VALENT
Asset Management

November 2020

Neodymium-iron-boron and other permanent magnets

The rapid migration towards renewable energy electricity generation and consumption from electric mobility will significantly increase demand for high magnetic flux permanent magnets (PM). Though both PM and induction motors and generators have been deployed in various applications, PM motors have been gaining market share due to lower aggregate costs and higher thermal efficiency. Neodymium-iron-boron (NdFeB) magnets currently offer the highest energy products of magnetic alloys available. Historically, analyses of the materials required to expand electricity generation, infrastructure, and consumption have focused on the more exoteric markets such as nickel and cobalt for battery production or copper for improving grid efficiency. However, given the critical role NdFeB magnets and related materials will play in the coming global restructuring, it is imperative to ensure sufficient supply. The following analysis seeks to assess both the supply and demand components of the neodymium market and show that higher neodymium prices will be necessary to responsibly supply the steadily increasing demand in the decades to come.

NdFeB (Neodymium) Permanent Magnets

Substantially all of neodymium demand is for production of NdFeB permanent magnets. As the name suggests, these magnets are primarily composed of neodymium, iron and boron in a $Nd_2Fe_{14}B$ tetragonal crystalline structure, and are the strongest type of permanent magnet available today in terms of magnetic flux per unit volume (Figure 1)[1]. Thus, NdFeB magnets are necessary for applications sensitive to weight, size, and operating temperature. These applications include, but are not limited to, mobile phone speakers, vibration motors, hard disks, EV motors, and wind power generators (Figure 2). Specific properties of NdFeB may be altered with the addition of praseodymium, dysprosium, terbium, copper, cobalt and niobium to achieve characteristics specific to applications. The alloy mixture can be tailored to fit certain requirements for maximum energy product and thermal coefficient of coercive force (Figure 3).

