide demand of 0.17 kg, representing 8% of the final weight of the NdFeB magnet [46,51].

As climate goals and incentives heavily influence this industry, other scenarios were included to provide a comparison to the baseline scenario given above. One market growth prediction expects EV sales to overtake sales of internal combustion engine (ICE) vehicles by 2047 as a result of these other factors [52]. The IEA outlook runs through the year 2030 with a few scenarios, including the stated policies scenario (STEPS) and the sustainable development scenario (SDS) [53]. STEPS accounts for limitations in growth alongside goals for each country, and SDS focuses closely on overall energy goals [54,55]. Limitations considered in STEPS include the market, infrastructure, and overall finances as they pertain to each country's pledged energy goals. STEPS projects annual EV sales by 2030 to be over 25 million, whereas SDS predicts over 46 million [48]. Bloomberg and Wood Mackenzie base their projections on economic trends. Bloomberg's economic transition scenario (ETS) states that 60% of new vehicle sales will be EVs, and Wood Mackenzie expects new EV sales in 2050 to reach 62 million [52,56]. Further future market growth information is available in Appendix B. Figure 6 represents a comparison between these scenarios and their associated demands on NdPr oxide and Dy oxide, along with this study's findings as a baseline. Notably, projections based on net zero emissions (NZE) goals suggest that new EV sales will account for 100% of sales somewhere between 2035 and 2038, which is not fully represented in this figure [53,56]. The CAGRs in Figure 6 are ~8% from Wood Mackenzie (WM), 9% corresponding to this study's baseline, ~13% based on Bloomberg's ETS, and 23% and 31% for the IEA scenarios (STEPS and SDS, respectively) [52,53,56].

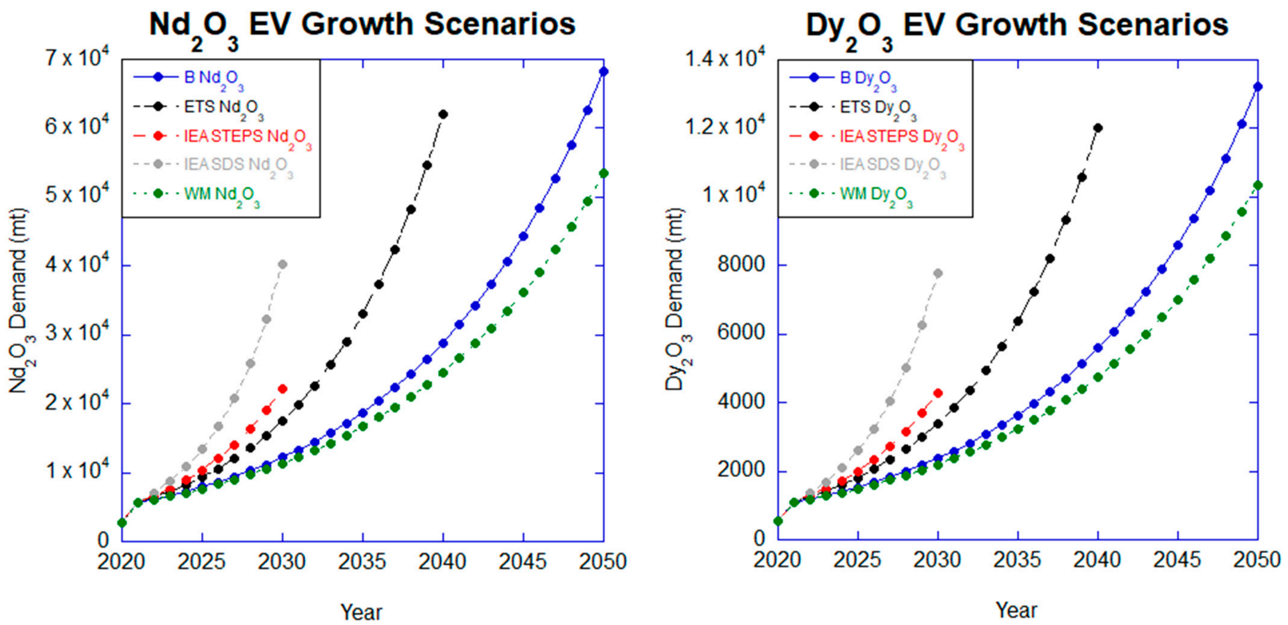

Figure 6. Nd_2O_3 and Dy_2O_3 demand based on EV growth scenarios. B—baseline demand in this study's findings. IEA STEPS—stated energy policies scenario. IEA SDS—sustainable development scenario, ETS—Bloomberg economic transition scenario, WM—Wood Mackenzie projection.

