



Adamas Intelligence

# SPOTLIGHT ON DYSPROSIUM

Reving Up for Rising Demand

April 2018

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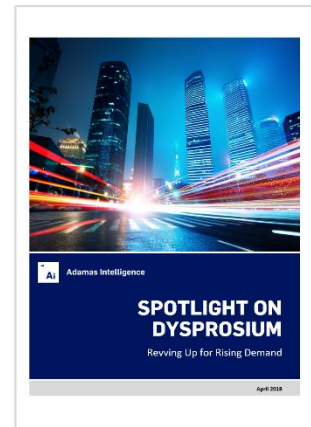
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## Executive Summary

Looking ahead, dysprosium demand growth will be increasingly driven by global megatrends linked to electric mobility, clean energy, energy efficiency, and automation. These fast-growing policy-driven sectors will propel global demand to new heights, requiring an unprecedented increase in global production to keep up.

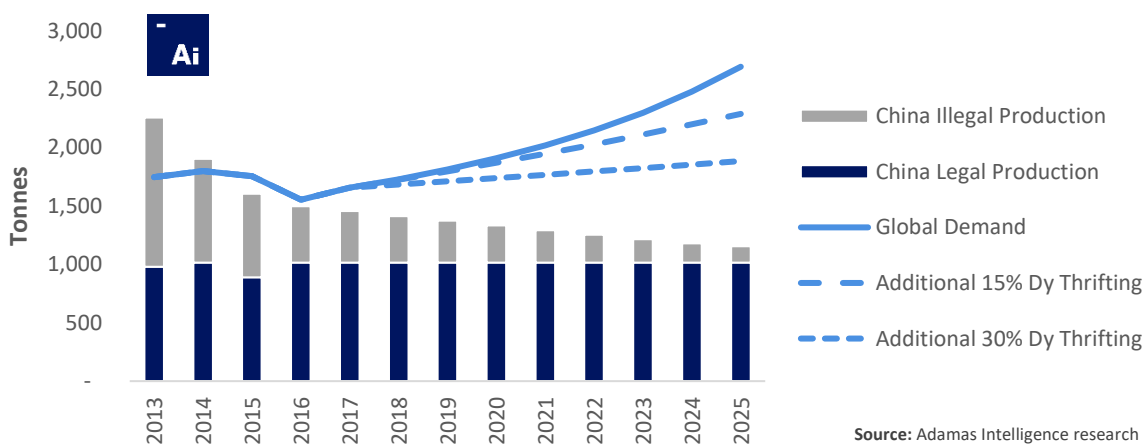
However, as China, the world’s dominant producer of dysprosium, continues to crackdown on unsanctioned production in the nation, Adamas Intelligence believes that global dysprosium production may in fact decrease, emphasizing the need for new sources of supply.

Adamas Intelligence was engaged by Northern Minerals to independently assess the near-term outlook for the global dysprosium market in the context of rapidly growing demand for electric vehicle traction motors, wind power generators, industrial robots, and numerous other applications.

Among the key findings of our research:

- An ongoing government-led crackdown on illegal rare earth mining in China has led to a 34% reduction in global dysprosium oxide production since 2013.
- Looking ahead, Adamas Intelligence believes that China’s production alone will be insufficient to support global demand growth.
- In fact, by 2025 China’s demand for dysprosium oxide for electric vehicle traction motors alone will amount to 70% of the nation’s current legal production level, emphasizing the imminent need for new supplies.
- Outside of China, there are a handful of advanced rare earth development projects with potential to add significant quantities of dysprosium oxide production annually by 2025.
- **If automakers, motor manufacturers, and other end-users of high-temperature NdFeB do not act today to secure long-term supplies, they will soon find themselves amidst a sellers’ market scrambling for rare earth motor metals the same way many are scrambling today for battery metals.**

Even with a further 30% reduction in dysprosium usage by the magnet industry, the outlook is concerning





# Introduction to Rare Earth Elements

## Small Market, Big Necessity

Compared to similarly-abundant elements in nature, such as copper, lead, and tin, global annual production of rare earth elements is exceptionally low.

Nevertheless, rare earth elements have become the critical enablers of ubiquitous consumer electronics that have pervaded modern society, and technologies that are at the heart of clean energy initiatives worldwide.

Rare earth elements are used in small, but necessary, amounts in hundreds of different technologies, materials, and processes worldwide in consumer, industrial, medical, and environmental applications.

In just a period of decades, rare earth elements have seeped deeply into the fabric of modern technology and industry, and have proven remarkably challenging to duplicate or replace.

In just a period of decades REEs have seeped deeply into the fabric of modern technology and industry

## Arbitrarily Divided into ‘Lights’ and ‘Heavies’

Rare earth elements comprise the lanthanide series on the periodic table of elements, plus scandium and yttrium (see Figure 1).

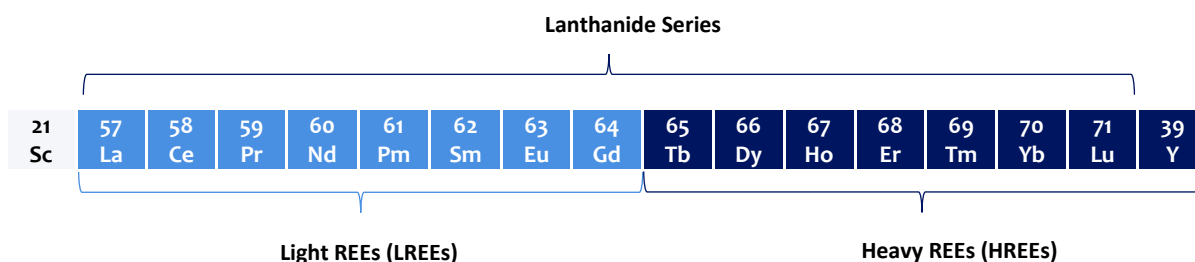
Yttrium is classified as a rare earth element because of its similar ionic radius to the lanthanides, as well as its similar chemical properties, whereas scandium is classified as a rare earth element because of its tendency to concentrate into many of the same minerals.

Rare earth elements are arbitrarily classified as ‘light’ rare earth elements or oxides (“LREEs” or “LREOs”) or ‘heavy’ rare earth elements or oxides (“HREEs” or “HREOs”) based on their electron configurations (see Figure 1).

Simply put, LREEs have an increasing number of unpaired electrons in their 4f shells, starting at lanthanum, which has zero unpaired electrons, through to gadolinium, which has seven unpaired electrons. HREEs, on the other hand, have paired electrons - a clockwise and counter-clockwise spinning electron – in their 4f shells.

Yttrium’s physical properties and chemical reactivity resemble those of HREEs, thus it is generally categorized as such by industry and academia.

Figure 1: Rare earth elements include the lanthanide series plus scandium and yttrium





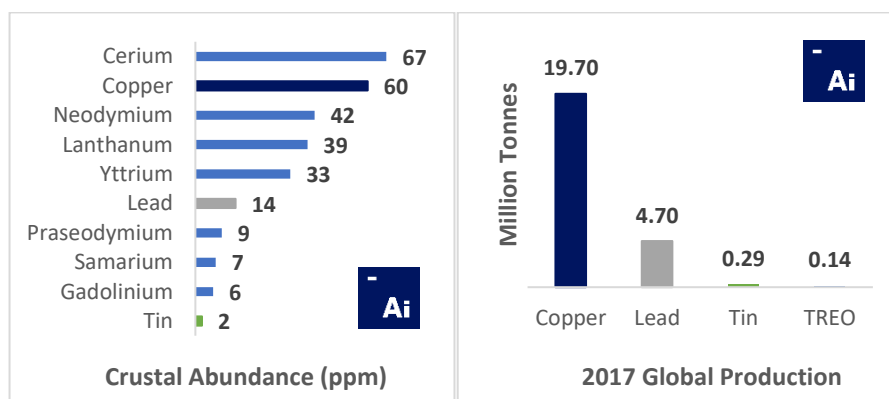
## Rarely Enriched in Nature

Despite the misleading moniker, most rare earth elements are not remarkably rare in nature, but are instead rarely concentrated into economically-significant amounts for extraction and processing owing to certain physical and chemical characteristics that promote their broad dissipation in most rock types.

In fact, cerium is more abundant than copper in Earth’s crust; lanthanum, neodymium, and yttrium are more abundant than lead; and praseodymium, samarium, and gadolinium are more abundant than tin (see Figure 2 – left side).

Despite this fact, there were only 138,900 tonnes of all 17 REOs combined (“TREO”) produced globally in 2017 versus 19.7 million tonnes of copper, 4.7 million tonnes lead, and 290,000 tonnes of tin (see Figure 2 – right side).

**Figure 2:** Compared to similarly-abundant elements, production of REEs is low

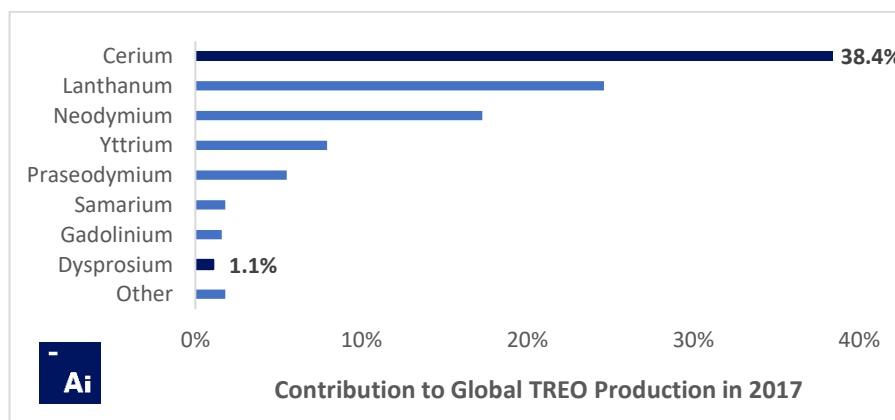


Source: Jefferson Lab

Source: USGS, Adamas Intelligence research

In the context of global rare earth production, some rare earth elements are indeed substantially rarer than others. Dysprosium, for example, made up just 1.1% of global TREO production in 2017 versus 38.4% for cerium (see Figure 2).

**Figure 3:** In 2017 dysprosium made up just 1.1% of total global REO production



Source: Adamas Intelligence research

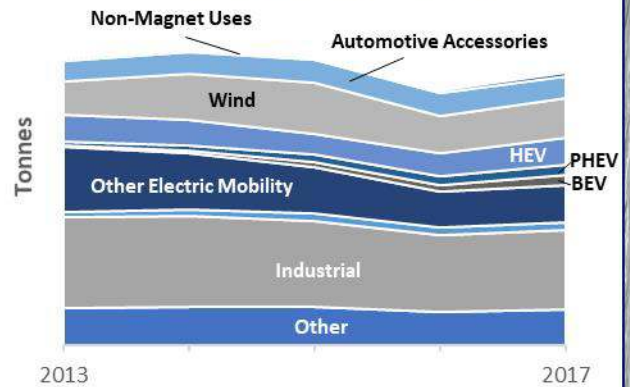
# Dysprosium Quick Facts

Dysprosium is a heavy rare earth element.

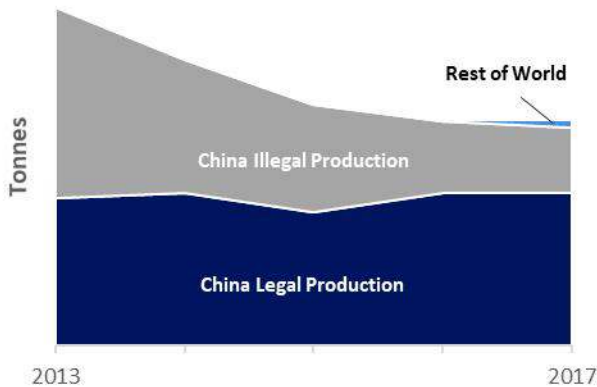
Dysprosium's primary use is in NdFeB magnets for EV traction motors, wind power generators, industrial robots, and hundreds of other applications in which the NdFeB magnet is exposed to elevated temperatures and/or strong demagnetization fields.

By 2025, electric vehicle traction motors are expected to become the single largest end-use of dysprosium oxide globally.

## Consumption by Category



## Production by Region



Over the past decade, China has been responsible for over 98% of global dysprosium oxide production each year.

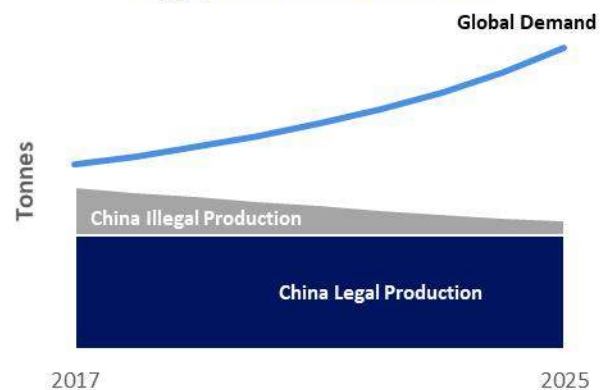
From 2005 through 2013, more than half of China's dysprosium oxide production each year was derived from unsanctioned/illegal mining activities.

An ongoing government-led crackdown on illegal mining in China has led to a 34% reduction in global dysprosium oxide production since 2013.

Looking ahead, dysprosium demand growth will be driven by global megatrends linked to electric mobility, clean energy, energy efficiency, and automation.

These fast-growing policy-driven sectors will propel global dysprosium demand to new heights, requiring an unprecedented increase in global production to keep up. Adamas Intelligence believes that China's production alone will be insufficient to support global demand growth.