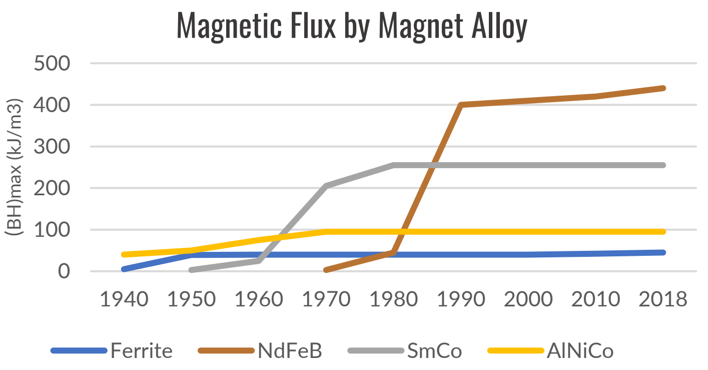

Figure 1: Source: Adamas Research

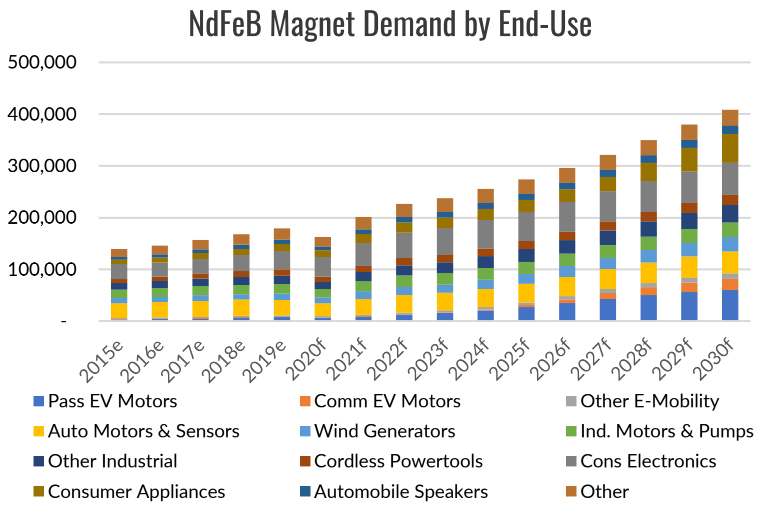

Figure 2 Source: Zutic[1], Adamas Research

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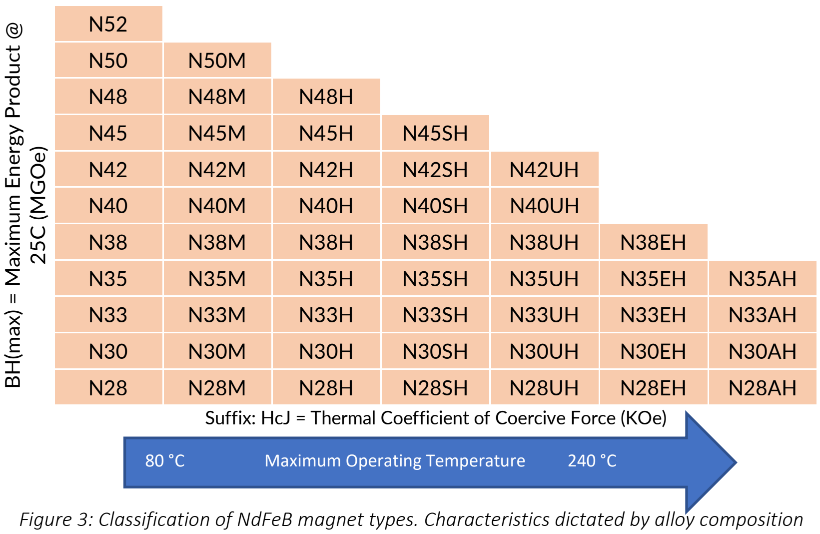
[1] Žutić, I.; Tsymbal, E. Handbook of Spin Transport and Magnetism. Taylor & Francis Group, 2012.

Pure neodymium only exhibits ferromagnetic properties at extremely low temperatures. To create permanent magnets which will operate at room temperature, it is necessary to alloy the Nd with iron and boron and create a tetragonal crystal structure. This structure preferentially magnetizes along a specific axis but is highly resistant to magnetization in other directions. Nd can retain a strong magnetic dipole moment due to its 4 unpaired electrons. When magnetized, the Nd atoms' unpaired electrons' quantum spins are aligned, creating a strong magnetic anisotropy.



N52						
N50	N50M					
N48	N48M	N48H				
N45	N45M	N45H	N45SH			
N42	N42M	N42H	N42SH	N42UH		
N40	N40M	N40H	N40SH	N40UH		
N38	N38M	N38H	N38SH	N38UH	N38EH	
N35	N35M	N35H	N35SH	N35UH	N35EH	N35AH
N33	N33M	N33H	N33SH	N33UH	N33EH	N33AH
N30	N30M	N30H	N30SH	N30UH	N30EH	N30AH
N28	N28M	N28H	N28SH	N28UH	N28EH	N28AH

Figure 3: Classification of NdFeB magnet types. Characteristics dictated by alloy composition

Electric Vehicles

In 2019, battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and hybrid electric vehicles (HEV) were collectively responsible for 5% of NdFeB magnet demand due to the permanent magnets in these vehicles' traction motors. However, recently enacted governmental policy and environmental regulations require an electric vehicles sales growth rate that will cause EVs to be the dominant end use of neodymium in the coming years (Appendix; Figure 4), accounting for 15% of NdFeB consumption by 2030. By that year, countries representing an aggregate 9% of global vehicles sales will have implemented bans on combustion engine vehicle sales (Appendix). By 2040, this proportion reaches 21%. In addition to these government mandates, auto producers have also set ambition goals for the production and sale of electric vehicle models (Appendix).