4.3. Electric Bicycles

EBs also contribute significantly to REE demand as a transportation sector. The material intensity is far less per unit than for EVs; for this study we use 0.2 kg as compared to 2 kg per EV unit [22,51]. Of the 0.2 kg, the material intensity for Nd is calculated at 30% of the magnet, or 0.06 kg per unit, while Dy is 4% of the magnet, or around 0.008 kg per unit [22,51]. While the material intensity is minimal compared to other industries, the overall demand is still impactful given recent global trends in EB sales. As EBs are not generally considered a necessity in terms of new technology implementation for the sake of climate change in comparison to other sectors, sales projections are based more on the social and economic implications. Past predictions showed low growths, some as low as 2.95% [22], but similar to EVs, recent sales increases have some firms forecasting CAGRs through 2030 to be anywhere between 5% and over 15% [57–61]. As with the EV analysis, REE production was considered alongside other predictions of some markets reaching saturation, as well as the top sales market in China showing predictions of slowing down [57,58]. The resulting baseline CAGR is estimated at 5%, taking into consideration further predictions that by 2050, the overall EB fleet may be around 2 billion with around 80 million sales per year [58], as reported in the Electric Bike Worldwide Report [59,60]. This figure of 5% is also supported by another firm, predicting a CAGR of 5.39% through 2029, which considers varying markets as well as different styles of EBs, specifically propulsion [57]. This baseline is shown below in Figure 7, showing Nd and Dy demand reaching over 10,000 and 1000 metric tons, respectively, through 2050. For comparison, Figure 8 considers varying predictions through 2030, where Inkwood Research predicts 9.84% and Markets and Markets forecasts 8.4% [57,61]. A low demand scenario was based on previous studies that found a CAGR around 2.95% up until 2020, which is considered the low demand for this study, as presently, the predictions are no longer below 5%.

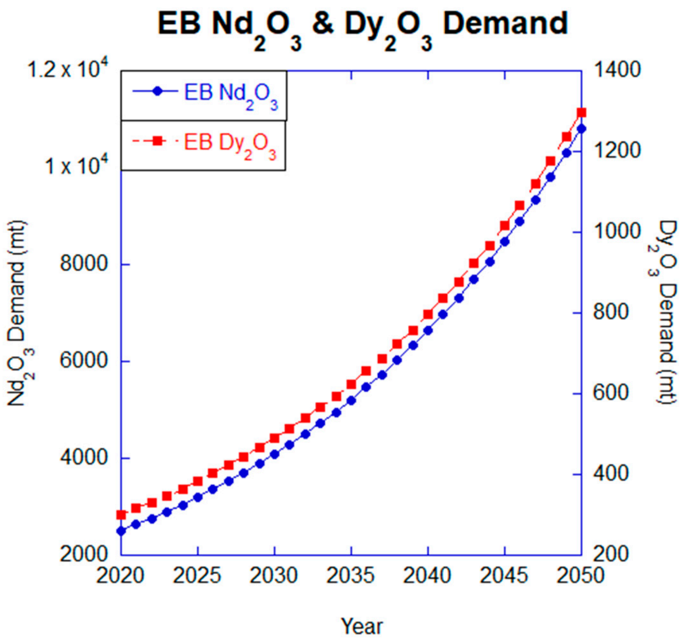

Figure 7. Nd_2O_3 and Dy_2O_3 demand, where Nd reaches an annual demand of 10,800 mt by 2050 and Dy reaches an annual demand of 1300 mt when considering a conservative 5% CAGR through 2050.

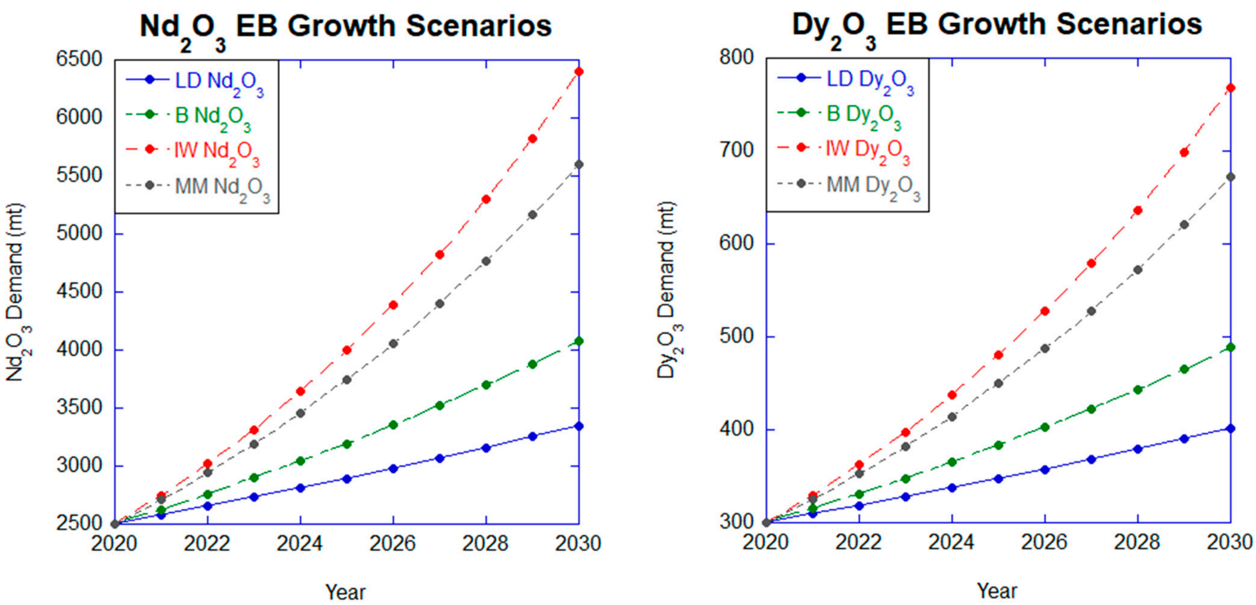

Figure 8. Demand for Nd_2O_3 and Dy_2O_3 through 2030 based on various CAGR projections. LD is a low demand scenario at 3%, B is the baseline 5% this study considers, IW is a 9.84% projection by Inkwood Research, and Markets and Markets predicts an 8.4% CAGR.

