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U.S. Industrial and Commercial Motor System Market Assessment Report

Volume 2: Advanced Motors and Drives Supply Chain Review

Alex Newkirk, Prakash Rao, and Paul Sheaffer

September 2021

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Prepared for the
Advanced Manufacturing Office
Office of Energy Efficiency and Renewable Energy
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Preface

In the late 1990s, the U.S. Department of Energy (DOE) conducted two seminal studies to better understand the installed stock and energy savings opportunities of industrial and commercial motor systems: *The United States Industrial Electric Motor Systems Market Opportunities Assessment* (industrial sector) and *Opportunities for Energy Savings in the Residential and Commercial Sectors with High Efficiency Electric Motors* (commercial sector). In the more than 20 years since the publication of these reports, the U.S. industrial and commercial sectors have undergone changes, including facility and/or motor system stock turnover, offshoring and onshoring of manufacturing, passage of motor efficiency standards, cost reductions in motor driven systems, and more. To gain a more current understanding of motor systems in the U.S. industrial and commercial sectors, DOE initiated an update to those two studies. Launched in 2016 and led by Lawrence Berkeley National Laboratory (Berkeley Lab), the Motor System Market Assessment (MSMA) provides an updated, more comprehensive assessment of the installed stock of motor systems in both the industrial and commercial sectors, a review of the supply chains supporting motors and drives in the U.S., and the performance improvement opportunities available from using best available technologies and maintenance and operation practices. The outcomes of the MSMA are documented in three *U.S. Industrial and Commercial Motor System Market Assessment* reports, with this report being the second listed:

1. *Volume 1: Characteristics of the Installed Base* documents the findings on the installed base of motor systems in the U.S. industrial and commercial sectors. Quantification of energy savings potential is not documented in this report but in Volume 3.
2. *Volume 2: Advanced Motors and Drives Supply Chain Review* (this report) reviews the state of supply chains for motors and drives installed in U.S. industrial and commercial facilities, focusing on advanced motor and drive technologies and their constituent materials.
3. *Volume 3: Energy Savings Opportunity* analyzes the energy performance improvement opportunity for the installed base of U.S. industrial and commercial motor systems.

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List of Acronyms and Abbreviations

AC	Alternating current
CMI	Critical Materials Institute
DC	Direct current
DOE	U.S. Department of Energy
EU	European Union
EV	Electric vehicle
GaN	Gallium-nitrate
HVAC	Heating, ventilation, and air-conditioning
I^2R	Resistive heating losses
MSMA	Motor System Market Assessment
NdFeB	Neodymium Iron Boron
NEMA	National Electrical Manufacturers Association
PLC	Programmable logic controllers
PM	Permanent magnet
PMSG	Permanent magnet synchronous generators
RPM	Revolutions per minute
SiC	Silicon-carbide
SmCo	Samarium-cobalt
USGS	United States Geological Survey
VFD	Variable frequency drive
WBG	Wide bandgap

Executive Summary

Electric motors in commercial and industrial applications account for almost a third of total electric grid load in the United States. With these applications representing such a significant level of energy use, increasing efficiency in these applications can help substantially increase resilience and lower total energy costs. This report examines stationary high-efficiency electric motor technologies and their supply chains.

The report begins with a technical overview of the main motor designs in these stationary industrial and commercial applications. This overview includes a discussion of AC induction motors, permanent magnet motors, and reluctance motors, followed by a discussion of motor components, and concluding with an overview of motor drives. This section also includes a table summarizing the output efficiency performance of these various technologies compared to a baseline. Broadly speaking, emerging motor technologies are more efficient than their conventional counterparts, and this difference is greatest in variable speed applications and motors operated at low horsepower.

Following the technical overview, the focus shifts to the supply chains for these various motor technologies, highlighting in particular key resource inputs. A *key resource input* refers to the most difficult-to-source raw material for a manufactured product. The focus on key resource inputs in this review serves to clarify where the supply chains of these technologies could be most vulnerable. Permanent magnet motors are constrained by their eponymous component, which is under increasing cross-sectoral demand and has a supply vulnerable to disruption. Electrical steel is characterized by weak relationships between motor manufacturers and steel suppliers and is only manufactured by a comparatively few companies. Wide bandgap semiconductors can serve as power electronics in variable frequency drives; accordingly, the challenges and opportunities of their supply chain are also discussed in this section. The supply chains of stationary motors are contrasted to the more robust supply chains of the related traction motors, with potential lessons highlighted. In contrast to these key resource input- or production-constrained technologies, reluctance devices possess a competitive performance profile and no inherent key resource or specialized facility constraints. We project growth across all these motor technologies, with particular emphasis on variable speed applications where they have an inherent advantage over conventional existing technologies.