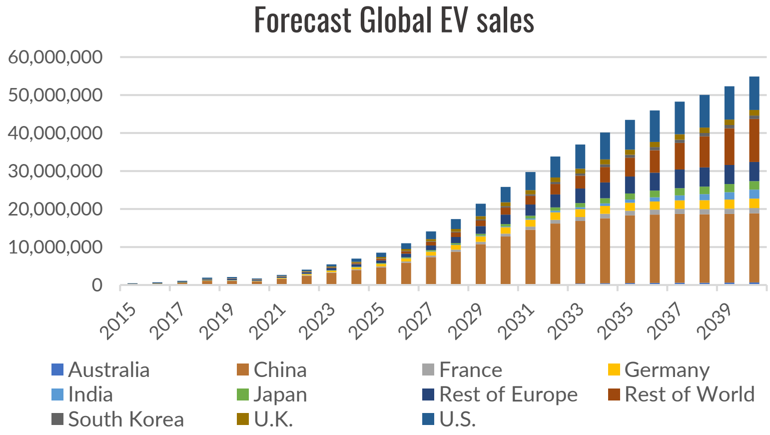


Figure 4: Source: BNEV

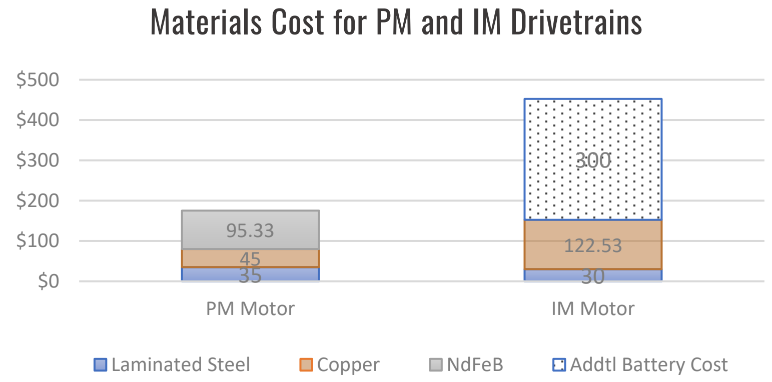


Figure 5: Source: Adamas Research

Electric vehicles currently utilize 3 variants of traction motors: permanent magnet motors (PM), induction motors (IM) and salient pole synchronous reluctance (SPSR) motors. PM motors are the most common type of electric vehicle drivetrain motor today and, as the name implies, is one of the two variants that utilize permanent magnets (the other being SPSR). In general, PM motors are the most power dense of all the traction motor types and offer greater energy efficiency due to magnetic pre-excitation. However, permanent magnet free IM motors offer higher torque and perfect flux regulation. This contrast in operating characteristics led Tesla to utilize a permanent magnet synchronous reluctance (PMSR) motor for the first time in their Model 3 to achieve their cost and efficiency targets. This PMSR motor pioneered by the Model 3 was subsequently integrated into the Model X and Model S alongside the induction motor Tesla has utilized since the launch of both models. This integration led to a 10% range increase with no changes to battery capacity. Thus, while PM motors may have higher material input costs as compared to IM motors, total drivetrain costs are lower when utilizing a PM motor due to the additional battery costs associated with IM motors (Figure 5).

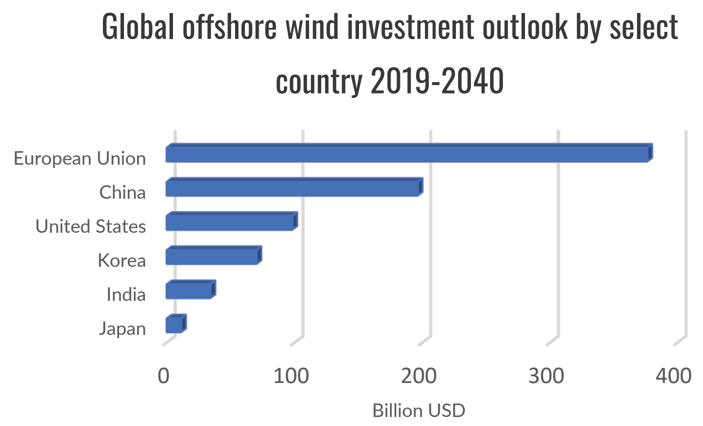


Figure 6: Source: World Bank

Wind Power Generation

Approximately a third of wind turbines installed globally in 2018 incorporated rare earth permanent magnet generators (PMGs). These PMG direct drive wind turbines are currently responsible for 10% of global dysprosium demand and 8% of global neodymium demand. PMG wind turbines eliminate the need for a large mechanical gearbox and therefore weigh less and generate higher power per turbine when compared to their traditional counterparts. Furthermore, while more expensive than geared turbines, PMG turbines require less maintenance, thereby offsetting the initial construction cost. This is due to PMG's comparatively simple designed. In wind turbine PMGs, the turbine is mated to the generator rotor, which contains the NdFeB magnets. This rotor is surrounded by the stator, which houses three conductors, constituting the three phases of a power circuit. These conductors are spaced 120 degrees apart for special uniformity. When the rotor rotates within the stator, the rotating magnetic field induces electron flow in the conductors.