4.4. Robots

An overlooked sector that is heavily dependent on REE magnets is robotics. This industry varies from industrial grade robotics to personal consumer robotics, and NdFeB magnets are a critical element of both, mostly used in sensors, actuators, internal motors, and to ease the movement of parts within. According to the International Federation of Robotics (IFR), industrial robot sales reached 383,500 units in 2020 with a CAGR of 9% for the period 2015–2020 (or 11% for 2016–2021), with higher rates forecast [62,63]. Industrial robots (IR) are employed in industrial automation, such as those utilized in vehicle manufacturing, and they may be either in-place and fully stationary or have mobile capabilities, often programmable. An additional 131,800 professional service class robots, which include medical and cleaning robots, for example, were added in 2020 for use in the non-manufacturing and manufacturing sectors, representing a 14% increase in this robotic class [62]. The current CAGR forecasts reported by IFR lie around 10% and are predicted to drop to 7% before 2025 [63]. Between this and the recent growth varying between the aforementioned 9 and 11%, this study assumes a CAGR of 10% [62,63]. The NdFeB content for an industrial robot is estimated to be ~15 kg per robot, which translates in our analysis to approximately 6 kg of NdPr oxide and 0.19 kg Dy oxide, considering conversion losses [18]. Peak Resources also reports relevant market shares for industrial robots to be around 50% [18]. At a reported 50% market share, sales in 2020 result in NdPr oxide and Dy oxide demands of 1213 and 37.50 metric tons, respectively. By 2050, the annual NdPr oxide and Dy oxide demands are predicted to reach 21,174 and 655 metric tons, respectively, should the industry continue growing as it has been.

In addition, according to the IFR, sales in the private sector, represented as service robots (SR) in this study, reached 19 million robotic solutions in 2020; these robots account for personal use, including mobility assistance robots and cleaning devices [62,63]. As the robots in this sector are much smaller than others, the magnet content is less, although the estimated market share is ~70% [18]. The NdFeB content of these robots is estimated at 0.6 kg per unit [18]. NdPr and Dy oxide weight is then calculated to be around 0.24 kg and 0.01 kg, respectively. Factoring in the 2020 sales, the total demand when accounting for the stated 70% market share is 323 metric tons of NdPr oxide and 10 metric tons of Dy oxide. For this sector of robots, a 7.5% CAGR is assumed when considering the recent and forecasted growth from the IFR, resulting in a 2050 demand of 2826 tons of NdPr oxide and 87 of Dy oxide [62,63]. This growth and demand can be seen for the private service sector and industrial robotics sector below in Figure 9.

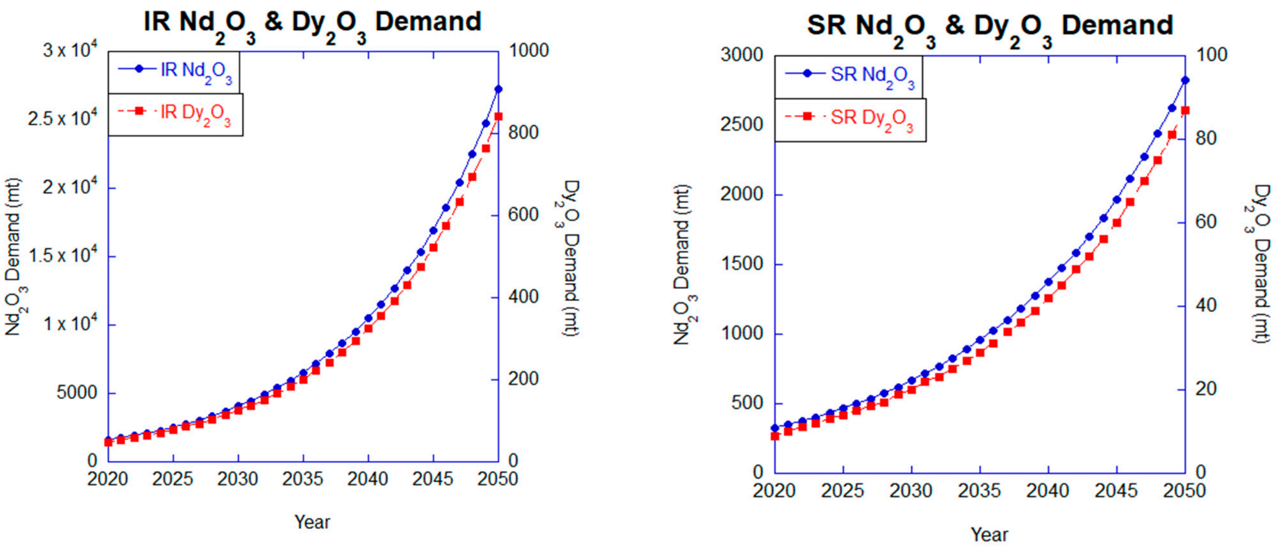

Figure 9. Nd_2O_3 and Dy_2O_3 demand for industrial (IR) and service robots (SR) based on IFR expected growths.

4.5. Consumer Electronics

The consumer electronics industry relies heavily on permanent magnets for a multitude of products, including hard disk drives, motors for printers and scanners, and a variety of other products, including appliances and fan motors in loudspeakers and computers, to name a few [1]. With the increasing demand for cloud computing, which requires centers where data can be stored, hard disk drives contribute to REE demand [1]. The reported PC shipments in 2020, according to Statista, totaled 214 million units globally, increasing to 328 million units in 2021 [64]. Other growth and demand for magnets throughout this industry can be attributed not only to growing populations but also to the development of certain regions, such as the Asia Pacific region [1,65].