## Supply and Demand to 2025



# Dysprosium Market Review

## Global Production

From 2013 through 2017 China was responsible for over 98% of global dysprosium oxide (or oxide equivalent) production each year (see Figure 4).

Over that period, global annual dysprosium oxide (or oxide equivalent) production decreased by 34%, from 2,265 tonnes in 2013 to 1,501 tonnes in 2017, resulting from a steady decrease in non-sanctioned (also referred to as “illegal”) rare earth production in China (i.e. production not permitted by the Ministry of Land and Resources’ semi-annual production quotas).

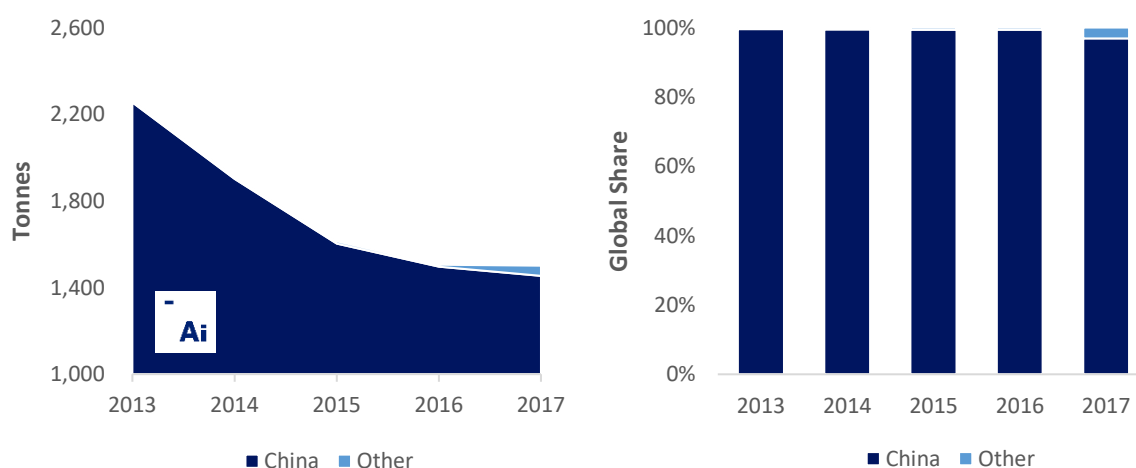
Outside of China, it is estimated that approximately 50 tonnes of dysprosium oxide equivalent was produced in 2017, primarily contained in mixed rare earth concentrate that Adamas Intelligence expects will be sold, or has been sold, to processing companies in China.

In 2017, production of dysprosium oxide (or oxide equivalent) made up just 1.1% of total global production of all rare earth oxides combined, down from 1.6% in 2013 due to an ongoing government-led crackdown on illegal production from China’s HREE-rich ion-adsorption clay (“IAC”) deposits and HREE-rich mineral sands deposits.

In an IAC deposit, dysprosium oxide can represent upwards of 5 weight percent of the total rare earth content in the ore thus unsanctioned overproduction of this material, whether increasing or decreasing, has a major impact on global dysprosium oxide production.

Since 2013 global dysprosium oxide production has fallen by 34%

Figure 4: From 2013 through 2017 China was responsible for over 98% of global annual production



Source: Adamas Intelligence research





## Illegal Production in China

From 2005 through 2013 Adamas Intelligence research indicates that more dysprosium oxide (or oxide equivalent) was produced illegally in China each year than legally (i.e. in accordance with semi-annual production quotas issued by China’s Ministry of Land and Resources).

From 2013 through 2017, however, Adamas estimates that illegal production’s contribution to total production in China decreased steadily, from 57% in 2013 to 30% in 2017 (see Figure 5), owing to ongoing efforts by Chinese authorities to crack down on illegal producers, coupled with a tempering of rare earth prices that has made illegal production less lucrative.

As noted on the previous page, the market for dysprosium (and other heavy rare earth elements) has been especially impacted by the issue of illegal rare earth production in China in recent years because the majority of that illegal production has been focused on IAC deposits that are highly enriched in HREEs versus LREEs.

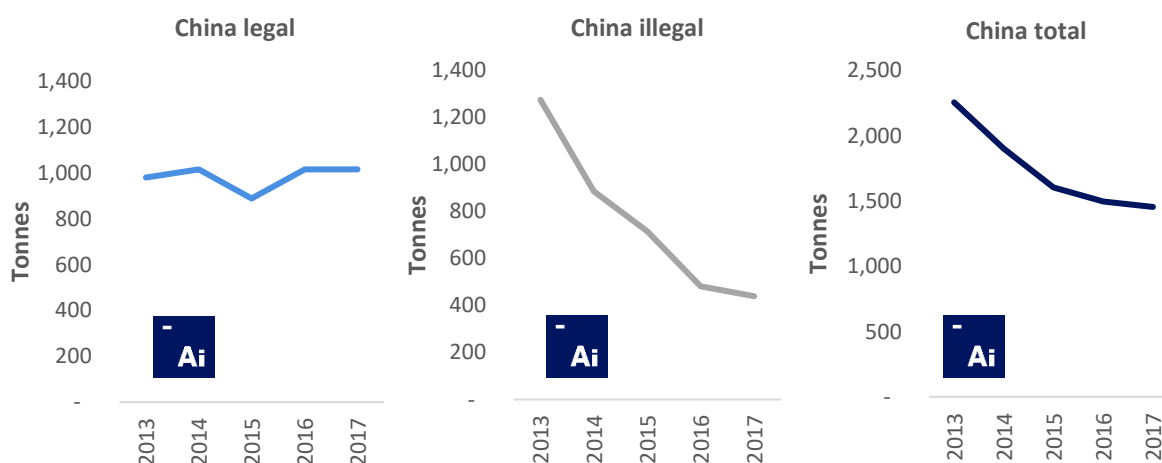
By nature, China’s IAC deposits present a low technical hurdle for opportunistic miners to exploit. Unlike a conventional hard-rock or mineral sands deposit in which the rare earth elements are contained within the crystal lattice of a host mineral, in an IAC deposit rare earth elements are present as ions or compounds on the outer surface of clay grains thus are relatively simple and low cost to recover.

In 2017 Chinese authorities commenced a nationwide audit of the domestic rare earth supply chain as part of Beijing’s ongoing effort to reduce illegal rare earth production and enforce environmental standards in the nation.

The ongoing inspections follow the recent consolidation of China’s rare earth enterprises into six large groups – a move that has done little to reduce the number of rare earth businesses operating in China – but has been effective in centralizing industry control, increasing government oversight, and strengthening the pricing power of China’s major rare earth producers, as evidenced by an upturn in rare earth prices in mid-2017 (see [report](#) from Adamas Intelligence).

In 2013 more dysprosium oxide was produced illegally in China than legally

Figure 5: Since 2013, a steady reduction in illegal production has drawn China’s total output ever-lower



Source: Adamas Intelligence research



## Global Consumption

From 2013 through 2017 Adamas Intelligence estimates that global annual consumption of dysprosium oxide (or oxide equivalent) decreased overall at a near-negligible CAGR of -1.3%, from 1,745 tonnes to 1,656 tonnes (see Figure 6).

In 2017 global dysprosium oxide demand returned to growth on the back of strong demand for EVs, wind power, and other end-uses

As shown in Figure 6, from 2014 through 2016 the market experienced a pronounced retraction in demand due to techniques developed and employed by permanent magnet manufacturers that reduce the amount of dysprosium used in certain grades of neodymium-iron-boron (“NdFeB”) magnets.

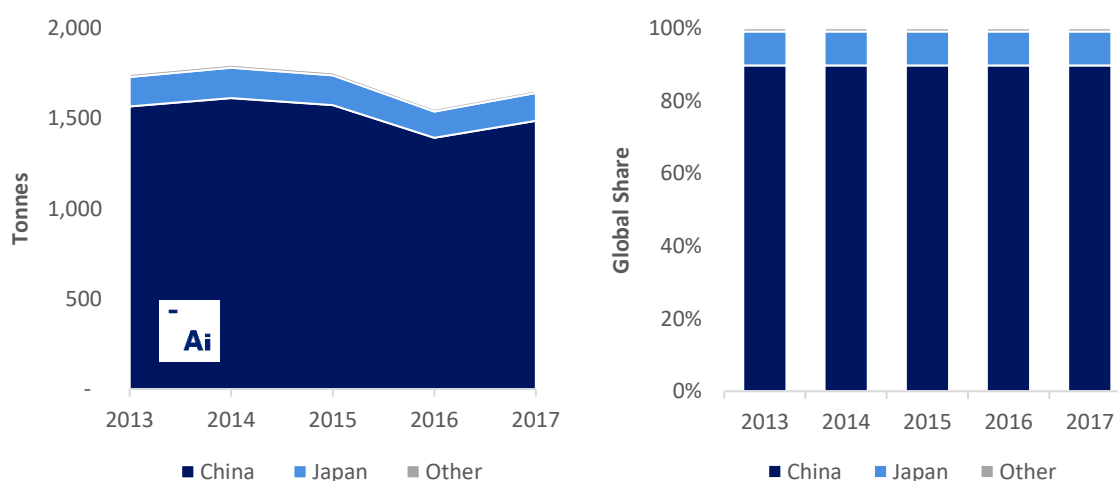
These developments are in direct response to the rare earth price spike of mid-2011, and reflect magnet end-users’ growing concerns regarding their reliance on China for virtually all of their dysprosium supplies.

Despite a reduction in dysprosium concentrations used in certain grades of NdFeB, global demand for dysprosium oxide returned to growth in 2017 on the back of strong demand growth for magnets used in electric vehicle traction motors, wind power generators, and numerous other applications.

As shown in Figure 6, from 2013 through 2017 China was responsible for approximately 90% of global dysprosium oxide (or oxide equivalent) consumption each year, Japan was responsible for 9%, and other nations 1%.

While China fuels approximately 90% of global demand each year, the nation uses approximately 40% of this amount to produce high-grade permanent magnets for subsequent export.

Figure 6: From 2013 through 2017 global annual consumption decreased at a near-negligible CAGR of -1.3%



Source: Adamas Intelligence research



## Global Consumption by End-Use Category

From 2013 through 2017 Adamas Intelligence estimates that over 99% of global dysprosium oxide (or oxide equivalent) consumption each year was for production of NdFeB permanent magnets.

As we will explore further in the coming pages, dysprosium is commonly added to NdFeB permanent magnet alloy for use in applications involving elevated temperatures (above 80 °C) and/or strong demagnetization fields.

With the addition of dysprosium (and often terbium) to NdFeB, the maximum operating temperature of the material can be tripled (up to 240 °C), making NdFeB the ideal material for an ever-growing list of end-uses and applications.

From 2013 through 2017 Adamas Intelligence estimates that electric mobility and industrial applications were the greatest demand drivers of dysprosium oxide (via use of Dy-containing NdFeB), followed by wind power, and vehicle accessory motors (see Figure 7).

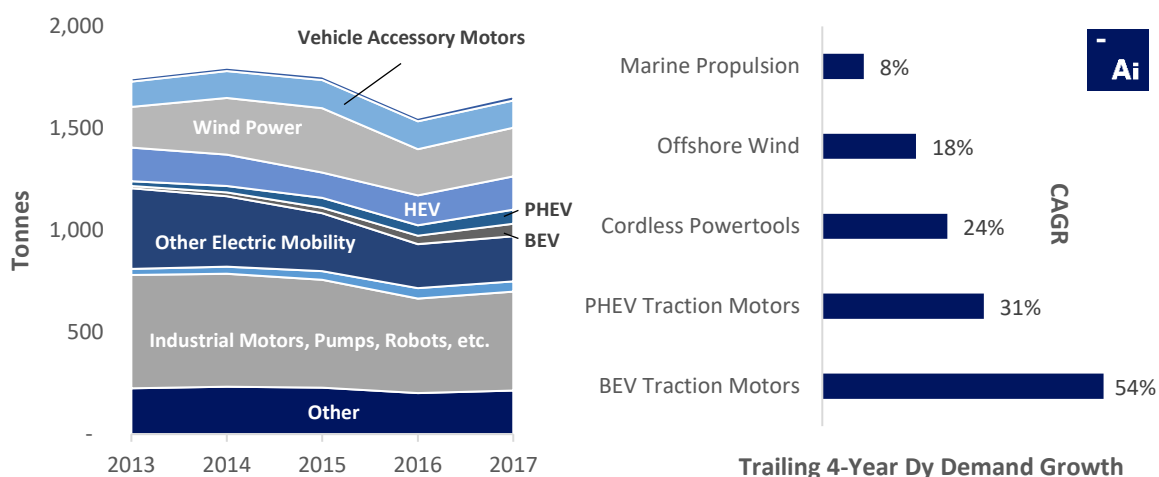
Within the category of electric mobility, Adamas research indicates that global consumption of dysprosium oxide (or oxide equivalent) for use in NdFeB for plug-in hybrid electric vehicle (“PHEV”) and battery electric vehicle (“BEV”) traction motors has grown exceptionally fast since 2013.

Specifically, from 2013 through 2017 Adamas Intelligence estimates that global consumption of dysprosium oxide (or oxide equivalent) for BEV traction motors increased at a CAGR of 54%, from 11 tonnes to 61 tonnes, while global consumption for PHEV traction motors increased at a CAGR of 31%, from 23 tonnes to 68 tonnes.

Collectively, BEV, PHEV and hybrid electric vehicle (“HEV”) traction motors were responsible for just 18% of total global dysprosium oxide consumption in 2017 but, at the current rate electric vehicle sales are growing, are poised to become the dominant end-use of dysprosium oxide by 2025.