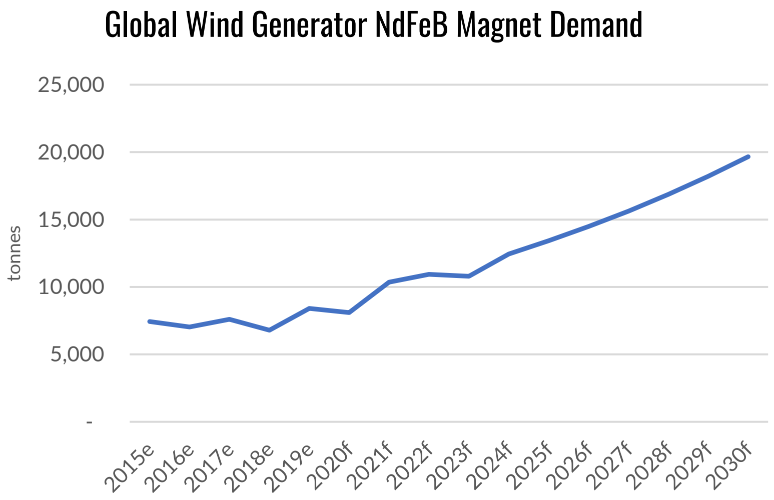


Figure 7: Source: World Banks; Adamas Research

With the global expansion of wind power installation, particularly offshore, this sector will require steadily increasing neodymium supply. NdFeB magnet demand for wind power generation is forecast to reach 19,661 tonnes in 2030 compared to 8,098 tonnes in 2020.

Consumer Electronics and Appliances

As of 2019, consumer electronics, cordless power tools and appliances accounted for 35% of NdFeB magnet demand[2]. Examples of these applications include brushless motors, small speakers, vibration motors, taptic feedback motors, camera auto-focus mechanisms, receivers, and wall chargers. In these applications, manufacturers tend to use N48 and N52 grade magnets to reduce weight and volume. It is this size requirement that make permanent magnet motors the only viable choice as NdFeB magnets allow a very strong magnetic field to be generated in a small volume. The alternative would be to use electromagnets, where a magnetic field is generated by passing current through a conducting coil. A 3 mm thick piece of NdFeB magnet produces the equivalent magnetic field to passing 13 amps (A) through a coil with 220 turns of copper wire. In terms of space, if a current density of 10 A/mm^2 is assumed in the conductor, then an equivalent electromagnetic coil might have five times the cross sectional area of the NdFeB magnet. At the same time the coil would produce losses in the windings of 50 W or more per meter length of the coil due to the electrical resistance of the conductor.

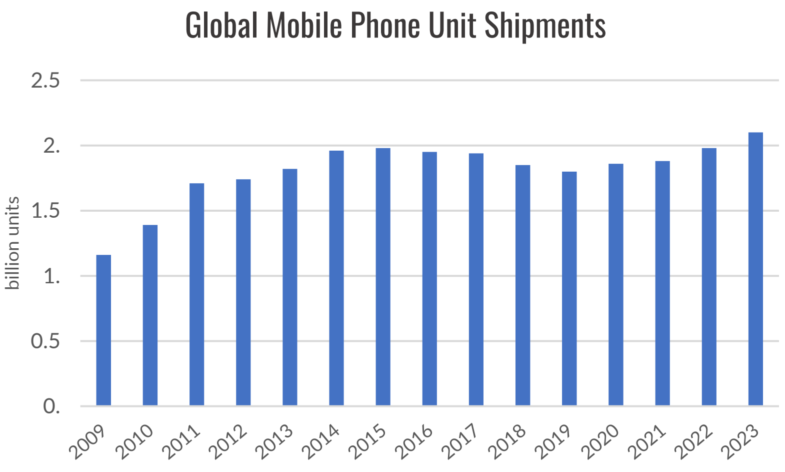


Figure 8: Source: CCS Insight

Thrifting

With demand concentrated in magnetic applications, it becomes crucial to assess the potential for neodymium thrifting or substitution. Many analyses of the REE markets will apocryphally claim that aggressive thrifting followed China's 2010 decision to ban REE exports. However, NdFeB content of EV traction motors per unit of power fell precipitously leading up to the export ban and made no further progress thereafter (Figure 9). With ever increasing EV motor power, the aggregate Nd consumption for this application has increased over this period. While research continues on Nd thrifting, Nd's unique magnetic characteristics and the lack of significant consumption reductions over the last eight years indicates that Nd thrifting has likely reached its physical limits.