For the class of magnet in consumer electronics, the NdPr content is 28.6 wt.% and the Dy content 1.4 wt.% [4]. Tablets, notebooks, and hard drives are estimated to have 0.06 g Dy content and 1 gm Nd content, the exception being HDDs with 2 gm per unit [66]. Overall, consumer electronics are estimated to consume 29.4% of global NdFeB magnet production, i.e., 35.1 kt in 2020, with the potential to consume 8.7% or 65.4 kt in 2050 [4]. This projected growth results in a 2% global CAGR, considered a high-demand scenario at the time of publication; however, other predictions and metrics show it may be slightly higher or lower than the baseline 2% growth [4]. High- and low-demand scenarios were based on general population growth projections, as well as economic circumstances leading to greater development across certain parts of the world, influencing a greater demand for GCE, as shown in Figure 10. For instance, developing markets, such as the aforementioned Asia Pacific region, contributed significantly to a higher CAGR through 2028, between 5% and 15.6% [65,67,68]. The high-demand scenario in this study was set at 3.5% to account for the longer term, whereas low demand is set to 1%, closely following population and GDP growth predictions [69,70].

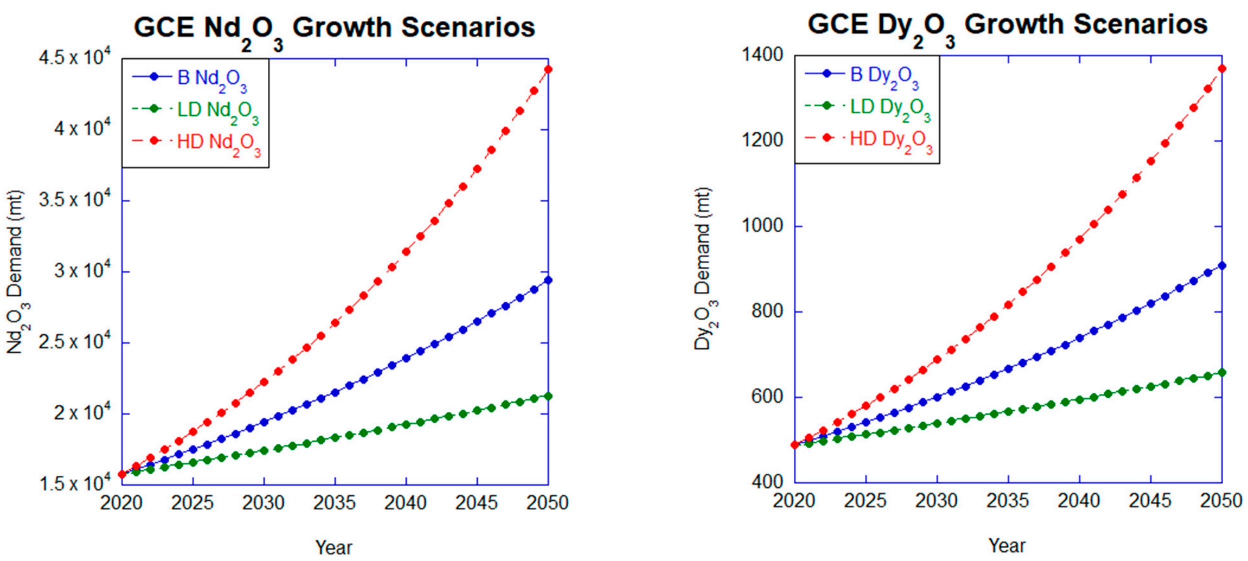

Figure 10. Projected Nd_2O_3 and Dy_2O_3 demand with "B" as baseline scenario, "LD" as low-demand, and "HD" as high-demand.

4.6. Industrial and Non-Drivetrain Motors

In 2020, industrial motors constituted the second-largest source of total U.S. demand for NdFeB magnets at 30%, surpassed only by consumer electronics at 45% [25]. Globally, industrial motors dominated at 30%, followed by consumer electronics [4]. With the uptick in wind turbines (off-shore specifically) and EVs/EBs dominating the market share projections through 2050, industrial motors and non-drivetrain motors represent a smaller share, although their NdFeB magnet consumption will continue to increase. For instance, in 2020, non-drivetrain motors in vehicles used 9.4 kt of NdFeB magnets, representing 7.9% of the market share, whereas projections for 2050 foresee an increase by over a factor of three (29.3 kt) with a market share of only 3.9% [25].

Industrial (permanent magnet) motors can be DC or AC and are further classified as asynchronous/synchronous [71]. Industrial motors can be used for any process that requires power or motion. Non-drivetrain motors in vehicles consist of any motor that is not contributing to the motion of the vehicle [72]. Examples of these include the motors found in power windows, windshield wipers, power seats, power mirrors, etc. [50]. NdFeB magnets allow for motor miniaturization, which is ideal for many automotive applications.

Due to the limited availability of information on industrial motor/non-drivetrain motors in vehicles, we adopted a CAGR of 2.9 and 3.9, respectively, calculated from 2020 to

2050, and reference values of 36.0 and 9.4 kt, respectively, given the total NdFeB magnet weight, from the DOE [4]. Figure 11 below is the resulting Nd_2O_3 and Dy_2O_3 demand based on these figures. Further refinement remained consistent with the analysis in other sections. The information on high/low growth scenarios was unavailable and, therefore, not included in these sectors.