This report is the second of a series of three reports documenting the outcomes of the U.S. Industrial Commercial Motor System Market Assessment (MSMA). Initiated by the U.S. Department of Energy and led by Lawrence Berkeley National Laboratory (Berkeley Lab), the MSMA provides a comprehensive assessment of the installed stock of motor systems in both the industrial and commercial sectors, a review of the supply chains supporting motor and drives in the United States, and the performance improvement opportunity available from using best available technologies and maintenance and operation practices. The three MSMA *U.S. Industrial and Commercial Motor System Market Assessment* reports are as follows, with this report being the second listed:

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Introduction: Application Scope/Focus

This report begins with a brief technical overview of motor technologies and some specific components and materials needed for their manufacture, followed by a supply chain analysis of emerging motor and drive technologies. The scope of this analysis includes electric motors for low to medium voltage (~1-1000 horsepower [hp]), industrial applications such as conveyors, extruders, pumps, compressors, blowers, refrigerators, and commercial heating, ventilation, and air-conditioning (HVAC). These stationary industrial and commercial electric motors account for 29% of total U.S. electrical energy use (Rao et al. 2021). Heavy industrial applications, including those from extractive industries (e.g., liquid natural gas pipeline compressors), are outside the scope of this report. Much of this review discusses the key resource inputs of these technologies. A *key resource input* refers to the most difficult-to-source component of a given motor. The focus on these key resource inputs informs which links in the supply chain are weakest. Note that sometimes key resource inputs are critical materials[1] or their derivatives, such as is the case of rare-earth permanent magnets, but in other cases, such as electrical steel, they are not. This report consists of two sections: a technical overview (Section 1) and a supply chain analysis (Section 2). There is some redundancy, to ensure that Section 2 does not require an exhaustive reading of Section 1.

Section 1: Technical Overview

Introduction

A variety of electric motors are available for commercial and manufacturing applications, so it is necessary to outline the design, efficiency, and performance differences of the motor technologies and components. These descriptions are not meant to be exhaustive; for more detailed information on the highest efficiency motor designs, consult the *Premium Efficiency Motor Selection and Application Guide* (McCoy 2014) from the U.S. Department of Energy's Advanced Manufacturing Office. Technology-specific sources on the performance and applications of these technologies provide further information. This section is only intended to provide sufficient context to meaningfully discuss the motor technologies' applications and supply chains. It will outline the baseline AC induction motor design, then the permanent magnet and reluctance advanced motor designs. It concludes with the performance characteristics when higher quality materials and components—including electrical steel, copper stators, and wide bandgap power electronics based variable frequency drives—are integrated.

The efficiency advantage of the best available designs over the standard efficiency models is significant. Advanced motor designs primarily differ from conventional AC induction motors in their inherent variable speed operation. While AC induction motors require a separate dedicated drive to vary their operational speed, the design of reluctance and permanent magnet motors each require drives, meaning the systems are inherently variable speed. This in turn makes the selection of the optimum motor design dependent upon the situation. Reluctance and permanent magnet motors are each high-power density, durable, and efficient across a range of speeds. If

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[1] The U.S. Department of Energy defines critical materials as materials essential to the generation, storage, or transport of energy for which there are no easy substitutes. For an up-to-date inventory of the minerals defined as critical by the United States, consult Fortier et al. 2018.

noise is not a significant concern, each will be viable when used with fans, conveyors, extruders, pumps, compressors, and other industrial and commercial applications.

A summary comparing the different motor technologies can be found in Table 3 following the technical review. References for the quantified savings in that table can be found in the respective technical overview sections. This review will typically consider performance as comprised of torque, operating temperature, and efficiency. These metrics are generally used to describe equipment performance. However, a systems approach is needed to better evaluate impact. To this end, there has been a shift towards lifecycle costing and measuring improvements in energy savings. Given that this report focuses on equipment improvements, nameplate efficiency[2] metrics will be used. While more sophisticated metrics of motor energy performance can provide important insights, comparing motor technologies requires a benchmark. For these reasons, we employ the most common metrics of energy efficiency and performance, despite those being somewhat limited. Volume 3 will quantify system level improvements and energy savings accordingly.