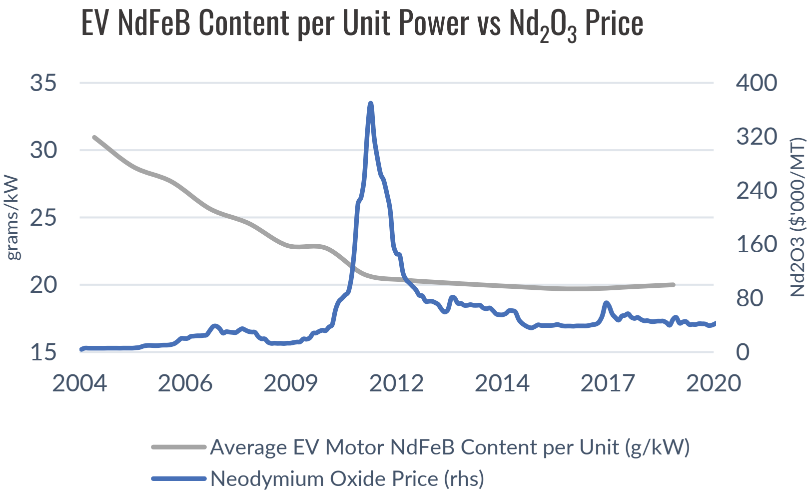


Figure 9: Source: Asian Metal; Adamas Research

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[2] Adamas Research

Supply

Despite the classification as a REE, neodymium is not particularly rare in terms of crustal abundance. Rather, neodymium's chemical characteristics promote broad dissipation in most ore types, so it is rarely concentrated in economically viable amounts. Unlike metals and minerals with concentrated deposits, neodymium is mined alongside other REEs and with a global average concentration of 17% as a proportion of total rare earth oxides (TREO) (Figure 10). Thus, neodymium has the supply economics of a partial byproduct; outright production levels will be dictated by the basket price of all REEs. For example, any increase in production will likely require higher cerium and lanthanum prices alongside higher neodymium prices.

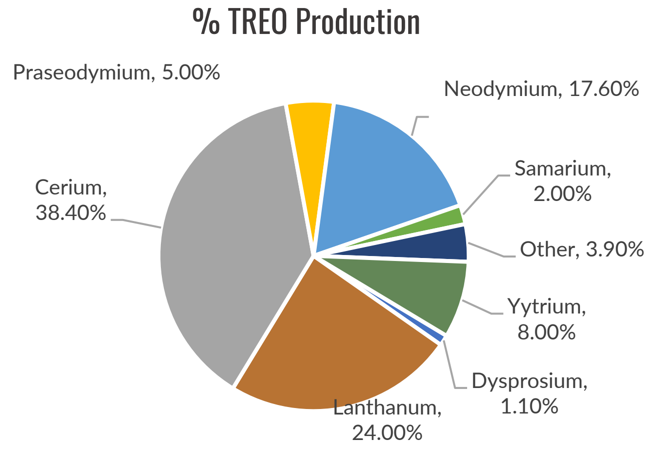


Figure 10: Source: VAM Research

Neodymium production is geographically concentrated, with China accounting for 70% of global mined output. NdFeB alloy production is even more concentrated, with China accounting for 90% of global production (Figure 11). From 2005 to 2013, over 25% of China's neodymium output was produced illegally. This unsanctioned mining was environmentally damaging and was focused in HREE rich ion-absorption clay (IAC) deposits. These IAC deposits were exploited by injecting ammonia sulfate, ammonia chloride and other chemicals directly into the ground to separate REEs from the soil. The resultant drinking water and soil contamination led China's central government to embark on a cleanup program, which has been effective in significantly reducing China's illegal REE supply.