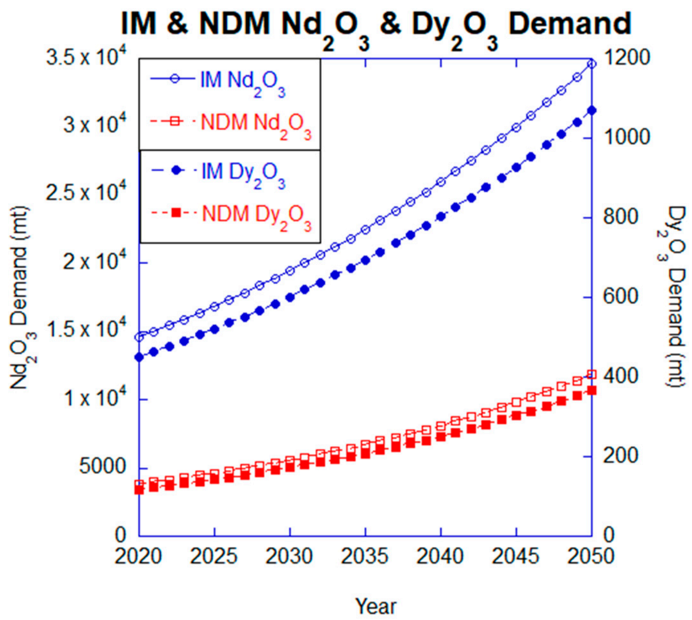

Figure 11. Nd_2O_3 and Dy_2O_3 demand from 2020 through 2050 in the industrial motors (IM) and non-drivetrain motors (NDM) industries.

5. Discussion

5.1. NdFeB Demand Growth across Sectors

With total rare earth oxide (TREO) production in 2020 estimated at 240,000 tons, the NdPr oxide amount of 46,000 tons is consistent with an overall ore fraction of ~ 19% [11,12]. The sectors evaluated include wind turbines (on- and off-shore); EVs, EBs, and scooters; global cell phones and consumer electronics; industrial and service robots; and industrial motors and non-drivetrain motors in automobiles. The cumulative Nd_2O_3 demand across these sectors is 49,437 tons, within 10% of the USGS estimate for TREO in 2020 [11]. The fastest growth areas are the permanent magnets in direct drive wind turbines, followed by industrial robots and consumer electronics. Our initial analyses used a compounded annual growth rate (CAGR) for on-shore wind of 6.1% and off-shore of 8.3% and a 7.5–10% CAGR across all robotic sectors [34,62,63]. While wind is considered to be one of the dominating drivers for Nd oxide demand, with an average 9% CAGR among EVs, the EV industry dominates both Nd and Dy oxide demand through 2050 at the current material intensities. A summary graph across all sectors is below in Figure 12, where EVs dominate demand by 2050, representing 22% of the NdPr oxide demand and 59% of Dy oxide demand throughout the period from 2020 through 2050, summarized below in Table 2.

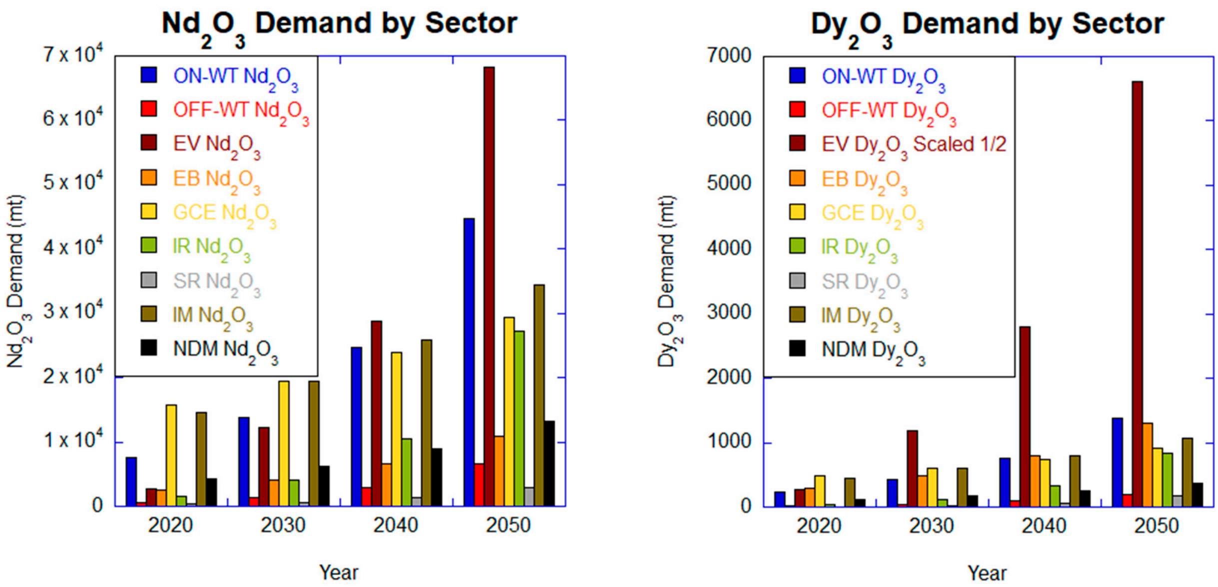

Figure 12. Summary graphs by decade for Nd_2O_3 and Dy_2O_3 demand.

