Rare Earth Materials and their Impact on the Future of Electric Motors

By Ram Subramanian, Dr. Matthew Younkins, Dr. Zhiqian Chen and Paul Van Heyningen

Tula Technology

Introduction

Annual increases in global atmospheric temperature, with increasingly severe weather events such as flooding, drought, wildfires, and hurricanes, point to marked changes in climate over the last 20 years. Figure 1 shows atmospheric CO_2 (a greenhouse gas or GHG) levels for a few millennia. The consensus among the world's foremost climate scientists is that the most recent increase in atmospheric CO_2 and other greenhouse gases, is a man-made phenomenon. To combat and reverse the negative effects of GHG driven climate change, governments around the world are looking at ways to dramatically reduce GHG emissions through new regulations. The Paris Agreement on climate change was adopted by 196 countries with a goal to limit global warming to below 2 degrees, preferably to 1.5 degrees Celsius[1]. Given that more than one-fifth of global CO_2 emissions are due to fossil fuels (high carbon fuels) used in the transportation sector there is a concerted effort towards vehicle electrification to reduce the tank to wheel emissions[2]. However, vehicle electrification is an effective solution only when the electricity generated to charge vehicles comes from clean renewable sources like solar, hydroelectric, wind or nuclear and not from burning fossil fuels. Over 40% of energy-related CO_2 emissions today are due to the burning of fossil fuels for electricity generation[3]. To make a significant reduction in CO_2 emissions towards a carbon-neutral future, it is important that the world see an exponential increase in both electric vehicles (EVs) and the clean electricity that powers them for decades to come. Consequently, the global demand for electric motors, generators and batteries will expand in lockstep with increased EVs. It is, therefore, important to understand some of the key technical differences among motor types, and the implications of those differences.

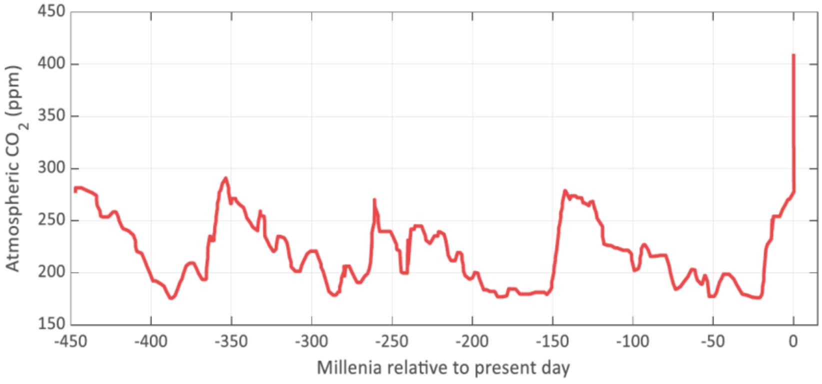

Figure 1: Atmospheric CO_2 levels through the ages

Permanent Magnet Motors

Electric motors and generators can be broadly classified based on their magnetic field excitation and internal construction as induction motors, permanent magnet (PM) motors and reluctance motors, including wound-rotor (WRM), externally excited synchronous motors (EESM) as well. Induction traction motors were used in the past in EVs (e.g., General Motors EV1 and Tesla Model S) for their robustness.

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[1] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[2] https://ourworldindata.org/co2-emissions-from-transport

[3] https://www.world-nuclear.org/information-library/energy-and-the-environment/carbon-dioxide-emissions-from-electricity.aspx

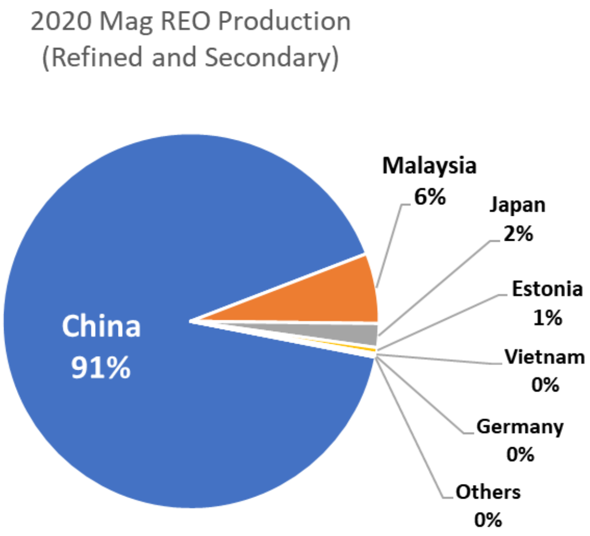

Figure 2: Magnet Rare Earth Oxide Production by Country

Today, over 92% of EVs use PM electric motors because of their efficiency and power-density[4], as do many of the world's turbines. In fact, the global transportation and wind power generation share of permanent magnet use is one-third today and rapidly rising towards half of all PM use by 2030 as the world moves towards carbon-neutrality[5].