Electric vehicle traction motors are poised to become the **dominant end-use of dysprosium oxide by 2025**

Figure 7: Electric vehicle traction motors were responsible for 18% of total global demand in 2017



Source: Adamas Intelligence research

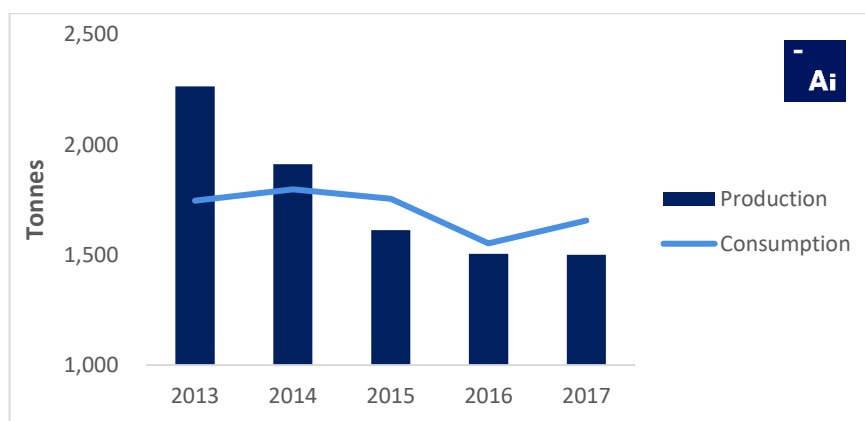


## Global Supply and Demand

From 2013 through 2017 Adamas Intelligence estimates that global annual production of dysprosium oxide (or oxide equivalent) decreased at a CAGR of -9.8%, from 2,265 tonnes to 1,501 tonnes, on the back of reduced illegal production in China (see Figure 8).

Over the same period, Adamas Intelligence estimates global annual dysprosium oxide (or oxide equivalent) consumption decreased at a CAGR of -1.3%, from 1,745 tonnes to 1,656 tonnes – an amount that has exceeded global annual production since 2015 (see Figure 8).

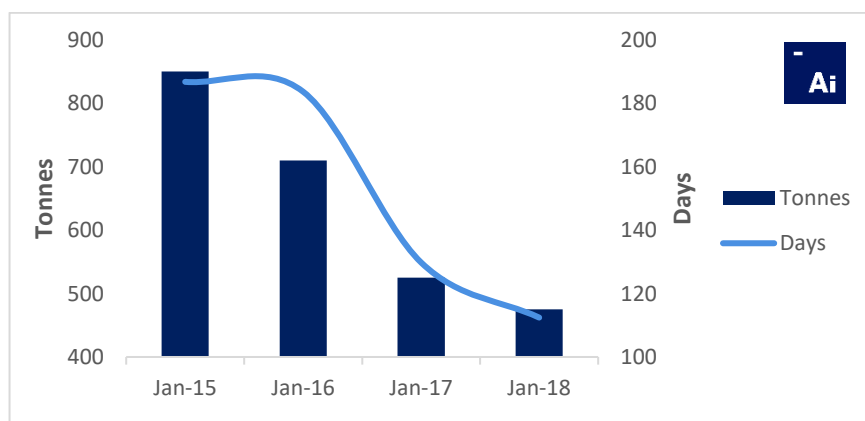
**Figure 8:** Since 2015 global annual consumption has exceeded production



Source: Adamas Intelligence research

To compensate for the growing disparity between global production and consumption since 2015, major suppliers in China have drawn-down historically-accumulated inventories to satisfy demand. As shown in Figure 9, the inventory levels reported by major producers in China have decreased steadily since 2015, from 850 tonnes (187 days of global consumption) in January 2015, to 475 tonnes (112 days of global consumption) in January 2018.

**Figure 9:** Major producer inventories in China have been drawn-down since 2015



Source: Adamas Intelligence research, Asian Metal



## A Market Reliant on Illegal Supplies

Following a review of global dysprosium oxide production, consumption, trade, and inventory levels, it is apparent that end-users of dysprosium have become precariously reliant on China’s illegal production – whether they realize it or not.

In 2017 China supplied approximately 1,750 tonnes of dysprosium oxide (or oxide equivalent) to domestic and foreign buyers (see Figure 10 – China Supply).

Of this 1,750 tonnes, Adamas estimates that approximately 1,000 tonnes was produced in accordance with government-issued production quotas, 440 tonnes was produced illegally (i.e. outside the scope of production quotas), and 310 tonnes was sourced from historically-accumulated inventories (see Figure 10).

In 2017 China exported approximately 200 tonnes of dysprosium oxide (or oxide equivalent in the form of dysprosium metal) to buyers in Japan (82%), South Korea (15%), and a handful of other nations (3%) (see Figure 10 – China Trade).

In 2017 China exported an additional 600 tonnes of dysprosium oxide equivalent contained within NdFeB, and consumed a further 1,050 tonnes domestically in NdFeB for the Chinese market (see Figure 10 – Global Use). Additionally, in 2017 China imported approximately 100 tonnes of dysprosium oxide equivalent contained in high-grade NdFeB, sourced primarily from Japan.

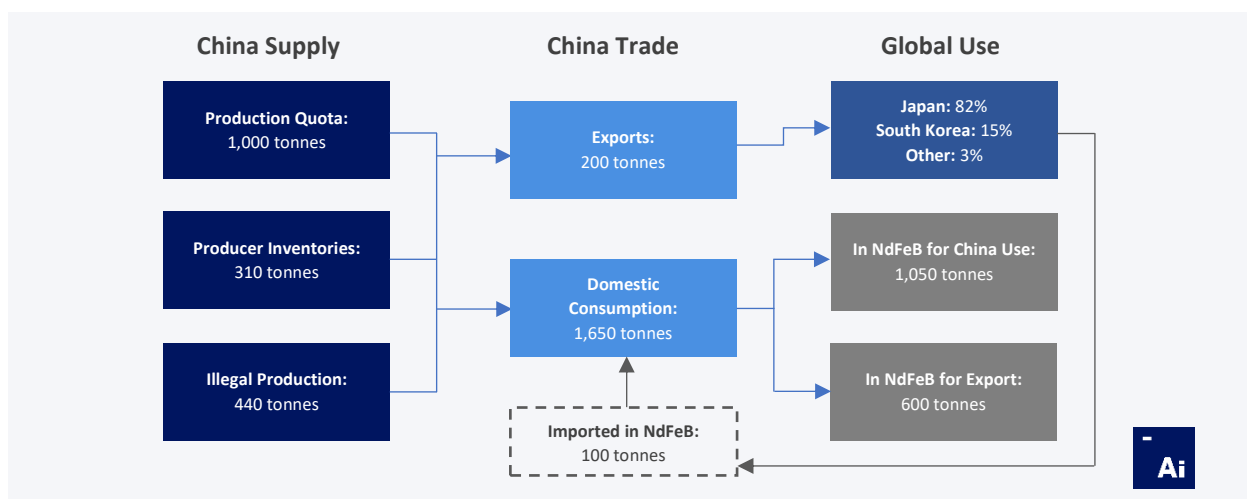
Taking the above-described material flows into account, it is apparent that the global market has grown increasingly reliant on China’s illegal supplies.

Specifically, without the contribution of illegal production in 2017, global consumption would have depleted China’s historically-accumulated inventories (see Figure 9) and pushed the market into short-supply by as early as 2018.

**Looking ahead, if Chinese authorities continue to clamp down on illegal production in the nation with minimal increases in legal production to compensate, China’s producer inventories will be rapidly consumed and supplies (particularly for those importing from China) will become increasingly scarce.**

The global market has become precariously reliant on China’s illegal supplies

Figure 10: Map of dysprosium oxide supply, trade, and use in 2017 demonstrating reliance on illegal supply



Source: Adamas Intelligence research, Asian Metal, China Customs



# NdFeB: Enabler of Modern Technology

## What is it?

Neodymium-iron-boron (“NdFeB”) is a permanent magnet alloy that was developed and commercialized in the 1980s as an alternative to costly samarium-cobalt (“SmCo”) alloy that was developed and commercialized three decades earlier (see Figure 11).

## What is it made of?

As the name suggests, NdFeB alloy is comprised primarily of neodymium, iron, and boron in a Nd<sub>2</sub>Fe<sub>14</sub>B tetragonal crystalline structure, and may contain minor concentrations of praseodymium, dysprosium, terbium, copper, cobalt, niobium, and other metals to optimize the alloy’s properties for certain applications.

## Why is it special?

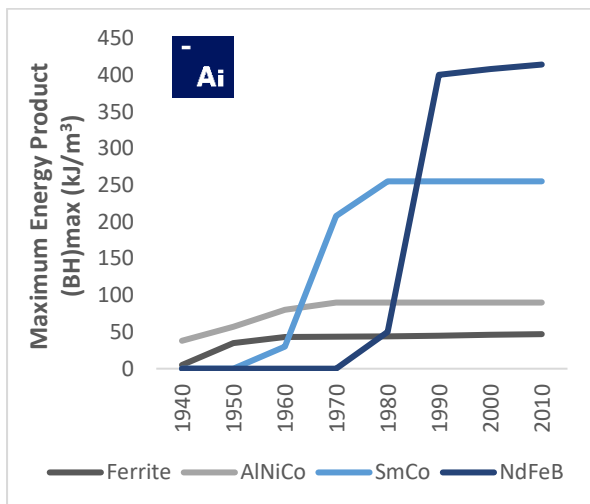
NdFeB permanent magnet alloy is the strongest type of permanent magnet material commercially available today in terms of maximum energy product (i.e. magnetic flux output per unit volume, measured in megagauss-oersteds (MGOe) or Joules per cubic meter (J/m<sup>3</sup>)) (see Figure 11).

As such, NdFeB magnets have largely supplanted SmCo, AlNiCo, and ferrite magnets in many size- and weight-sensitive applications since the 1980s, and simultaneously enabled the conception and miniaturization of a wide array of ubiquitous gadgets and electronics that have pervaded modern society.

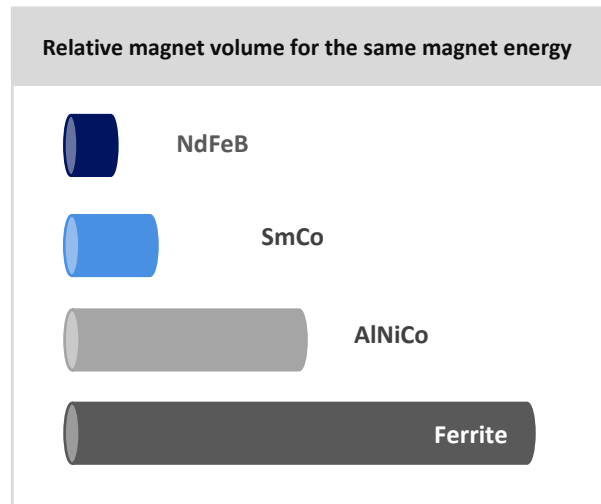
NdFeB permanent magnets are used in hundreds of different end-uses and applications – many of which we interact with daily whether we realize it or not. From mobile phone loudspeakers and vibration motors, to hard disk drives, optical disc drives, electric vehicle traction motors, wind power generators, and beyond – NdFeB permanent magnets are literally all around us.

NdFeB permanent magnets are used in hundreds of applications, many of which we interact with daily

Figure 11: NdFeB is the strongest permanent magnet material commercially available today



Source: after Kallaste et al. (2012), Adamas Intelligence research



Source: Adamas Intelligence research



## Dysprosium is Used in High-Temperature Grades of NdFeB

NdFeB permanent magnet alloy is available in over 50 different grades, each defined by its maximum energy product and thermal coefficient of coercive force.

As shown in Figure 12, each grade of NdFeB is coded with an “N” to signify that it is a NdFeB magnet. The number following the “N” indicates the maximum energy product of the grade in MGOe. The letter or letters following the number (i.e. M, H, SH, UH, EH, AH) indicate the thermal coefficient of coercive force – a metric that corresponds roughly with the maximum operating temperature of the grade.

It should be emphasized that the maximum operating temperature of each grade is approximate. The magnet shape and size can impact the actual maximum temperature and performance, as can environmental conditions, or other components in the total magnetic circuit (i.e. other components in a motor).

Different grades of NdFeB often have slightly different chemical compositions due to the addition of other metals or alloys to modify the magnet’s maximum energy product and/or thermal coefficient of coercive force.

Dysprosium is often added to high-temperature grades of NdFeB as a partial substitute for neodymium. Dysprosium increases the magnet’s thermal coefficient of coercive force and resistance to demagnetization, but generally decreases maximum energy product and increases magnet costs.

**The concentration of dysprosium used in NdFeB ranges from zero weight percent in certain N- and M-series grades to as high as 7.5 weight percent in certain AH-series grades (see Figure 12) although significant variation exists among different producers.**

Dysprosium boosts NdFeB’s maximum operating temperature and resistance to demagnetization

Figure 12: Estimated average dysprosium concentrations in commercially-available grades of NdFeB





## Dysprosium Thrifting

Over the past decade, permanent magnet producers in Japan and China have developed and successfully employed methods for manufacturing high-temperature grades of NdFeB with reduced concentrations of dysprosium (and terbium) or in some cases, have eliminated its use altogether.

Since 2010 these efforts have slashed the average dysprosium concentration used in NdFeB by 50% meaning that the average electric vehicle traction motor produced in 2010 with 'UH' or 'EH' grade magnets used NdFeB containing upwards of 10 weight percent dysprosium (plus a significant concentration of terbium).