Table 2. Nd_2O_3 and Dy_2O_3 market shares by industry by total demand from 2020 through 2050.

Nd Market	% Share	Dy Market	% Share
On-shore	18%	On-shore	8%
Off-shore	2%	Off-shore	1%
EV	21%	EV	59%
EB	5%	EB	8%
GCE	19%	GCE	8%
IR	8%	IR	3%
SR	1%	SR	<1%
IM	20%	IM	9%
NDM	6%	NDM	3%

5.2. Dysprosium Considerations

REE permanent magnets contain approximately 31–32 wt% REEs (mainly 21–31 wt% (NdPr), 0–10 wt % Dy, plus small amounts of Gd and Tb) [5]. Dy in the larger weight percentages from 4 to 5% used in wind turbines proves useful in resisting demagnetization at the temperatures of up to 150 °C commonly present in the generators [73]. This extends to EVs, as they experience substantial demagnetization stress along the magnets leading and trailing edges, which is alleviated by using up to 11% Dy [73].

Arnold Magnetic Technologies reported in 2014 that, in order for Dy supply and demand to be balanced with the production of Dy REO, given that NeFeB magnets contain an average of 32% rare earth, Dy content within NdFeB magnets should not exceed 2.2% of the magnet alloy [73]. Notably, Dy as a produced mined ore represents 1.5% of all REE mined ores and 2.8% of the available REEs on earth but is far more difficult to mine than other ores since higher abundances are found in ores not frequently mined [73]. Nd is more abundant, as it comprises 15% of all mined ores, with an 18.8% availability when compared to all REEs [73]. Nd content may be reduced by increasing Pr with only small reductions in performance (field strength and energy product). Pr represents 4 to 5% of all REEs in these ores [73].

5.3. Rare Earth Value

The rare earths used for permanent magnets, namely, Nd, Pr, Dy, and Tb, make up a quarter of the overall rare earths production volume, but their market value lies between 80 and 90% of the rare earths total, according to Roskill [15,17].

China continues to dominate REE mine production (see Figure 1), while simultaneously, as the largest producer of permanent magnets, accounting for over 90% of the market share [17]. It considers the rare earths value chain highly strategic to the acquisition of a growing market share in important downstream industrial sectors [17].

The potential this creates for supply chain disruptions was amply illustrated by the new Chinese "Export Control Law" of 1 December 2020 [17]. The largest rare earths mining and processing companies are state-owned and are the recipients of numerous direct and indirect state subsidies. The concentration of these rare earths supply chains, coupled with the exponential growth in the high-performance PM demand in the car and renewables industries especially, creates the ideal conditions for supply chain disruptions [17]. Despite the permanent magnet market being a relatively small piece of the market share, its downstream leverage is vast. In addition, rare earths have strategic importance for defense applications. It is, therefore, critical to create a circular economy around rare earths by developing and promoting their recycling and substitution [17]. Exploration, extraction, processing, separation, metal manufacture, alloy production, magnet making, and motor design must also be further developed [17].

5.4. Other Demand Considerations and REE Recycling

While the current state of the REE market shows that mining production is capable of keeping up with demand, REEs are not an infinite resource, and great possibilities for bottlenecks exist, despite the fact that current global reserves amount to 130 million metric tons [74]. By 2050, the total Nd and Dy demand alone across the sectors considered here will total roughly 280,000 tons. The most recent report from the USGS shows total REE production in 2022 to be nearly 300,000 tons, as demonstrated in Figure 1. It is important to note that this considers all mined REEs. For example, estimates have shown that Nd_2O_3 accounts for 18% of REO production, amounting to roughly 34,000 tons in 2018 [15]. This study predicts that by 2025, the Nd_2O_3 demand will be over twice that amount, at over 71,000 tons. The possible problems, aside from mining/production and currently available reserves, and specifically the limited quantity of Nd and Dy within those reserves, center on global policy and economics.

Consulting firms have discussed the role of policy in mining activities and the capability to allow for production to keep up with demand [75]. To combat supply shortages due to the constraints in supply and value, many industries are working towards a future using fewer NdFeB magnets. The wind turbine scenario previously discussed accounts for the potential decrease in NdFeB market share within the industry as turbine drives are optimized to reduce the NdFeB content that the current state of the industry requires. Furthermore, beyond the use of REOs within these products, the final product waste production common in manufacturing is generally expected to increase alongside the regular demand [76]. Consequently, recycling of the final product waste and end-of-life waste becomes essential to any discussion of supply and demand.

For recycling to have an impact on demand requires numerous important inputs. Not the least of these is the sufficient accumulation of recyclable material. The duration of the "in-use" phase, i.e., the service stage of the product life cycle, determines the minimum time required for the development of a circular system, while accelerating growth imposes a delay before sufficient quantities are built up. For example, a steady-state system with a 10-year vehicle service life and without a preceding growth phase would require 10 years of new magnet supply integration before any recycled material would be available for reuse. However, a 10% CAGR would mean that the quantity of NdFeB magnets made available for recycling in any given year would be only 38% of that required by the new, larger demand. Though this is a simplistic calculation, the current US mandate (via EPA vehicle emissions regulation) that more than two-thirds of all new vehicle sales should be EVs by 2032 [77], and similar mandates in Europe and China give weight to the estimate [78,79]. There will not be sufficient NdFeB magnet quantities accumulated over currently begun service phases to cover the demand a decade in the future.