PMs are made of rare earth (RE) materials and increasing demand for PMs means increasing demand for RE metals. Economically recoverable sources of RE metals are concentrated in only a few places on earth, with China supplying 91% of the global refined primary and secondary rare-earth oxides (REOs) from which RE metals are extracted (Figure 2). This poses challenges in demand management, supply-chain management, price volatility, technology, policy, and environmental issues in mining, processing, and production of RE metals. Given these challenges and with the current global semiconductor chip shortage providing a cautionary tale of constrained supply, more companies are exploring RE-free magnet motors. Motor designs that favor more reluctance torque than magnetic torque to reduce or, better yet, eliminate RE usage are being considered today.

Rare Earth Elements

Rare earth elements are the Lanthanide series on the Periodic Table and include yttrium and scandium. They are not rare in nature, but rather are rarely concentrated in economically significant amounts for extraction and processing. They are used in hundreds of applications in tiny amounts but collectively fall into a few end-use categories – battery alloys, catalysts, ceramics, pigments, glass polishing powders, glazes, metal alloys, permanent magnets, phosphors, and others. According to Adamas

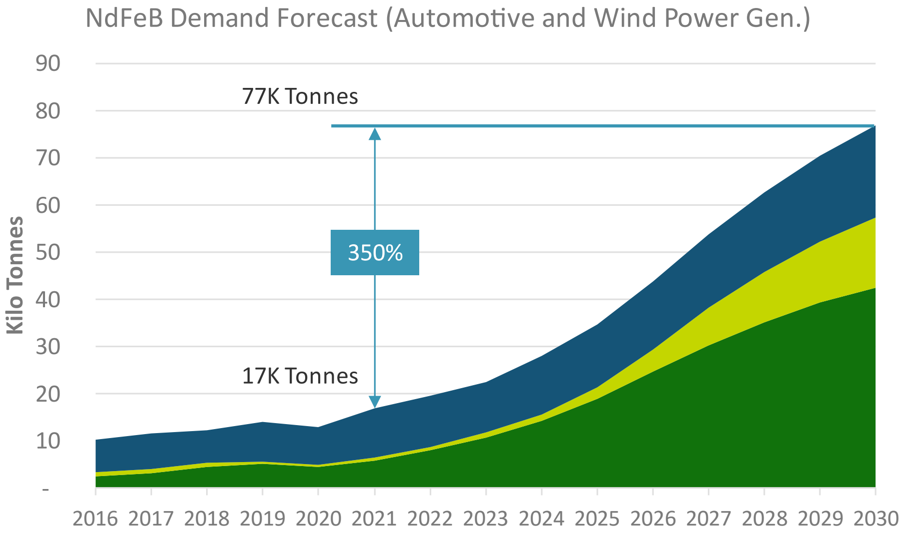

Figure 3: Global NdFeB demand forecast for automotive traction and wind power generation)

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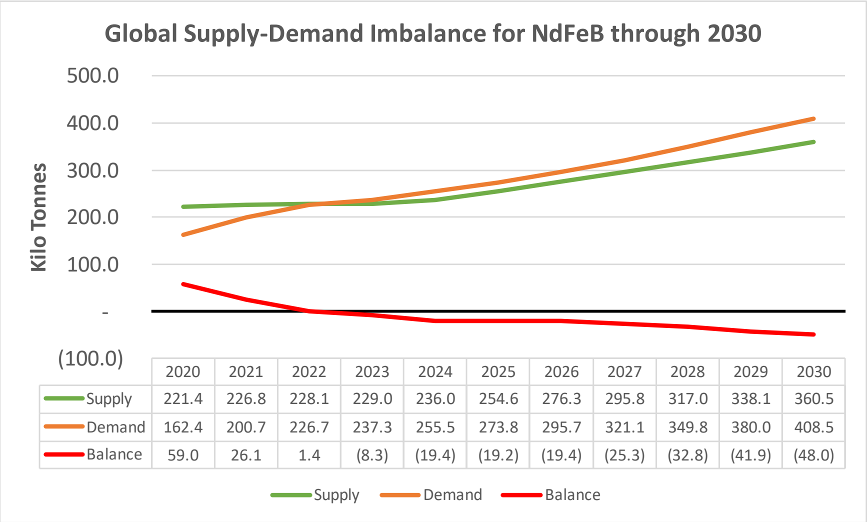
[4] https://www.adamasintel.com/pmsm-market-share-rising-in-face-of-higher-ree-prices/