Some notable companies at the forefront of developing and employing methods for manufacturing high-temperature grades of NdFeB with reduced concentrations of dysprosium (and terbium) include:

**Hitachi** has developed a method for thermally-treating thin sintered magnets in a dysprosium-vapor-rich environment. The vapor diffuses dysprosium along the boundaries of grains in the sintered magnets, achieving desired levels of coercivity with a 50% reduction in dysprosium usage versus traditional methods.

**TDK** has developed a parallel method, dubbed the HAL process, that selectively diffuses dysprosium along the boundaries of grains in sintered NdFeB magnets, achieving desired levels of coercivity with a 20% to 50% reduction in dysprosium usage versus traditional methods.

**Shin-Etsu** has developed its own method for selectively diffusing dysprosium along grain boundaries which involves the coating of thin sintered magnets with dysprosium oxide and/or dysprosium fluoride slurries and subsequent heating for up to 10 hours at 800 to 900 °C. The technique yields a 60% reduction in dysprosium usage versus traditional methods.

The three aforementioned companies, and others, have been successful in reducing dysprosium concentrations in high-temperature NdFeB permanent magnets through processes of **grain boundary diffusion** ("GBD").

In other cases, magnet manufacturers have successfully reduced dysprosium usage through **grain size refinement** ("GSR") of the NdFeB alloy, which increases the thermal coefficient of coercive force of the magnet, enabling a reduction in dysprosium usage.

**Neo Magnequench** (formerly Molycorp Magnequench) has developed powders for producing hot-pressed isotropic ("MQ2") and hot-extruded anisotropic ("MQ3") fully dense NdFeB magnets with grain sizes 20 to 100 times smaller than traditional sintered NdFeB magnets. Despite having a relatively low maximum energy product, MQ2 magnets contain no dysprosium and can operate at temperatures upwards of 175 °C with low irreversible flux loss, making them suitable for numerous automotive applications.

**Given the pronounced decline in global dysprosium production since 2013, coupled with explosive demand growth for electric vehicle traction motors, wind power generators, industrial robots, and other end-uses of high-temperature NdFeB, Adamas Intelligence believes that if not for the above-described dysprosium thrifting techniques, the global market would currently be facing substantial dysprosium shortages.**

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Since 2010, the concentration of dysprosium used in most grades of NdFeB has been reduced by 50%

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This reduction has been realized through use of grain boundary diffusion and grain size refinement

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# Welcome to the EV Revolution

## Fueled by Ambitious Government Policy

Over the past decade, the global market for electric vehicles has grown incredibly fast on the back of ambitious government policy and incentives, coupled with cost-focused innovation and investment from the auto industry.

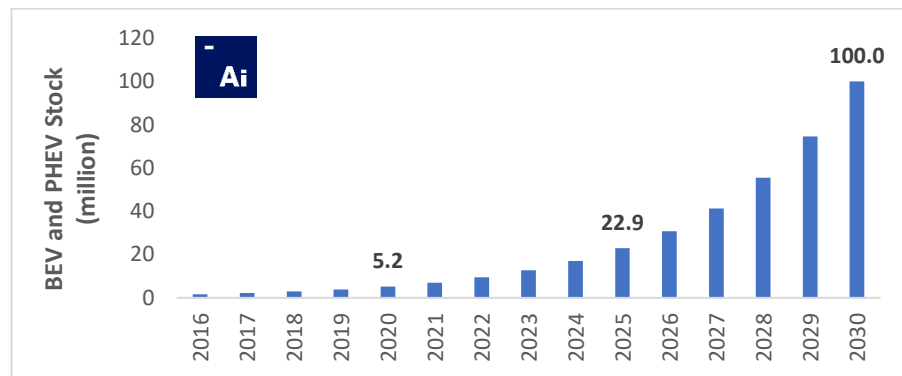
Meeting the Paris Agreement targets for electromobility will require **annual plug-in electric vehicle sales of 35 million by 2030**

In December 2015, leaders from 195 countries gathered in Paris, France, for the 21<sup>st</sup> Conference of the Parties to the United Nations Framework Convention on Climate Change and forged an agreement (“the Paris Agreement”) aimed at collectively reducing emissions of greenhouse gases to limit global warming.

Born out of the Paris Agreement was the Paris Declaration on Electromobility which calls for increasing the global stock of battery and plug-in hybrid electric vehicles on the road to 100 million by 2030 from just over 1 million at the start of 2016 (see Figure 13).

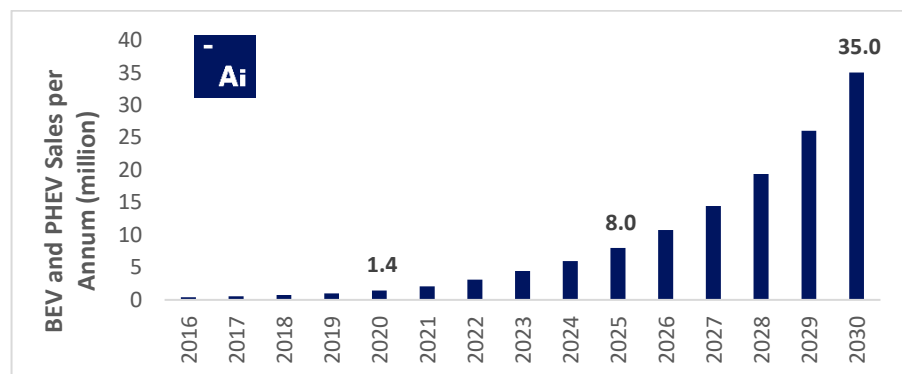
As shown in Figure 14, reaching this target will require global annual sales of battery and plug-in hybrid electric vehicles to reach approximately 1.4 million by 2020, 8.0 million by 2025, and 35.0 million units by 2030, assuming an eight-year operating life per vehicle.

**Figure 13:** The Paris Agreement calls for 100 million B/PHEVs on the road by 2030



Source: Inferred from Paris Agreement electromobility targets

**Figure 14:** Reaching the target will require annual B/PHEV sales of 35M by 2030



Source: Inferred from Paris Agreement electromobility targets



An ever-growing list of nations have announced plans to ban future sales of gasoline- and diesel-powered passenger vehicles

### Driven by Ambitious National Targets

Towards the goal of meeting or exceeding the Paris Agreement commitments, an ever-growing list of nations have since announced plans to ban sales of new gasoline- and diesel-powered passenger vehicles from as early as 2025.

Norway has put forward a plan to ban sales of new internal combustion energy powered passenger vehicles by as early as 2025 (see Figure 15). While the Norwegian passenger vehicle market is relatively small (0.2 million sales in 2017), the move would pave a path forward for other nations to follow suit.

By 2030, at least five other nations have put forward plans to ban sales of new gasoline- and diesel-powered passenger vehicles, including Germany, Ireland, Israel, India, and the Netherlands (see Figure 15). In 2017 these five nations collectively comprised a passenger vehicle market totaling 8.7 million vehicles per annum.

By 2040, another three nations and one U.S. state have put forward plans to ban sales of new gasoline- and diesel-powered passenger vehicles; namely the U.K., France, Taiwan, and the U.S. state of California (see Figure 15). As of 2017, these three nations plus the state of California represented a collective passenger vehicle market of 7.8 million vehicles per annum.

In total, the targets of these nine nations and one U.S. state have potential to fuel electric vehicle sales to upwards of 10 million per annum by 2030 and 20 million per annum by 2040.

In the coming two to three years, Adamas Intelligence believes numerous other nations, including China, will announce similar plans for banning new gasoline- and diesel-powered vehicle sales within the 2040 timespan, accelerating the global shift to electric mobility.

**Figure 15:** A growing list of nations have announced plans to ban sales of new gasoline- and diesel-powered passenger vehicles from as early as 2025

Country	Ban Commences	Passenger Vehicle Market Size (2017)
Norway	2025	0.2 million
Germany	2030	3.8 million
Ireland	2030	0.2 million
Israel	2030	0.3 million
India	2030	4.0 million
Netherlands	2030	0.4 million
U.K.	2040	2.9 million
France	2040	2.6 million
Taiwan	2040	0.3 million
U.S. (California)	2040	2.0 million

Source: MarkLines, Adamas Intelligence research

## Echoed by Ambitious OEM Strategies

In response to ambitious government policy and a growing list of nations planning to ban sales of gasoline- and diesel-powered vehicles, virtually all the world's leading automakers have announced equally ambitious electric vehicle production, sales, and deployment targets (see Figure 16).

For example, Volkswagen is targeting sales of 2 to 3 million electric vehicles per annum by 2025, and plans to only manufacture battery electric vehicles and plug-in hybrid electric vehicles from 2030 on (see Figure 16).

Similarly, Toyota plans to electrify its entire vehicle lineup by 2025 and is targeting sales of 5.5 million battery electric and plug-in hybrid electric vehicles annually by 2030 – an amount equal to roughly half the company's global sales in 2017.

The ambitious targets listed in Figure 16 speak to an industry on the precipice of rapid change. If just a fraction of the automakers below successfully realize their near-term aspirations, global electric vehicle deployment will accelerate well-beyond the Paris Agreement target by 2030.

**Figure 16:** Virtually all leading automakers have announced near-term electrification strategies and targets

Group	2017 Annual Sales (All Pass. Vehicles)	2017 Annual Sales (EV Only)	EV Sales and Deployment Targets
Renault - Nissan	10.6 million	0.3 million	Aims for 20% of sales in 2022 to be EVs
Volkswagen	10.5 million	0.1 million	Targeting sales of 2 to 3 million EVs annually by 2025; plans to only offer B/PHEVs from 2030
Toyota	10.2 million	1.3 million	All vehicles electrified by 2025; targeting sales of 5.5 million BEVs and PHEVs per annum by 2030
GM	10.0 million	0.1 million	Plans to offer 20 BEV models by 2023; targeting sales of 1 million BEVs annually by 2026
Hyundai - Kia	7.3 million	0.2 million	Targeting 14 BEV models and 24 PHEV, HEV, and FCEV models by 2025
Ford	6.2 million	0.1 million	Plans to offer 16 BEV models and 24 PHEV and HEV models by 2022
Honda	5.3 million	0.2 million	Aims for two-thirds of sales to be EVs by 2030
PSA	3.6 million	0.01 million	Plans to offer an electrified variant of every model it produces by 2025
Daimler	3.3 million	0.05 million	Plans to offer an electrified variant of every Mercedes-Benz model by 2022
BMW	2.2 million	0.1 million	Aims for 15% to 25% of group sales to be EVs by 2025
BAIC	1.3 million	0.1 million	Targeting sales of 0.5 million B/PHEVs by 2022; plans to only offer B/PHEV from 2025
Changan	1.3 million	0.03 million	Plans to only offer B/PHEV from 2025
Volvo	0.5 million	0.02 million	Plans to only produce EVs from 2019; targeting sales of 1 million EVs annually by 2025
Tesla	0.1 million	0.1 million	Targeting production of 0.5 million BEVs in 2018 and 1 million BEVs in 2020

Source: MarkLines, EV-Volumes, Adamas Intelligence research

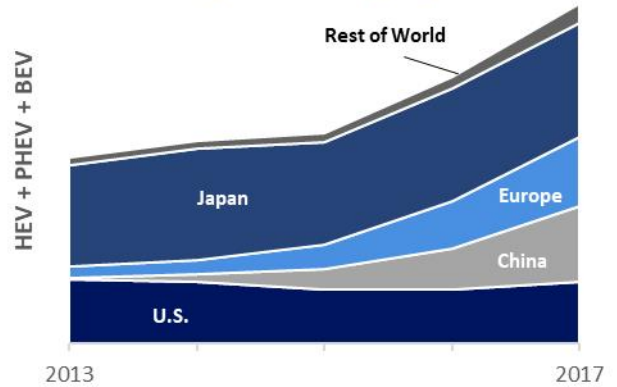
# China in the Fast Lane

From 2013 through 2017, electric vehicle sales in China increased at a mind-blowing CAGR of 142.9%.

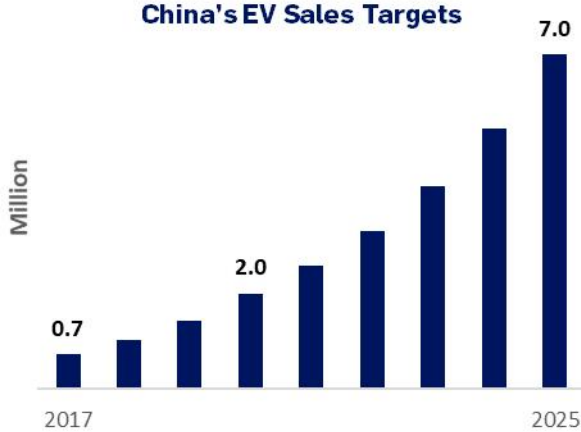
Over the same period, China's share of global annual electric vehicle sales increased to 22.6% in 2017 from a near-negligible 1.2% in 2013.

China is currently the largest market globally for plug-in electric vehicles and is second only to Japan for sales of all electric vehicle types combined.

### EV Registrations by Region



### China's EV Sales Targets



China is targeting sales of 2 million plug-in hybrid and battery electric vehicles annually by 2020, and 7 million annually by 2025.