Nearly as important as the recyclable material itself is the infrastructure required to process it. The recycling of NdFeB magnets is difficult. It is critically important to research and develop recycling methods to meet the challenge at the necessary scale, and, thus, to make recycling economically viable. However, the policy initiatives and substantial funding for this vital step are currently lacking.

Despite the limited potential of NdFeB recycling to offset demand near-term, the perennial lesson, as learned with other resources, is that the development and implementation of recycling should and must occur concurrently with original implementation. A prime example is seen with lead acid batteries. Recycling of these batteries has been practiced since the 1920s, but on an artisanal basis; though it was variably and poorly executed and often environmentally damaging [80] and had severe health consequences, the same methods are still in use in many parts of the world [81]. Only since the 2000s has the recycling of lead acid batteries reached a level of 98% [82]. In the case of NdFeB magnets, the recovery of the REE metals is technically more challenging, and while it is feasible, it is not economical at present [83]. Either policy changes and/or new processing technology, in addition to significant financial investment, will be required to overcome the latter barrier to implementation.

6. Conclusions

NdFeB permanent magnets are used in a multitude of industries, especially as electric motors for electric and hybrid vehicles and wind turbines, and for many other functions [18]. For example, highly efficient REE permanent magnet traction motors are used in 95% of EVs to provide increased driving range. The REEs used in these motors are also strategically used in other high-tech sectors, including electronics and robotics, communication devices, aerospace, and defense applications and within renewable energy generation [17]. Demand across all sectors considered in this study shows considerable increases through 2050, due to multiple factors including economic and population growth as well as the implementation of new policies.

Robotics and consumer electronics in particular contribute substantially to NdFeB permanent magnet demand. Industrial and professional service robot sales in 2020 reached 383,500 and 131,800 units, respectively, with each unit requiring 2.5 times the NdFeB weight of an EV [9,10]. Meanwhile, it was estimated that consumer electronics account for approximately a third of all NdFeB magnet use [22]. A full accounting of Nd and Dy demand must include these sectors as well.

Predicting the timing of future REE shortfalls is extremely difficult, given that the sourcing of the materials is subject to considerable natural, economic, and political uncertainties. The USGS estimates the worldwide REE reserves at 130 million tons, which indicates that rare earths are quite abundant in the earth's crust; however, only a fraction of it can be mined [14]. This is the distinction between reserves and resources in that resources are accessible and extractable. An accurate prediction would require future values for the latter, which are not available and evolve according to the mentioned factors and, most of all, the technological advances in the mining industry. REEs used in permanent magnets, specifically Nd, Pr, Dy, and Tb, are found in mineral deposits that vary significantly in their composition, making predictions of each constituent's relative amount within a deposit even more difficult to accurately quantify or estimate. This uncertainty further serves to highlight the extreme urgency of critical recycling infrastructure, research into possible substitutions and exploratory efforts to broaden the sourcing and processing of rare earths.

Information pertaining to the availability of REEs, particularly NdPr and Dy, sufficient to cover the substantial and rapidly growing demands from these broad industrial sectors is manifestly important. Projections of the future demand for these strategically vital materials must incorporate a myriad of factors including predicted growth in the various sectors, economic and political concerns and forecasts, climate-related policy, and many other variables, not least, the considerations related to China's current near-monopoly of the rare earth supply chain. In this paper, we have attempted to use the most pertinent and up-to-date information available to arrive at predictions indicating probable future shortages in these rare earths and their associated permanent magnet applications that may have significant national security impacts.

Author Contributions: Conceptualization, R.L.V.W.; methodology, R.L.V.W. and J.W.H.II; validation, J.W.H.II; formal analysis, J.W.H.II; investigation, J.W.H.II and R.L.V.W.; resources, R.L.V.W.; data curation, J.W.H.II; writing—original draft preparation, R.L.V.W. and J.W.H.II; writing—review and editing, J.W.H.II; visualization, J.W.H.II; supervision, R.L.V.W.; project administration, R.L.V.W.; funding acquisition, R.L.V.W. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available in the article and cited references.