[5] https://www.adamasintel.com/report/rare-earth-magnet-market-outlook-to-2030/

Intelligence Rare Earth Magnet Market Outlook 2020 report, permanent magnets and catalysts were collectively responsible for over 60% of global REO consumption by volume in 2019. However, by value, PMs alone were responsible for about ***90% of the total,*** and this share is poised to expand further as demand and prices of rare-earth elements continue to rise.

Most of the PMs used in EVs and wind turbines are primarily made of NdFeB (Neodymium-iron-boron) alloy as this is the strongest type of PM material commercially available today in terms of maximum "energy product" (magnetic flux output per unit volume). Motors made with NdFeB based magnets are usually the most efficient. Dysprosium (Dy) is added to the alloy to maintain its magnetic properties at high temperatures, a common occurrence with high wattage power-dense motors used in EVs and high-powered generators. From the global demand forecasts for NdFeB for passenger and commercial EVs and for wind generation shown in Figure 3, the world is looking at a 450% increase in demand by 2030 from today!



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Supply	221.4	226.8	228.1	229.0	236.0	254.6	276.3	295.8	317.0	338.1	360.5
Demand	162.4	200.7	226.7	237.3	255.5	273.8	295.7	321.1	349.8	380.0	408.5
Balance	59.0	26.1	1.4	(8.3)	(19.4)	(19.2)	(19.4)	(25.3)	(32.8)	(41.9)	(48.0)

Figure 4: Imbalance in global supply-demand for NdFeB alloys and powders

Although the strategy of using NdFeB based PM motors is effective in producing efficiency gains for some of the roughly 7 million electric vehicles in use today, it is not likely to be an adequate solution for a 1.4-billion-unit automotive fleet[6]. It is not clear that mining and recycling can produce the RE metals required for an EV fleet two hundred times larger than the current one. By 2030, an annual shortage of 48,000 tonnes is forecast for NdFeB (Figure 4) and an additional $1.6 billion worth of Nd and Pr oxide demand will go unmet, along with $840 million of Dy oxide.

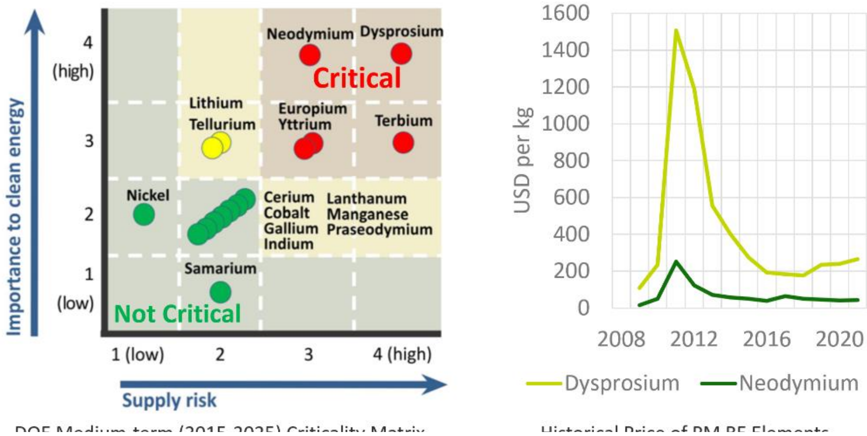


Figure 5: Supply risk and historical price of rare-earth metals

Along with the soaring demand, sources of economically recoverable RE metals are concentrated in limited geographic locations that