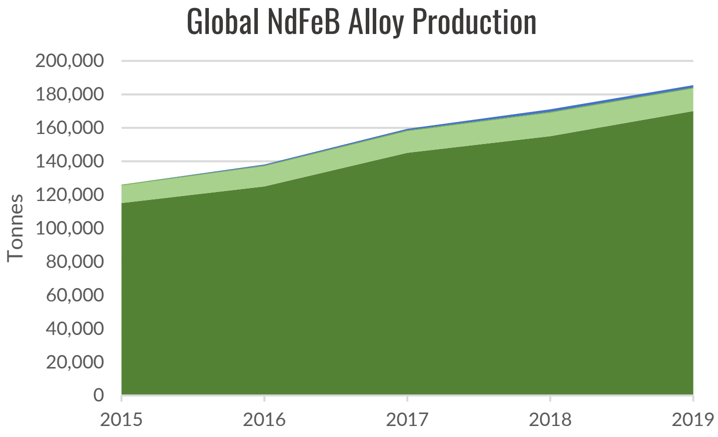


Figure 11: Source: VAM Research

For rare earth deposits contained in alkali igneous rocks, carbonatites, and granites, REE containing ore is first ground and crushed prior to beneficiation. The crushed material is then upgraded via floatation, magnetic separation, and other steps to eliminate waste material and produce a REE concentrate. This concentrate is then fed into a leaching circuit in which REEs are dissolved in high temperature hydrochloric or sulfuric acid. This process liberates any radioactive elements such as thorium, uranium, and fluorite and produces a REE-rich pregnant leach solution (PLS). Lastly, the PLS is treated in a chemical fractionation process designed to separate, purify and precipitate individual REE oxides.

For most commercial applications, REEs must be purified further from their oxide forms via calciothermic or electrolytic processes. The calciothermic process is used for all rare earth metals aside from those characterized by high vapor pressures. Initially, the REE oxide is converted to a fluoride, mixed with calcium, and heated in a tantalum crucible. This yields calcium fluoride and purified rare earth metal. The rare earth metal purity may be further increased via sublimation or distillation. The electrolytic process is generally used for processing REEs with low melting points, including neodymium. This process involves either converting the REE oxides to chloride or fluoride before reducing in an electrolytic cell or direct reduction via molten salt immersion.

Once neodymium or neodymium based alloys are purified, they are processed further into sintered NdFeB alloys and powders before being formed into permanent magnets. Neodymium, iron and boron are combined, melted and cast into a steel or rubber mold, then allowed to cool to form NdFeB ingots. The addition of iron and boron is allows neodymium to retain its ferromagnetic properties at a wider temperature range. Pure neodymium's Curie temperature, the temperature above which it loses its ferromagnetic properties, is 19 Kelvin, so it must be alloyed for any practical permanent magnet application. Once cool, the NdFeB ingots are pulverized, milled, pressed and sintered while being exposed to a strong magnetic field, which permanently imparts magnetic anisotropy by aligning the quantum spin of neodymium's 4 free electrons.

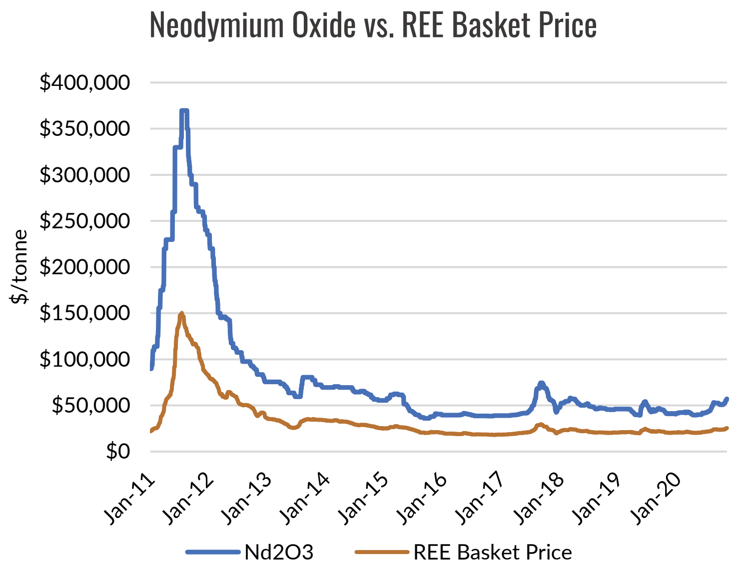


Figure 12: Source: Asian Metal

The Balance Problem

The mismatch between market demand for and the natural concentrations of REEs is referred to as the Balance Problem. The proportional output of each REE from a given mine is dictated by the composition of the ore, which often does not match the composition of demand. This leads to production of sacrificial elements that must be stockpiled. In general, the REEs become more scare with increasing atomic number. Additionally, the Oddo-Harkins rule, which postulates that elements with odd atomic numbers are less stable than those with even atomics numbers, leads to lower concentrations of REEs with odd atomic numbers as compared to those with even atomic numbers. Though neodymium's properties allow it to exist in relatively high concentrations, cerium is the dominant REE in bastnäsite and monazite ores and yttrium is the main REE in xenotime and ion-absorption ores.