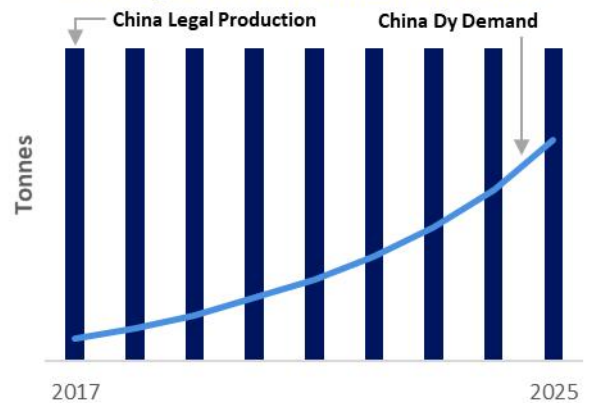
Based on China's sales growth to-date, the nation's 2020 and 2025 targets appear easily attainable.

If China reaches its 2025 target, the nation alone will put the world on a path towards achieving over 80% of the Paris Agreement target.

By 2025 China's demand for dysprosium for electric vehicle traction motors alone will amount to 70% of the nation's current legal production level, emphasizing the imminent need for new supplies.

If global production does not increase to fill the impending void **Adamas Intelligence** believes the probability of illegal production resurging in China is **very high** – an outcome that would fundamentally increase supply risks for end-users of NdFeB.

### China Dy Demand for Traction Motors





## Electrification is Upending the Automotive Supply Chain

The rapid acceleration of electric vehicle sales globally is upending the traditional automotive supply chain, creating unprecedented opportunities for new suppliers offering new components that utilize new materials.

Regarding rare earth elements, the deployment of electric vehicles is increasing demand for NdFeB magnets, which are used in nearly all traction motors and generators deployed to-date, as well as dozens of lightweight micro-motors used to power vehicle functions and accessories, such as power steering, power seats, power windows, and more.

A 2017 study by investment bank UBS found that in the case of the Chevrolet Bolt battery electric vehicle, new entrant LG Chem alone supplies a staggering 56% of the parts, components, and electronics the vehicle contains (see Figure 17).

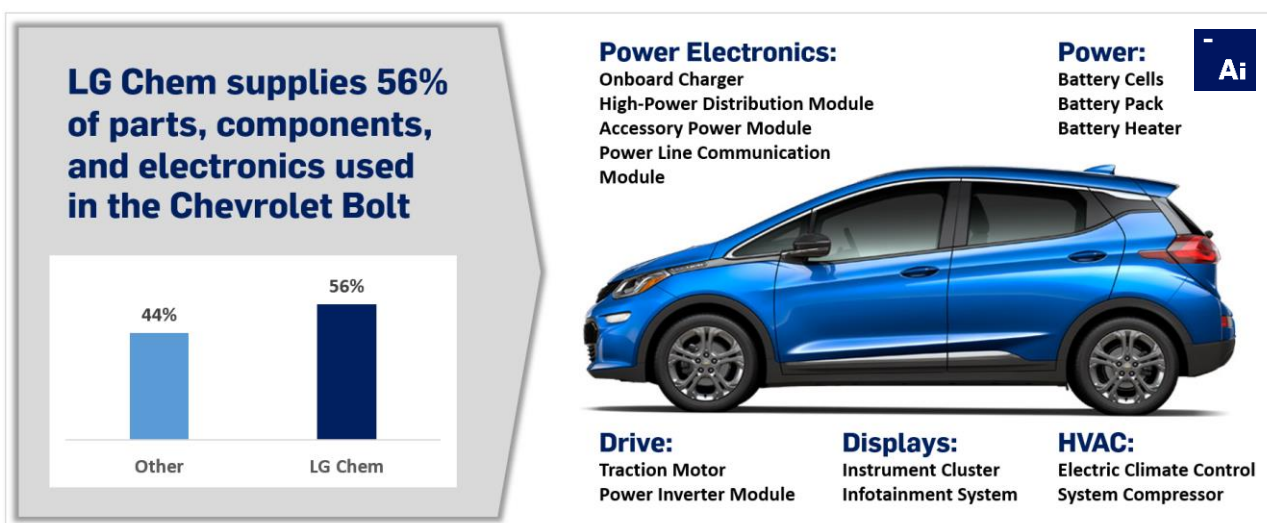
The study also revealed that, in the case of the Chevrolet Bolt, traditional Tier-1 suppliers contribute solely to parts, components, and electronics that operate outside the electric powertrain suggesting that traditional suppliers may be poised to see a rapid downturn of their addressable market as electric vehicle sales rise.

However, for suppliers of battery active materials, such as lithium, cobalt, nickel, and graphite, as well motor metals, such as neodymium, praseodymium, and dysprosium, the ongoing global shift to electric mobility will foster a wealth of near-term demand growth.

**Looking ahead, Adamas Intelligence research indicates that increasing electric vehicle range (mileage per charge) will remain a primary focus for automakers thus we expect that lightweight PM micro-motors will continue finding more-and-more applications in next generation models.**

Lightweight PM micro-motors will continue finding more-and-more applications in next generation EV models

Figure 17: New entrant LG Chem supplies 56% of parts, components, and electronics in the Chevrolet Bolt



Source: UBS, General Motors, Adamas Intelligence research



PHEVs and BEVs use electric motors of similar power – an important fact in the context of rare earth demand

### Three Main Types of Electric Vehicles

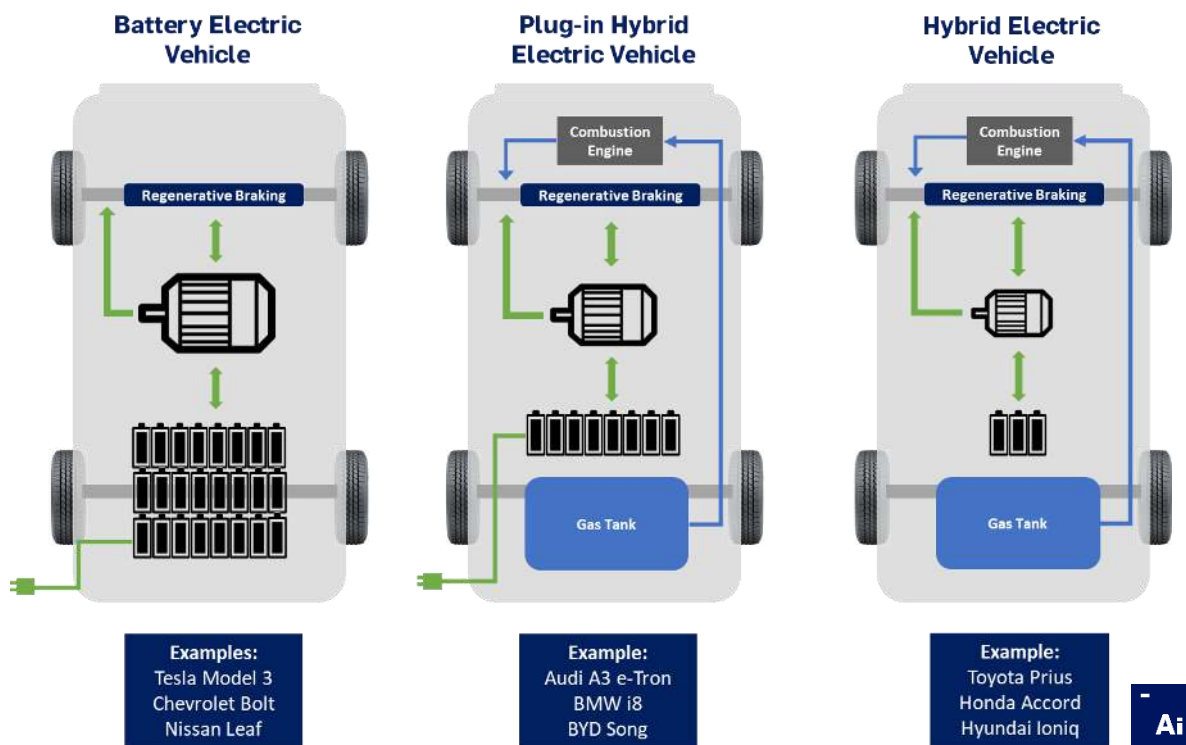
There are three main types of electric vehicles: battery electric vehicles (“BEVs”), plug-in hybrid electric vehicles (“PHEVs”), and hybrid electric vehicles (“HEVs”) – all of which contain electric traction motors, most often containing NdFeB permanent magnets.

**Battery electric vehicles** are powered solely by electricity from an onboard battery. Most BEVs have a driving range of 150 km to 300 km, while some luxury models have ranges up to 500 km. BEVs are propelled by one or more electric motors that convert energy stored in the battery into motion.

**Plug-in hybrid electric vehicles** on the other hand are powered by electricity from an onboard battery, and when the battery is depleted, switch to an internal combustion engine powered by gasoline or diesel. While PHEVs typically contain much smaller batteries than BEVs, they use electric motors of similar size – a noteworthy fact in the context of rare earth demand for electric vehicles.

**Hybrid electric vehicles**, like their plug-in hybrid counterparts, combine an internal combustion engine system with an electric propulsion system but generally cannot be propelled by electricity alone. In a typical HEV, the internal combustion engine and electric motor transmit power simultaneously thereby improving fuel efficiency.

Figure 18: Generalized comparison of the three main electric vehicle types and powertrain architectures



Source: Adamas Intelligence research





## Three Main Types of Traction Motors

There are three main types of electric vehicle traction motors in commercial use: permanent magnet (“PM”) motors, induction motors, and salient pole synchronous reluctance (“SPSR”) motors. Of the three motor types, PM motors are the only variety that contain rare earth permanent magnets (see Figure 19).

PM motors are the most commonly used traction motors in electric vehicles today

**Permanent magnet motors** are the most commonly used traction motor type in electric vehicles today. A PM motor has rare earth permanent magnets mounted on or embedded in its rotor, which cause the rotor to spin when exposed to a rotating magnetic field produced by windings in the stator. PM traction motors are up to 15% more efficient than induction motors, and are the most power dense type of traction motor available (in terms of kW/kg and kW/cm<sup>3</sup>).

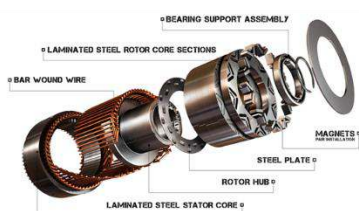
**Induction motors** are the second most commonly used type of traction motors in electric vehicles today. In an induction motor, alternating current is fed through distributed windings in the stator core, inducing a current in secondary windings on the rotor, causing it to rotate relative to the fixed stator. Induction motors are less efficient than PM motors, particularly at low speed, and are heavier and more voluminous.

**Salient pole synchronous reluctance motors** have electromagnets embedded in the rotor, as opposed to permanent magnets, such as in a PM motor. The electromagnets cause the rotor to spin when exposed to a rotating magnetic field produced by windings in the stator. SPSR traction motors are more efficient than induction motors and relatively cheap to manufacturer but offer lower peak efficiency and lower torque and power density than PM traction motors.

In recent years, a number of variants of the aforementioned motors have been developed – most notably the PM-assisted reluctance motor used in the BMW i3 and BMW i8 – a hybrid motor type that contains permanent magnets in the rotor and external flux influencing groups that improve efficiency at high revolutions.

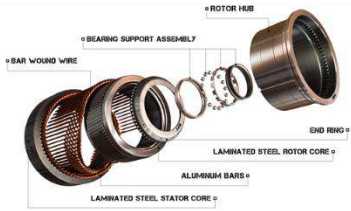
Figure 19: Generalized comparison of the three main traction motor types used in electric vehicles

### Permanent Magnet Motor



Examples:  
BMW i3  
BYD e6  
Chery eQ

### Induction Motor



Examples:  
Tesla Model S  
Renault Twizy  
BJEV EC180

### Salient Pole Synchronous Reluctance Motor



Examples:  
Renault Zoe  
Renault Fluence  
Smart Fortwo

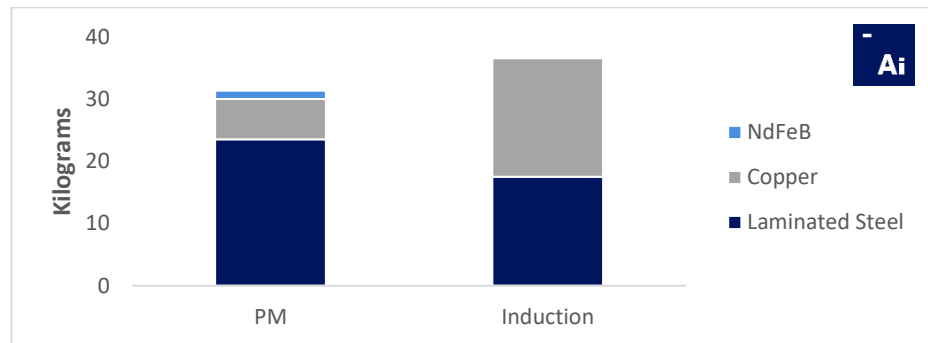


Source: General Motors, Renault, Adamas Intelligence research

## Traction Motor Materials Cost Comparison

As noted above, PM traction motors are more power dense than alternative traction motor types. In Figure 20 below we can see that the combined weight of metals used in a PM traction motor is approximately 16% lower than the combined weight of metals used in a comparable induction motor.