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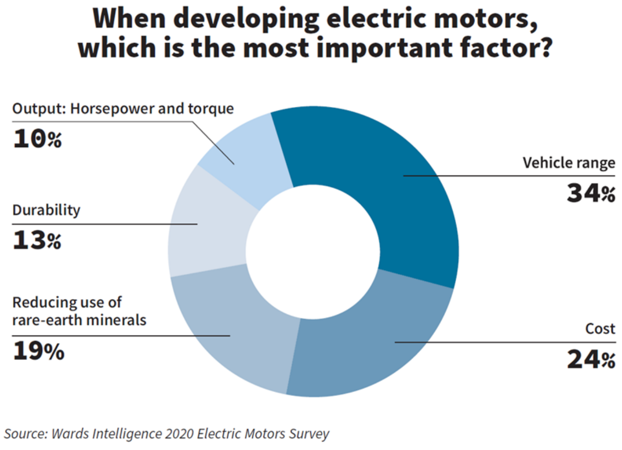
[6] https://bnef.turtl.co/story/evo-2021/page/4/2?teaser=yes

significantly impact their production and supply. In Figure 5, the left panel rates the importance and risk of each of these metals; among them neodymium and dysprosium are of critical importance and risk according to the US Department of Energy[7]. The right panel highlights the historical volatility of these RE metals with the price of both Nd and Dy oxides having more than doubled from the year 2020 to 2021[8]. Although RE metals and PMs will be a key enabler of the internal combustion engine (ICE) to EV conversion, we cannot rely exclusively on them being available or affordable in the future.

What is the Industry Doing?

According to a Wards Intelligence 2020 Survey, the top three concerns of Original Equipment Manufacturers (OEMs) for EV motors development are vehicle range (efficiency), cost and reducing use of rare-earth minerals (Figure 6). The world is amid a semiconductor chip shortage and automakers are facing significant vehicle production delays and reeling from their financial impact. To prevent the next crisis in the form of RE supply-chain risk, the transportation industry will have to quickly get ahead of the supply-demand imbalance. Given the magnitude of the challenges facing the transportation industry in the path to full electrification, a range of strategies to both increase the efficiency of the drivetrain and reduce the dependence on RE metals are now being employed by manufacturers.



Source: Wards Intelligence 2020 Electric Motors Survey

Figure 6: Wards Intelligence 2020 Survey of the Automotive Industry

Many Chinese OEMs are already vertically integrated around PM based electric motors, given the abundance of RE material extraction, refinement, and production facilities in China.

OEMs like Toyota use PM electric motors but have a goal of reducing the use of RE metals within the next 10 years[9]. OEMs such as Honda have reduced dysprosium and terbium, the more expensive of RE metals, but by increasing the amount of neodymium to maintain similar performance metrics. The upside is a cost reduction, but the downside is still being reliant on RE metals. Automakers like BMW are redesigning drive units to combine components to reduce space and weight and increase inter-component efficiency to compensate for efficiency lost by moving away from PM motors[10]. Tesla initially used induction motors but has now taken the route of using multiple motors in the same platform – induction and PM motors - to obtain both power and efficiency but at the expense of system cost. Volkswagen has also used a similar strategy in its ID.4 platform.

General Motors is reported to be working on the supply side of the RE demand and supply equation. General Motors is partnering with General Electric to increase the supply of RE materials used in their

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[7] https://www.energy.gov/sites/prod/files/edg/news/documents/criticalmaterialsstrategy.pdf

[8] https://www.kitco.com/strategic-metals/

[9] https://www.reuters.com/article/us-toyota-magnet/new-toyota-magnet-cuts-dependence-on-key-rare-earth-metal-for-ev-motors-idUSKCN1G413F

[10] https://finance.yahoo.com/news/factbox-automakers-cutting-back-rare-061341108.html

Ultium drivetrain platform and look to the North American and European-based supply chains for these materials.

One of the first OEMs to announce full electrification of its vehicles was Volvo. Volvo is making significant investments into in-house design and development of newer electric motors. Daimler, with its acquisition of YASA motors known for the unique axial-flux motor technology, is also looking at in-house expertise for its next generation motors.

Many others are looking at similar in-house design and development expertise and continue to invest in R&D to both improve the efficiency of motors and reduce the cost and reliance on RE metals.

Suppliers such as Bosch and Continental and motor manufacturers such as Nidec, ABB, and others are responding to the industry's push and moving towards RE-free motor and e-axle designs.

Resurgence of Synchronous Reluctance Motors and Wound-Rotors

Synchronous reluctance motors (SynRM) and wound-rotor, EESM motors are seeing a resurgence due to their simple, cost-effective, rare-earth free architectures driven by sophisticated software control drives. Such motors are not yet as efficient or power dense as permanent magnet motors but the potential for efficiency improvement exists. Solutions to improve SynRM motor efficiency involve modulating frequency/speed of motors through variable frequency drives and using a hybrid PM reluctance motor for both magnetic and reluctance torques. SynRM motors are more commonly used in industrial applications, whereas EESM motors are commonly used in EV applications.