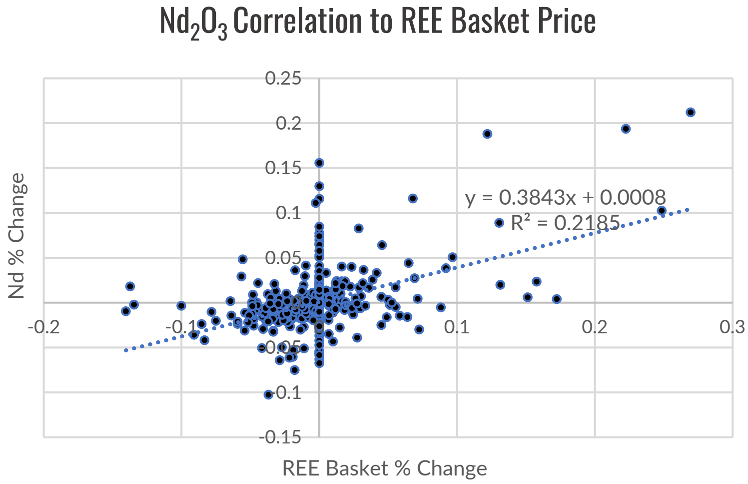


Figure 13: Source: Asian Metal; VAM Research

Thus, the incentive to expand production of Nd is not solely determined by Nd price, but rather the basket price of all REEs (Figure 12,13). While Nd constitutes 20% of REE basket value (based on global average production profile and October 2020 prices), it may still deviate considerably from the REE basket price. This will likely remain true as any increase in production will exacerbate the oversupply of sacrificial products.

Conclusion

Despite viable prospects for expanding production, neodymium production is likely to fall short of demand in the coming years (Figure 14). China's production dominance has led governments such as the US, Australia and Canada to recognize rare earth production as a national security issue. As such, these governments have promoted domestic production and refining of neodymium, which will likely reduce China's market share by 2030. However, the drastic increase in demand presented by the renewable energy revolution coupled with the physical limitations on further thrifting means that neodymium will be in deficit for years to come. As with other relatively price inelastic metals and minerals, dramatically higher prices will be required to ensure sufficient supply to power these renewable technologies.