**Figure 20:** Metals and materials usage in comparable PM and induction motors



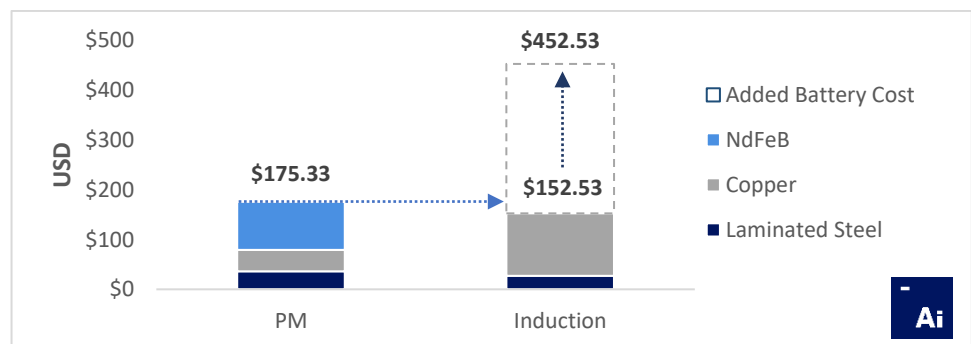
Source: UBS, Adamas Intelligence research

However, in a comparison of material input costs, as shown in Figure 21, it can be observed that the direct bill of materials for a PM traction motor is approximately 15% higher than that of a comparable induction motor – primarily because of NdFeB magnet costs – a fact that proponents of induction motors often cite as the architecture’s main advantage.

What this argument ignores however is that induction motors are upwards of 15% less efficient than PM traction motors, especially at low speeds, thus an automaker using an induction motor may need to compensate with a larger (and costlier) battery pack so as to offer a competitive driving range (mileage per charge).

As shown in Figure 21 below, the cost of increasing the capacity of a 60-kWh battery pack by just 5% to compensate for use of an induction motor can increase powertrain costs by upwards of \$300 (optimistically assuming an added cost of just \$100/kWh), **suggesting that use of a PM traction motor is substantially more economically attractive despite higher direct material costs.**

**Figure 21:** Bill of materials for comparable PM and induction motors



Source: Adamas Intelligence research



# Global EV Market Review

## China is Poised to Pull Ahead of the Pack

Collectively, from 2013 through 2017 global sales of electric vehicles increased at a CAGR of 16.3%, from 1.74 million units to 3.18 million units (see Figure 22). Global sales of BEVs increased a blistering CAGR of 60.5%, sales of PHEVs increased at a CAGR of 46.6%, and sales of HEVs increased at a CAGR of 6.3%.

Stemming from these disparate growth rates, BEVs and PHEVs have made ever-larger contributions to overall electric vehicle sales versus HEVs since 2013, netting BEVs and PHEVs a combined 38.5% of total sales in 2017 versus just 12.2% in 2013 (see Figure 22).

From 2013 through 2017 electric vehicle sales in China grew at an unprecedented CAGR of 142.9%, boosting China's share of global annual electric vehicle sales to 22.6% in 2017 from a near-negligible 1.2% in 2013 (see Figure 22).

Over the same period, electric vehicle sales in Europe grew at a towering CAGR of 56.7%, lifting Europe's collective share of global annual electric vehicles sales to 20.4% in 2017 from just 6.2% in 2013 (see Figure 22).

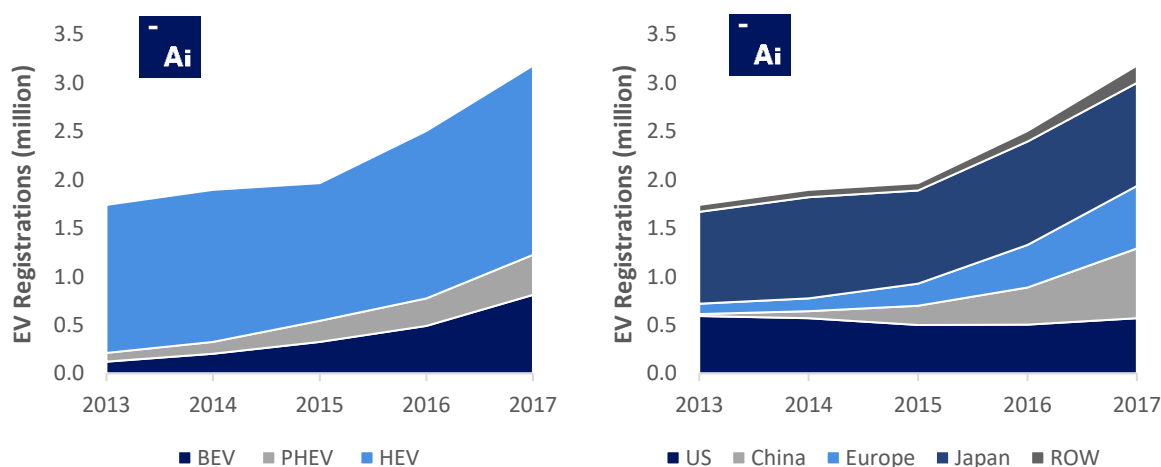
From 2013 through 2017, electric vehicle sales in the U.S. decreased at a CAGR of -0.9%, eroding the nation's share of global annual electric vehicle sales to 18.0% in 2017 from 34.1% in 2013 (see Figure 22).

Over the same period, electric vehicle sales in Japan, the world's largest electric vehicle market, increased at a CAGR of just 2.9%, dropping Japan's share of global electric vehicle sales to 33.4% in 2017 from 54.5% in 2013 (see Figure 22).

Lastly, from 2013 through 2017 electric vehicle sales in the rest of the world ("ROW") increased at a combined CAGR of 26.5%, lifting the collective's market share to 5.7% in 2017 from 4.0% in 2013 (see Figure 22).

On average since 2013, sales of electric vehicles in China have increased by 142.9% annually

Figure 22: From 2013 through 2017 electric vehicle sales in China increased at a CAGR of 142.9%



Source: MarkLines, EV-Volumes, Adamas Intelligence research



## PM Traction Motors Dominate the Global Fleet

From 2013 through 2017 permanent magnet traction motors were used in nearly all EVs sold globally, although the technology has ceded market share to alternative motor types in recent years – primarily due to Tesla’s use of induction motors in its Model S, Model X, and Roadster.

That said – Tesla has switched to permanent magnet motors for its latest release, the Model 3, thus we expect the market share of induction motors to recede in the coming years.

In a recent interview with Electrek, Tesla’s principal motor designer justified the switch as a “tradeoff between motor cost, range, and battery cost” and explained that “the permanent magnet machine better solved [Tesla’s] cost minimization function, and it was optimal for the range and performance target”.

From 2013 through 2017 the number of electric vehicles sold globally with a permanent magnet traction motor (or motors) increased at a CAGR of 14.4%, from 1.7 million to 2.9 million, buoyed ever-higher by strong sales in China.

Over the same period, the number of electric vehicles sold globally with an induction traction motor (or motors) increased at a CAGR of 56.4%, from 41,200 in 2013 to 246,500 in 2017, primarily on the back of Tesla’s Model S and Model X.

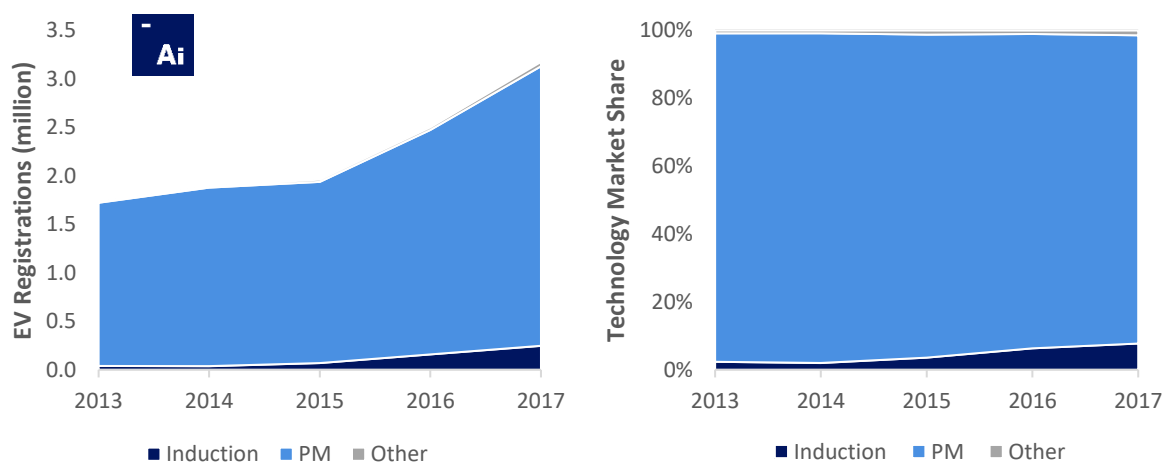
From 2013 through 2017 the number of electric vehicles sold globally with a salient pole synchronous reluctance motor increased at a CAGR of 31.3%, from 15,000 to 44,700 units, primarily resulting from growing sales of Renault’s Zoe, Fluence, and Kangoo electric vehicles, as well as Daimler’s Smart Fortwo and Forfour models.

Overall in 2017, 91% of electric vehicles sold globally were equipped with permanent magnet traction motors, down from 97% in 2013. An additional 8% of electric vehicles sold in 2017 came equipped with induction motors, up from 2% in 2013, and the remaining 1% of electric vehicles sold each year were equipped with salient pole synchronous reluctance motors (see Figure 23).

*“The permanent magnet machine better solved our cost minimization function”*

**Konstantinos Laskaris,**  
Principal Motor Designer,  
Tesla Inc.

**Figure 23:** From 2013 through 2017 over 90% of EVs sold globally each year contained PM traction motors



Source: Adamas Intelligence’s “EV, Motor Capacity, and Motor Metals Tracker”



## PM Traction Motors Dominate by Total Motor Power

In general, motor power is a function of the mass (and grade) of NdFeB used in a permanent magnet traction motor. As such, total motor power is a primary determinant of overall demand.

Collectively, from 2013 through 2017, the total combined motor power of all electric vehicles sold globally each year increased at a CAGR of 23.1%, from 109,000 MW in 2013 to 250,000 MW in 2017, resulting from strong electric vehicle sales growth and higher average motor power in newer electric vehicle models.

Over the same period, the combined power of all permanent magnet traction motors sold each year increased at a CAGR of 19.2%, while the combined power of all induction motors increased at a CAGR of 59.7%, and the combined power of all salient pole synchronous reluctance motors sold increased at a CAGR of 34.3%.

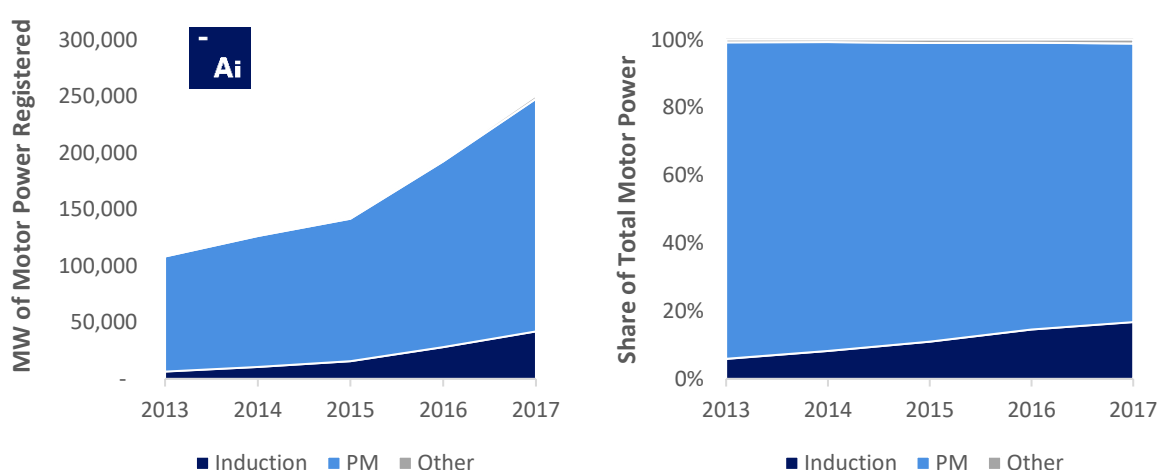
Despite induction motors being present in just 8% of all electric vehicles sold globally in 2017, these vehicles (namely the Tesla Model S and Model X) have substantially higher motor power (kW or horsepower) than the average PM- or SPSR -powered vehicle, netting induction motors a 17% of the market in 2017 in terms of total motor power sold (see Figure 24).

Permanent magnet traction motors comprised 82% of the total motor power sold in 2017, down from 93% in 2013, and salient pole synchronous reluctance motors made up 1% of the total power sold in 2017, the same fraction as in 2013 (see Figure 24).

**While the historic trend would suggest that induction motors are poised to increasingly capture market share, we believe the opposite is true given Tesla’s recent switch to permanent magnet motors in its mass-market Model 3.**

In general, motor power is a function of the mass of NdFeB used in a PM traction motor

Figure 24: From 2013 through 2017 PM traction motors dominated EV sales by total motor capacity



Source: Adamas Intelligence’s “EV, Motor Capacity, and Motor Metals Tracker”



## Global Average Motor Power is Steadily Increasing

From 2013 through 2017, the global sales-weighted average PM traction motor power increased by 18%, from 61 kW (82 hp) to 71 kW (95 hp) (see Figure 25 – red line).

Over the same period, the sales-weighted average power of all PM traction motors used in HEVs increased by 9%, the sales-weighted average power of all PM traction motors used in BEVs increased by 7%, and the sales-weighted average power of all PM traction motors used in PHEVs decreased by 13% (see Figure 25 – left side).

Interestingly, as shown in Figure 25 (left side), the sales-weighted average PM traction motor power of all PHEVs sold each year from 2013 through 2017 was 55 to 110% higher than the sales-weighted average PM traction motor power of all BEVs sold each year.