A novel approach called Dynamic Motor Drive (DMD), introduced at the 42nd International Vienna Motor Symposium by Tula Technology, enables synchronous reluctance motors to approach PM motor efficiency[11].

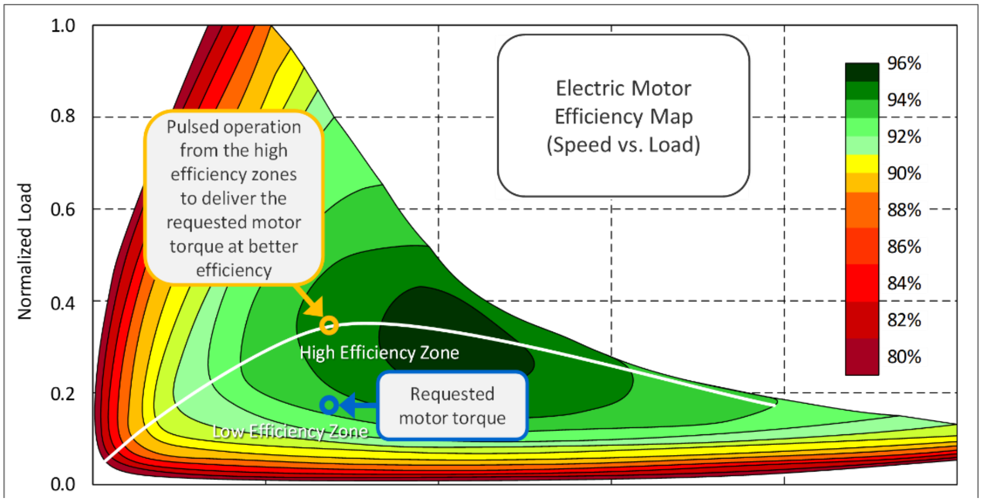

Figure 7: Concept of Dynamic Motor Drive Technology

DMD is a software solution that enables operating RE-free or RE-reduced motors at their peak efficiency points through torque modulation. The concept, shown in Figure 7, is to intermittently operate the electric motor only at the highest possible electromagnetic efficiency. When requested torque is below the torque that produces highest electromagnetic efficiency, an algorithm pulses the electric motor at higher efficiency points. In the example shown,

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[11] https://www.tulatech.com/wp-content/uploads/2021/04/Vienna-2021-Dynamic-Motor-Drive-Optimizing-Electric-Motor-Controls-to-Improve-Efficiency.pdf

optimal efficiency is at 34% of peak torque, and requested torque is at 19% of peak torque. The controller will therefore operate at the optimal efficiency point roughly 19/34 = 56% of the time.

The control architecture mitigates the light-load efficiency losses of electric motors in conjunction with the use of RE-free motors. By using the DMD pulse density strategy for electric motor control, inverter losses and core losses are mitigated. Experiments have demonstrated efficiency improvements of up to 7% at light loads, with SynRM cycle efficiency improvements of 2.5-5% simulated on WLTP and US City cycles. Peak system efficiencies will be reached on externally excited synchronous machines (EESM), which are under development now by Tula. Those improvements enable reduced battery size and increased range while lowering total energy consumption without changes to the vehicle or motor hardware. Tula also brings decades of noise and vibration mitigation expertise to bear on DMD technology, to ensure a smooth driving experience.

Conclusion

Climate change is an existential threat that can only be addressed by a concerted, worldwide effort. Electrification of the transportation sector and clean, renewable electricity generation are important elements in reducing humanity’s carbon footprint and both call for high power, high efficiency electric motors and generators. The use of NdFeB based permanent magnet electric motors promises high power and efficiency but at the cost of using Rare Earth (RE) metals. Rare earth metal supply and demand imbalance is a huge challenge as the world’s economies march towards a carbon-neutral future. The recent momentum in transportation electrification likely will be derailed by both the availability and affordability of rare earth elements. The transportation industry is responding to this supply threat by investing in innovative, RE-free synchronous reluctance motor and wound-rotor technologies, offering the potential of superior performance, availability, and value, compared to today’s permanent magnet motors. Tula’s Dynamic Motor Drive is a high efficiency software solution, which when paired with RE-free motors, offers a cost-effective means to move beyond today’s constraints and re-energize the drive to an electrified transportation future.