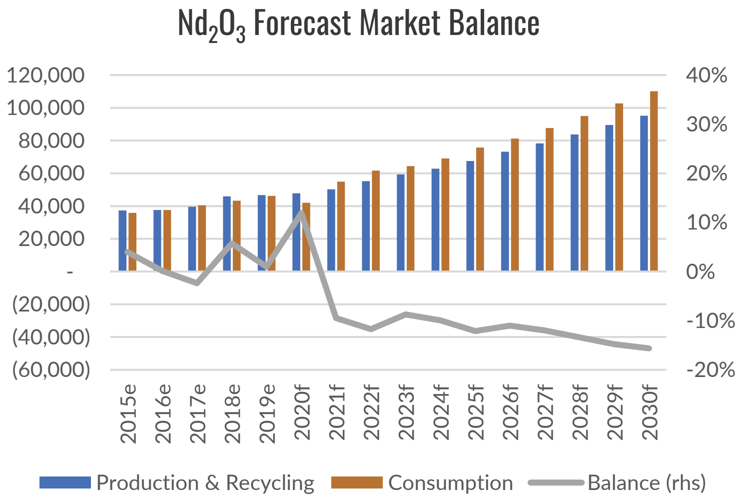
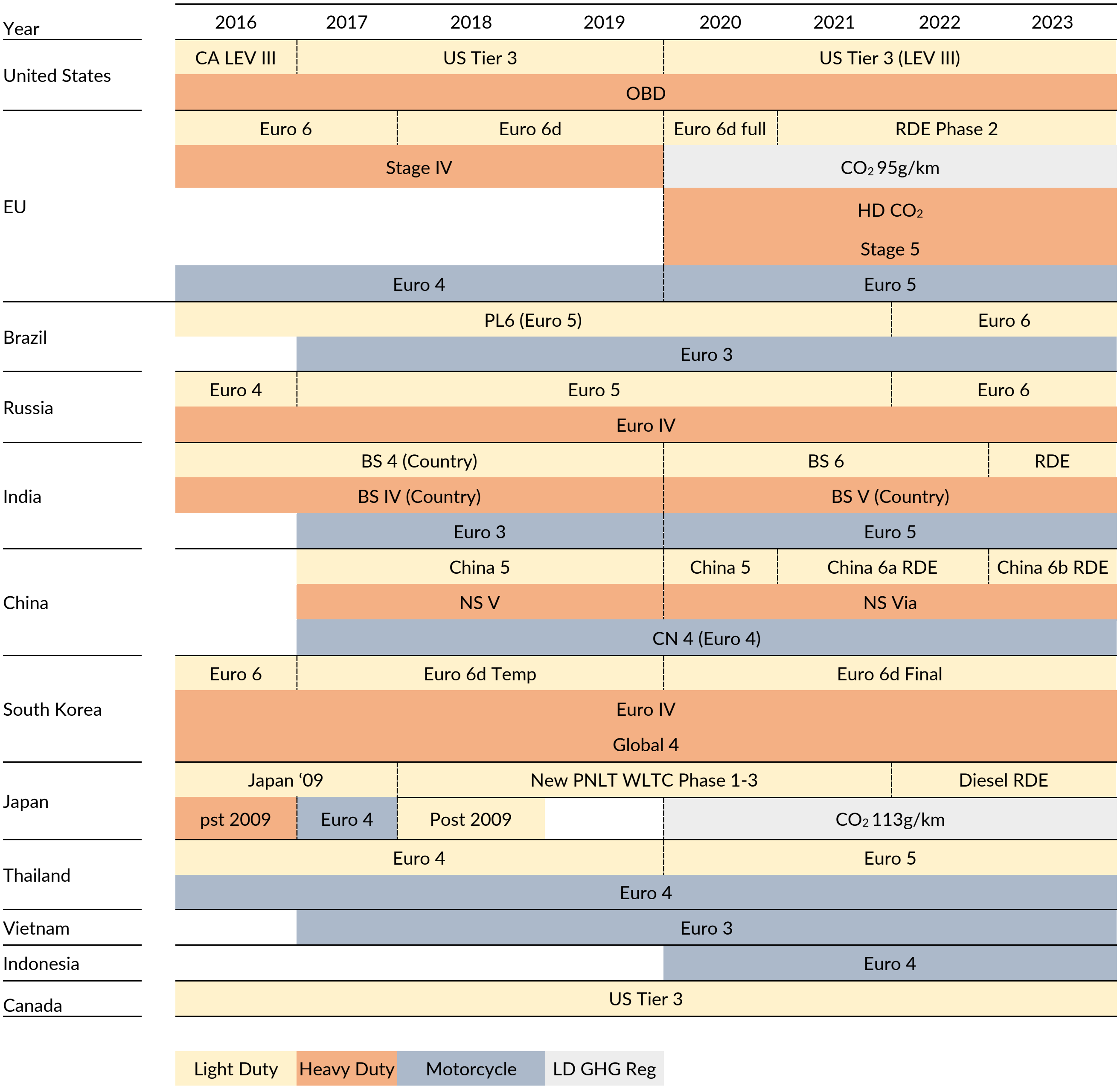


Figure 14: Source: Adamas Resarch; World Bank; VAM Research

Appendix



Year	2016	2017	2018	2019	2020	2021	2022	2023
United States	CA LEV III	US Tier 3			US Tier 3 (LEV III)			
	OBD							
EU	Euro 6		Euro 6d		Euro 6d full	RDE Phase 2		
	Stage IV				CO_2 95g/km			
					HD CO_2			
					Stage 5			
	Euro 4				Euro 5			
Brazil	PL6 (Euro 5)						Euro 6	
		Euro 3						
Russia	Euro 4	Euro 5					Euro 6	
	Euro IV							
India	BS 4 (Country)				BS 6			RDE
	BS IV (Country)				BS V (Country)			
		Euro 3			Euro 5			
China		China 5			China 5	China 6a RDE		China 6b RDE
		NS V			NS Via			
		CN 4 (Euro 4)						
South Korea	Euro 6	Euro 6d Temp			Euro 6d Final			
	Euro IV							
	Global 4							
Japan	Japan '09		New PNLT WLTC Phase 1-3				Diesel RDE	
	pst 2009	Euro 4	Post 2009		CO_2 113g/km			
Thailand	Euro 4				Euro 5			
	Euro 4							
Vietnam		Euro 3						
Indonesia					Euro 4			
Canada	US Tier 3							

Light Duty	Heavy Duty	Motorcycle	LD GHG Reg