This discrepancy occurs for a couple of reasons. First, it occurs because PHEV models sometimes contain separate permanent magnet generators, in addition to permanent magnet traction motors, thereby increasing the vehicle’s collective motor-generator capacity (i.e. Cadillac ELR, Toyota Prius PHEV, Chevrolet Volt).

Second, this discrepancy occurs because of high sales volumes of several high-power PHEV models in China, including the BYD Qin PHEV (220 kW), the BYD Song PHEV (220 kW), and the BYD Tang PHEV (220 kW), since 2013.

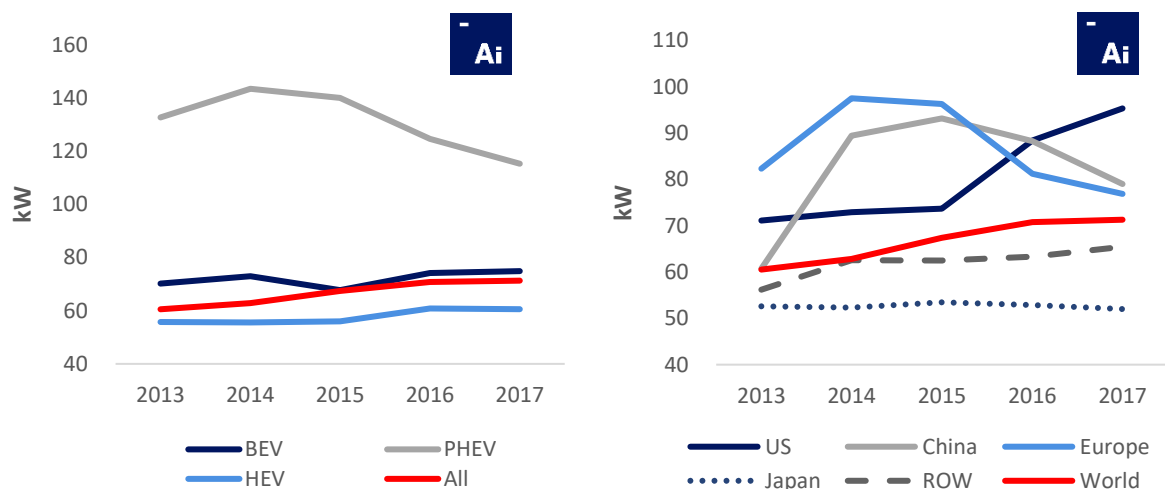
Globally, the U.S. sold the most powerful PM traction motor -powered electric vehicles on average in 2017 (95 kW), followed by China (79 kW), Europe (77 kW), the rest of world (“ROW” – 65 kW), and Japan (52 kW) (see Figure 25 – right side).

Despite being the largest market for electric vehicles globally, the sales-weighted average motor capacity in Japan is significantly lower than that of other regions (see Figure 25) due to the high proportion of HEVs sold relative to BEVs and PHEVs.

In 2017 the average PM traction motor deployed globally had a power of 71 kW, up 18% from 2013 \*

\* The average power refers to sales-weighted average per vehicle, not necessarily per individual motor.

Figure 25: Since 2013 the global sales-weighted average PM traction motor power has increased steadily



Source: Adamas Intelligence’s “EV, Motor Capacity, and Motor Metals Tracker”



In 2017 the average PM traction motor deployed globally contained 1.35 kg of NdFeB, up 14% from 2013 \*

\* The average NdFeB mass may be contained in multiple traction motors/generators per vehicle.

### Mass of Magnet Used per Motor Also Increasing

As the global sales-weighted average PM traction motor power increased in recent years, so too did the amount of NdFeB permanent magnet used per average motor (or motors if multiple per vehicle), albeit at a slower rate (see Figure 26 – left side).

From 2013 through 2017 the global sales-weighted average PM traction motor power increased by 18%, from 61 kW to 71 kW, while the amount of NdFeB permanent magnet used per average motor (or motors if multiple per vehicle) increased by 14%, from 1.2 kg to 1.35 kg (see Figure 26 – left side).

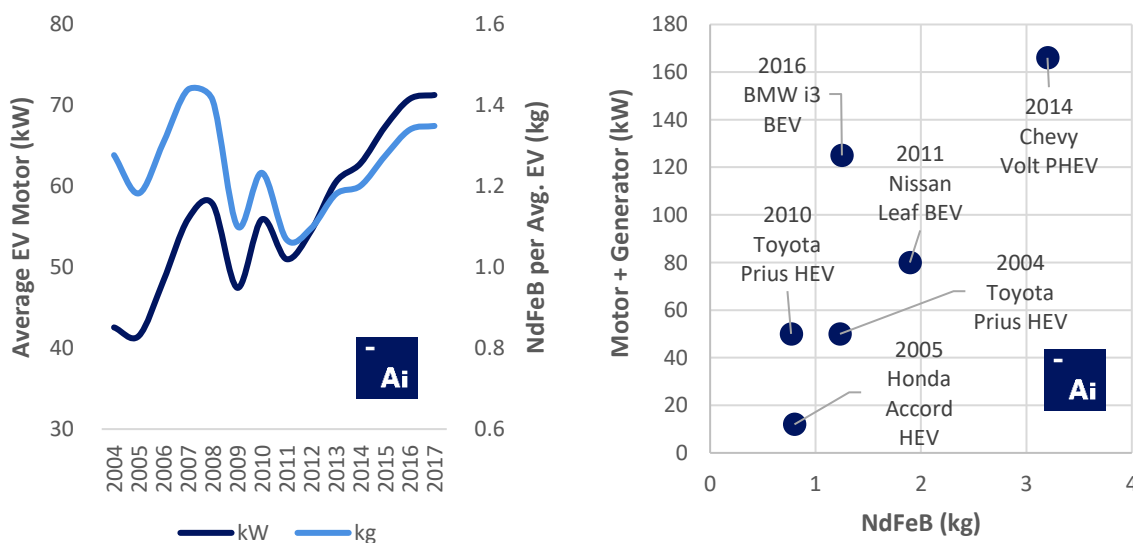
As observed in Figure 26, from 2004 through 2013 the NdFeB power factor (motor power yielded (kW) per kilogram of NdFeB) increased by 54% as automakers and motor manufacturers optimized next-generation motor designs and improved materials efficiency (i.e. BMW’s PM-assisted reluctance motor).

From 2013 through 2017, however, Adamas Intelligence estimates the NdFeB power factor increased by just 5% further, which we attribute to the following:

- First, many of the electric vehicles released in 2013 (or 2014/15) continue to be sold today and have not had major powertrain updates since inception.
- Second, opportunities for major NdFeB power factor improvements beyond the current status quo are increasingly limited without a fundamental motor redesign, such as that undertaken by BMW for the commercial BMW i3 BEV and i8 PHEV models.

**Looking ahead, our research suggests that future NdFeB power factor improvements will be largely offset by increases in average motor power, resulting in the stabilization of NdFeB usage (in kg) per average motor.**

**Figure 26:** From 2013 through 2017 the amount of NdFeB used per average traction motor increased by 14%



Source: Adamas Intelligence’s “EV, Motor Capacity, and Motor Metals Tracker”



## Mass of Dysprosium Used per Motor Has Stabilized

As discussed on Page 15, in recent years the global dysprosium oxide market experienced a pronounced retraction in demand due to techniques developed and employed by permanent magnet manufacturers that reduce the concentration of dysprosium used in certain grades of NdFeB – including grades used in electric vehicle traction motors.

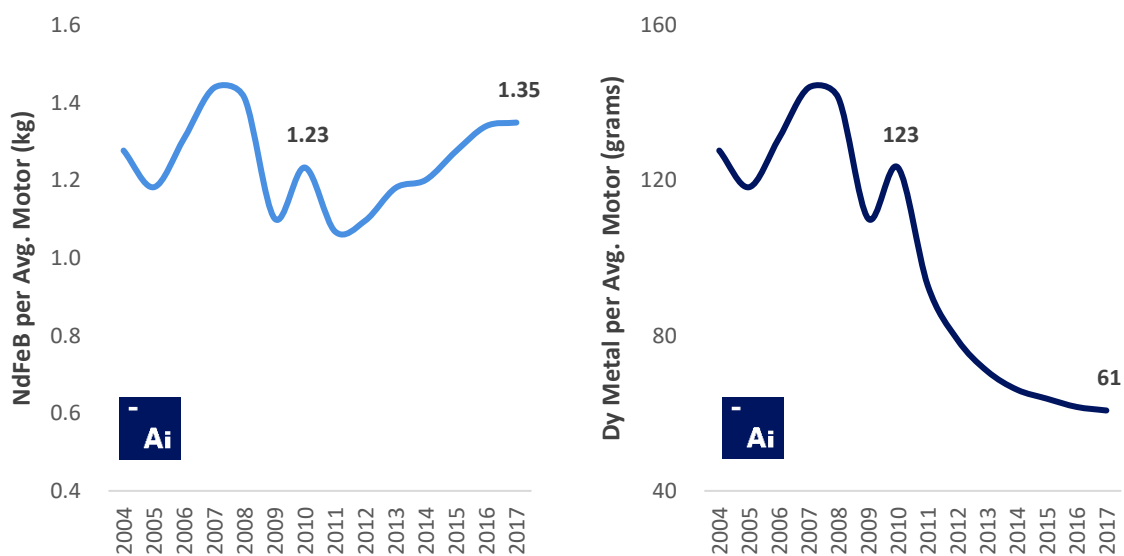
Since 2010, Adamas Intelligence research suggests that these efforts, in combination with NdFeB power factor improvements, have led to a more-than 50% reduction in dysprosium usage per average PM traction motor – from 123 grams per motor in 2010 to 61 grams in 2017 (see Figure 27).

However, from 2013 through 2017, Adamas Intelligence estimates that the amount of dysprosium used per average PM traction motor has been relatively stable (see Figure 27 – right side) as reductions in the concentration of dysprosium used in NdFeB have been offset by increases in average motor power and NdFeB usage per motor (see Figure 27 – left side).

**Looking ahead, we expect further reductions in the concentration of dysprosium used in NdFeB for traction motors to be largely offset by increases to average motor power, resulting in relatively stable dysprosium usage per average traction motor in the years to come.**

Looking ahead,  
dysprosium usage  
per average  
traction motor is  
expected to remain  
relatively stable

Figure 27: Dysprosium reduction in NdFeB has cut usage-per-average-motor in half since 2010



Source: Adamas Intelligence’s “EV, Motor Capacity, and Motor Metals Tracker”



Upwards of **40%** of dysprosium input material enters waste streams along the value chain from mine to motor

### Mine to Motor Losses

Adamas Intelligence research suggests that approximately 40% of the initial mass of dysprosium oxide input material enters waste streams along the value chain from mine to motor.

As such, for every gram of dysprosium metal used in an electric vehicle traction motor, 1.67 grams of dysprosium oxide is drawn into the value chain.

During conversion of dysprosium oxide to dysprosium metal (or ferro-alloy), approximately 13% of the input mass is lost as a result of deoxidation and an additional 4% is lost to processing yields (see Figure 28).

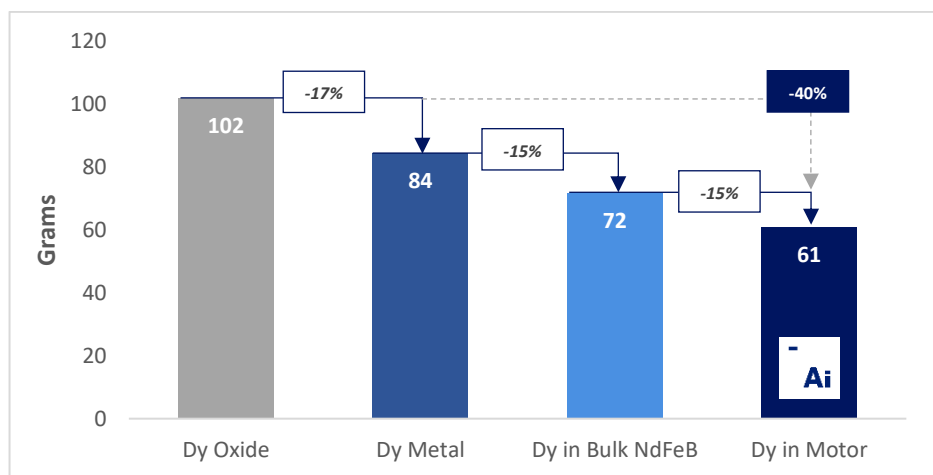
During manufacture of bulk NdFeB ingots, strip cast, or powder an additional 10 to 15% of the dysprosium metal or dysprosium-ferro-alloy input mass is lost to manufacturing yields and losses during handling (see Figure 28).

Lastly, during crushing, sintering, cutting, diffusing, polishing, coating, and installation of the final NdFeB magnets into an electric vehicle traction motor, an additional 10 to 15% of the NdFeB precursor is lost (see Figure 28).

Taking these compound losses into account, it can be observed in Figure 28 below that while the average PM traction motor in 2017 contained 61 grams of dysprosium metal, **a total of 102 grams of dysprosium oxide was consumed along the value chain from mine to metal to magnet to motor.**

With upwards of 40% of dysprosium input material entering waste streams, recycling and recovery have potential to make a meaningful contribution to supply as the market continues to grow.