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Appendix A

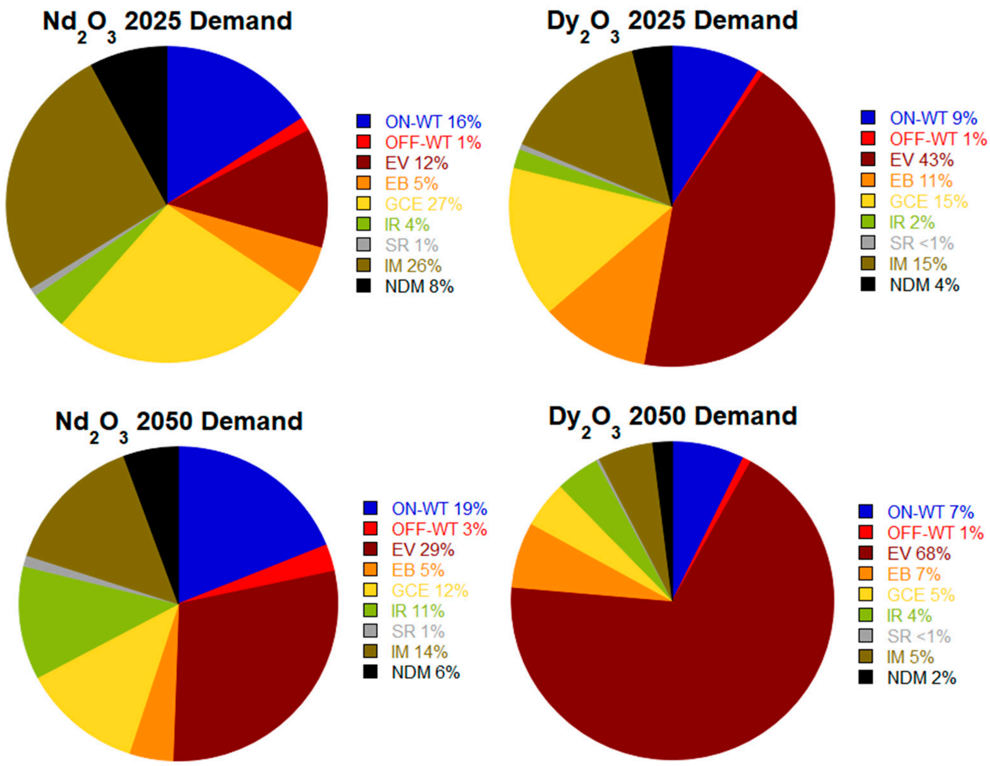

Figure A1. Share of end-use sectors for Nd (**left**) and Dy (**right**) for 2025 and 2050 based on current growth projections. Abbreviations: ON-WT—on-shore wind turbines, OFF-WT—off-shore wind turbines, EV—electric vehicles, EB—electric bicycles, GCE—global consumer electronics, IR—industrial robots, SR—service robots, IM—industrial motors, NDM—non-drivetrain motors.

Table A1. Summary of factors used in Nd and Dy demand calculations.

Industry	NdFeB Content	Nd Content	Dy Content	Losses	Market Share
On-shore Wind Turbines	500 ton/GW, 30% Nd and Dy	97%	3%	1.39	50% (Baseline) 32%−40% by 2050 (Low demand) [a] 32% to 68% (High demand) [a]
Off-shore Wind Turbines	500 ton/GW, 30% Nd and Dy	97%	3%	1.39	50% (Baseline) 76% to 41% (Low Demand) [a] 76% (High Demand) [a]
Electric Vehicles	2 kg/EV [b]	31% [b]	6% [b]	1.39	100%
Electric Bicycles	0.2 kg/EB [c]	30% [b]	3% [b]	1.39	100% Nd, 90% Dy [c]
Global Consumer Electronics	N/A (Given in tons of NdFeB, 30% is Nd and Dy)	97%	3%	1.39	100%
Industrial Robots	15 kg/unit, 30% is Nd and Dy [d]	97%	3%	1.39	50% [d]
Service Robots	0.6 kg/unit [d], 30% is Nd and Dy	97%	3%	1.39	70% [d]
Industrial Motors	N/A (Given in tons of NdFeB)	97%	3%	1.39	100%
Non-drivetrain Motors	N/A (Given in tons of NdFeB)	97%	3%	1.39	100%

Notes: [a] JRC [32], [b] Bauer and RAND [22,51], [c] RAND [22], [d] Peak Resources [18].

Appendix B

Market Growth

Bloomberg's Energy Outlook 2017 predicts that by 2040, on-shore wind levelized costs will fall 47% as a result of less expensive, more efficient turbines and advanced operating expense regimes [18]. Off-shore wind costs, meanwhile, will benefit from a competitive market and economies of scale to shrink an astonishing 71% over the same time [18].

According to Bloomberg, by 2040, 10.2 trillion USD will be invested in new power generation capacity worldwide [18]. Of this investment, the lion's share of about 7.4 trillion USD will go into renewables, 2.8 trillion USD to solar energy and 3.3 trillion USD to wind [18]. Investment in renewable energy will grow to about 400 billion USD per year, corresponding to an average increase of 2%–3% a year. Investment in wind (averaging 3.4% annually) will increase faster than solar (2.3%) [18]. By 2040, the combined electricity generation worldwide will be 34% for wind and solar, representing 48% of the installed capacity, compared to 5 and 12% today (respectively) [18]. The installed solar capacity will undergo a factor of 14 increase, wind a factor of 4. The GWEC predicts an even larger 5-fold increase in the latter [18,34].

EV demand is subject to more factors than wind energy, where investment translates into wind turbines, one of these being consumer acceptance. EVs merely displace the energy source; until renewables match the energy consumption represented by ~135 billion gallons of gasoline and ~38 billion gallons of diesel, they will only push fossil-based electrical production [84]. Though the benefits of a vastly simpler energy conversion system and zero (local) emissions are tangible economic gains, consumer acceptance may be slow, particularly until charging locations exceed the number of gas stations, at approximately 125,000 [18]. Over the last decade, EV sales, including those of the Chevy Bolt, Nissan Leaf and Tesla models, have received critical support in the form of government subsidies, which largely offset price differentials to the gasoline equivalents. However, experts believe that these subsidies are unsustainable as sales reach millions.

Perhaps the better indicator are the actions of vehicle manufacturers, who have committed billions of USD to the production of new models [18]. As mentioned, more than 90% of these vehicles will probably feature permanent magnet motors. Announcements made by Hyundai-Kia, GM, the BMW Group, Honda, the VW Group, Daimler, Nissan, BYD, Ford, Toyota, the Porsche Infinity Motor Company, and Volvo all support this claim [18]. Several of these companies have announced plans for their own battery "giga-factory".

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