**Figure 28:** Estimated dysprosium losses from mine to metal to magnet to motor



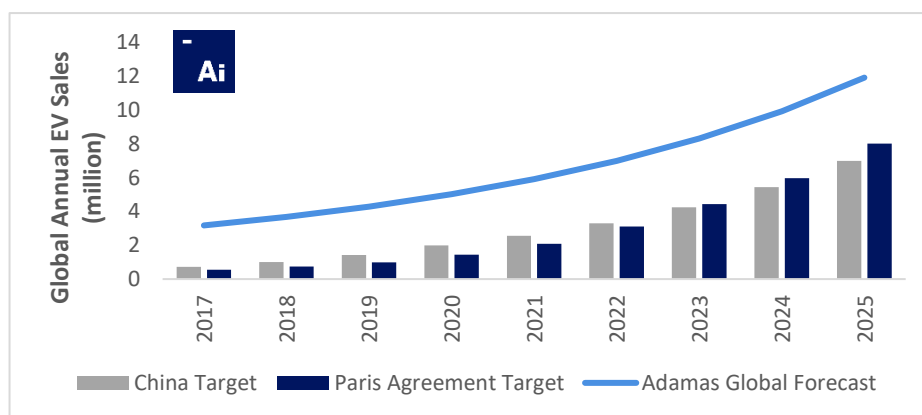
Source: Adamas Intelligence research

# Global EV Market Outlook to 2025

## Global EV Sales Approaching 12 Million per Annum

From 2017 through 2025 Adamas Intelligence forecasts that global annual electric vehicle sales will conservatively increase from 3.2 million to 11.9 million units – a projection that is well-aligned with the Paris Agreement targets (see Page 16), along with China’s own electric vehicle sales target (see Page 19).

**Figure 29:** Global annual EV sales to conservatively rise to 11.9 million by 2025

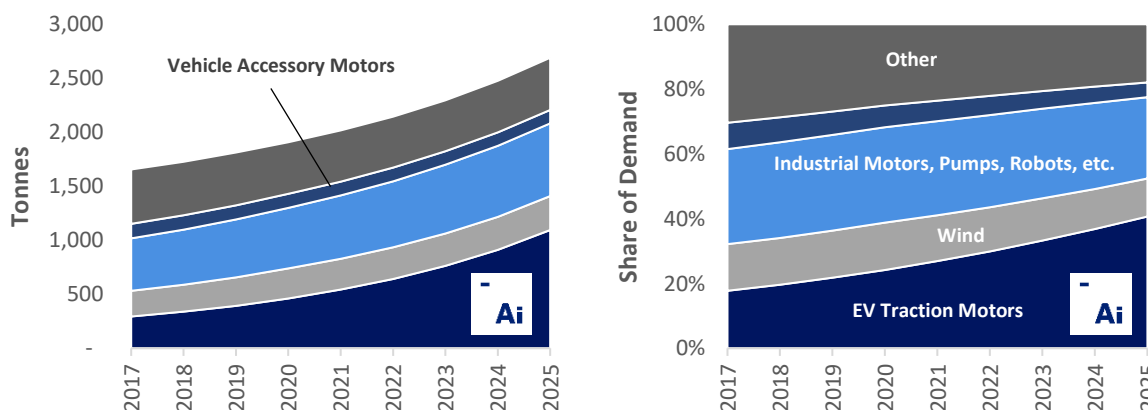


Source: Adamas Intelligence research

## Traction Motors to Become the Dominant Use of Dysprosium

Assuming 90% of electric vehicles sold each year will come equipped with a PM traction motor, and that each PM traction motor will create demand for 102 grams of dysprosium oxide (see Page 30), Adamas Intelligence forecasts that global annual demand for dysprosium oxide for EV traction motors will rise from 294 tonnes in 2017 to 1,094 tonnes in 2025 at a CAGR of 17.8%, making EV traction motors the single largest end-use of dysprosium oxide by 2025 (see Figure 30).

**Figure 30:** By 2025 EV traction motors will be the single largest end-use of dysprosium oxide globally



Source: Adamas Intelligence research





## China’s Production Alone Insufficient to Support Demand

As examined on Page 7, from 2013 through 2017 China was responsible for over 98% of global dysprosium oxide (or oxide equivalent) production each year. Moreover, from 2013 through 2017, global production of dysprosium oxide (or oxide equivalent) decreased by 34% due to an ongoing government-led crackdown on illegal rare earth production in China (see Page 8).

By 2025 China’s national production quotas need to increase by 150% to keep up with rising demand

Looking ahead to 2025, while taking heed of the historic trends detailed herein, Adamas Intelligence believes that China’s dysprosium production alone, if not increased at an unprecedented rate, will be insufficient to support rising demand (see Figure 31).

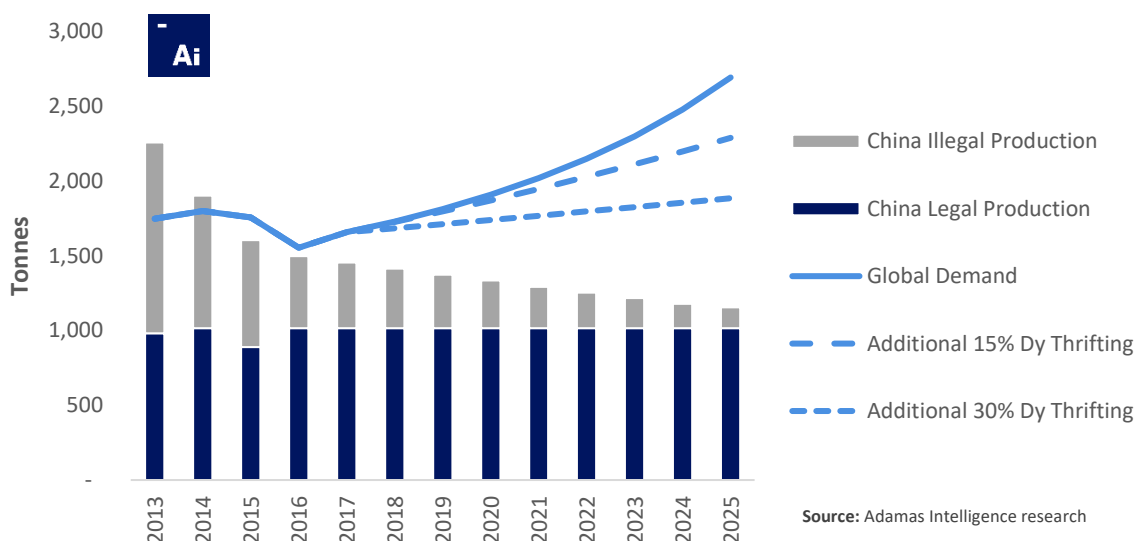
From 2017 through 2025, Adamas forecasts that global dysprosium oxide demand will increase at a CAGR of 6.2%, while at the same time total global production, as per the current status quo, is poised to decrease at a CAGR of -2.8% as China’s authorities continue to clamp down on illegal production.

As such, for China’s legal dysprosium oxide producers to keep up with rising global demand from 2017 through 2025, the nation’s Ministry of Land and Resources (“MLR”) will need to increase the national production quota by approximately 150% over the next eight years – an increase that seems highly unlikely given that production quotas in China have gone unchanged for more than five years.

As shown in Figure 31, even if the permanent magnet industry achieves a further 30% reduction in dysprosium usage by 2025, the spread between China’s current legal production level and future global demand is concerning.

**Should global dysprosium oxide production not increase substantially in the coming years to support rising demand, Adamas believes the probability of illegal production resurging in China is very high** – an outcome that would fundamentally increase supply risks for end-users of NdFeB in the automotive industry, wind industry, defense sector, and beyond.

Figure 31: Even with a further 30% reduction in dysprosium usage in NdFeB, the outlook is concerning





## A Handful of Potential Producers Advancing Outside China

Outside of China there are eight advanced rare earth projects at various stages of pre-production development with potential to add significant quantities of dysprosium oxide supply annually by 2025 (see Figure 32).

These eight projects are in six nations on five continents and collectively have potential to add upwards of 1,200 tonnes of dysprosium oxide (or oxide equivalent) supply annually over the coming eight years.

Three of the eight projects (Lofdal, Bokan, and Ashram) have advanced through completion of a compliant preliminary economic assessment (“PEA”).

An additional four of the eight projects (Kvanefjeld, BioLantanidos, Kipawa, and Dubbo) have advanced further through completion of a compliant feasibility study (“FS”).

One of the eight projects (Browns Range) has commenced mine development and is aiming to start small-scale production in 2018 (see Figure 32).

The projects listed in Figure 32 have potential to capture a substantial share of the growing dysprosium oxide market in the coming years and offer strong economic exposure to end-use markets in which demand is being driven by megatrends linked to electric mobility, clean energy, energy efficiency, and automation.

The Browns Range project in Australia, for example, is projected to produce approximately 280 tonnes of dysprosium oxide (or oxide equivalent) per annum at full-scale, inferring from the development plan put forward in the project owner’s latest feasibility study.

**At full-scale, Browns Range dysprosium production would be sufficient to supply the traction motors of approximately 2.7 million electric vehicles annually.**

At full-scale,  
Browns Range  
output would be  
sufficient to supply  
the traction motors  
of 2.7 million EVs  
annually

Figure 32: A handful of advanced rare earth projects outside China have potential to add supply by 2025

Project	Primary Owner	Country	Project Stage	Projected Dy Oxide Production (tonnes per annum) *
Browns Range	Northern Minerals Ltd.	Australia	Construction	280
Kvanefjeld	Greenland Minerals and Energy Ltd.	Greenland	FS complete	245
BioLantanidos	Mineria Activa	Chile	FS complete	150
Kipawa	Matamec Explorations Inc.	Canada	FS complete	145
Lofdal	Namibia Rare Earths Inc.	Namibia	PEA complete	140
Dubbo	Alkane Resources Ltd.	Australia	FS complete	125
Bokan	Ucore Rare Metals Inc.	U.S.	PEA complete	80
Ashram	Commerce Resources Corp.	Canada	PEA complete	70

Source: Adamas Intelligence research

\* Tonnes of Dy oxide or oxide equivalent inferred from projects’ latest technical reports



## Supply Risks Revving Up as EV Sales Rise

Given the confluence of rising demand, falling supply, dwindling inventory levels, and uncertainty regarding future rare earth production quotas in China, Adamas Intelligence believes that if automakers, motor manufacturers, and other end-users of high-temperature NdFeB do not act today to secure long-term supplies, they will soon find themselves amidst a sellers' market scrambling for rare earth motor metals the same way many are scrambling today for battery metals.

A major risk facing end-users of dysprosium is the market's precarious reliance on China's illegal production. As these supplies continue to be suppressed, and producer inventories continue to trend lower, Adamas Intelligence believes the potential for supply disruptions and price increases will escalate rapidly and, for some, unsuspectedly.

In hindsight, surely the procurement teams of nearly every major automaker regrets not locking in supply agreements for battery metals five years ago when prices were lower and suppliers were eager to forge deals. But five years ago, none of the world's leading automakers had clearly articulated strategies for electric vehicle development thus had a lack of foresight as to how their needs would evolve.

**Today, virtually all the world's leading automakers do have clearly defined strategies for electric vehicle development and deployment thus the time to secure long-term supply of motor metals is now.**

The time for end-users to secure long-term supply of motor metals is now

Figure 33: Dysprosium oxide demand at various levels of EV sales and PM traction motor penetration

		Global EV Sales per Annum						Dysprosium Oxide Demand (tonnes)
		2 M	5 M	7 M	10 M	15 M	30 M	
Percent Using PM Traction Motors	100%	204	510	714	1,020	1,530	3,060	5,100
	95%	194	485	678	969	1,454	2,907	4,845
	90%	184	459	643	918	1,377	2,754	4,590
	85%	173	434	607	867	1,301	2,601	4,335
	80%	163	408	571	816	1,224	2,448	4,080
	75%	153	383	536	765	1,148	2,295	3,825
	70%	143	357	500	714	1,071	2,142	3,570
	65%	133	332	464	663	995	1,989	3,315

Source: Adamas Intelligence research



## Key Takeaways

- Dysprosium's primary use is in NdFeB magnets for EV traction motors, wind power generators, industrial robots, and hundreds of other applications in which the NdFeB magnet is exposed to elevated temperatures and/or strong demagnetization fields.
- Looking ahead, dysprosium demand growth will be increasingly driven by global megatrends linked to electric mobility, clean energy, energy efficiency, and automation.
- These fast-growing policy-driven sectors will propel global dysprosium demand to new heights, requiring an unprecedented increase in global production to keep up.
- Over the past decade, China has been responsible for over 98% of global dysprosium oxide (or oxide equivalent) production each year.
- From 2005 through 2013 more than half of China's dysprosium oxide (or oxide equivalent) production each year was derived from unsanctioned/illegal mining activities.
- An ongoing government-led crackdown on illegal rare earth mining in China has led to a 34% reduction in global dysprosium oxide production since 2013.
- Looking ahead, Adamas Intelligence believes that China's production alone will be insufficient to support global demand growth.
- In fact, by 2025 China's demand for dysprosium oxide for electric vehicle traction motors alone will amount to 70% of the nation's current legal production level, emphasizing the imminent need for new supplies.
- Outside of China, there are a handful of advanced rare earth development projects with potential to add significant quantities of dysprosium oxide production annually by 2025.
- **If automakers, motor manufacturers, and other end-users of high-temperature NdFeB do not act today to secure long-term supplies, they will soon find themselves amidst a sellers' market scrambling for rare earth motor metals the same way many are scrambling today for battery metals.**

# About Adamas Intelligence

## Independent research and advisory services



Adamas Intelligence helps clients make informed decisions involving strategic metals and minerals.

We empower clients on six continents with the data-backed insight, analysis, and foresight needed to capitalize on emerging trends and new business opportunities.



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