AC Induction Motor

The bulk of this report concerns advanced motor designs for industrial and commercial applications. Before that discussion, it is necessary to describe the standard design: the AC induction motor. The exact baselines against which more efficient designs are compared vary by case. Older analyses tend to employ a baseline of a standard efficiency, three-phase AC induction motor, and many contemporary summary findings and survey results still display these topline numbers. More recent analyses tend to compare against a NEMA (National Electrical Manufacturers Association) Premium model.[3] Regardless of the efficiency level of the baseline comparison, the baselines, unless otherwise stated, are of the AC induction design. This is because AC induction motors are commonplace and suitable for most industrial and commercial applications (Goetzler, Sutherland, and Reis 2013). To better understand the nature of the energy efficiency improvements offered by advanced motor technologies, it is necessary to briefly review the operating principle and nature of energy losses of AC induction motors. AC induction motors are driven by electromagnetic induction: an alternating current through a coil creates a rotating magnetic field. The stationary part of the motor, referred to as a *stator,* is composed of layered steel with a hollow core. This core contains conductive material - typically coils of copper wire (windings) - in which the magnetic field is produced. The rotating part of the motor, referred to as the *rotor,* is also composed primarily of layered steel with attached conductive material, typically a cast aluminum squirrel cage or fabricated copper bars. As current flows through the stator, a magnetic field rotates within the stator at a speed based on the frequency of the input current and the number of magnetic poles. The number and arrangement of the poles is based on the architecture and quantity of the windings. This field rotating relative to the rotor induces a current in the rotor, which in turn creates a magnetic field of opposite polarity. The

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[2] Nameplate efficiency can vary dramatically from actual energy performance in an application.

[3] NEMA is the largest trade association for U.S. electrical equipment manufacturers. The "Premium" designation is a NEMA product labelling regime designating the highest efficiency class of motors manufactured by constituent members. Consult the Energy Independence and Security Act (2007) https://www.epa.gov/laws-regulations/summary-energy-independence-and-security-act or https://www.nema.org/directory/products/nema-premium-motors for more information.

interaction of the stator and rotor magnetic fields applies a torque to the rotor, causing the shaft to spin on its bearings.

Because these motors contain conductive components, the driving magnetic field also introduces some losses through induced eddy currents[4] and magnetic hysteresis.[5] These can occur in both the stator and the rotor. *Core losses* refer to the energy required to overcome the hysteresis in the core of the motor and resistive heat losses from induced eddy currents in the motor core. *Windage losses* refer to losses due to air resistance; there are also losses due to bearing and seal friction. Collectively, core, friction, and windage losses are called *fixed losses,* as they scale independent of the motor load. Conversely, there is also a class of motor losses called *variable losses* that depend on motor load. These include stator power losses, rotor power losses, and stray load losses. Variable losses are also referred to as I^2R losses. Stator I^2R losses refer to resistive heating losses in the stator. Rotor I^2R losses are resistive heating losses in the rotor. *Stray load losses* are due to magnetic flux leakage from induced load currents. Both variable and fixed losses can be mitigated through design optimization and improved material quality. Table 1 summarizes the typical proportion of total losses comprised by each loss type, as well as mitigation strategies. The usage of higher quality materials will be discussed in greater detail in the copper rotor and electrical steel sections.

Table 1: Typical proportion of total losses by loss type

FIXED LOSSES	**TYPICAL LOSSES (% OF TOTAL LOSSES)**	**FACTORS AFFECTING LOSSES**
CORE LOSSES	15 to 25	Type and quantity of magnetic material
FRICTION AND WINDAGE LOSSES	5 to 15	Selection and design of fans, bearings, and seals
VARIABLE LOSSES		
STATOR I^2R LOSSES	25 to 40	Stator conductor size
ROTOR I^2R LOSSES	15 to 25	Rotor conductor size and material
STRAY LOAD LOSSES	10 to 20	Manufacturing and design methods

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[4] "Eddy currents" are electric currents induced in conductive material in the presence of a changing magnetic field. These currents then dissipate as resistive heat.

[5] "Magnetic hysteresis" refers to the induction of a countervailing magnetic field by conductive material in response to a change in magnetic field.

Source: Premium Efficiency Motor Selection and Application Guide: A Guidebook for Industry (McCoy 2014)

Advanced Motor Technologies

This section will discuss advanced motor technologies, how they differ from conventional AC designs, and the scale of the operating efficiency advantage. When motor technology case studies are discussed, the comparison baseline is noted. When discussing component integration, the type of loss being addressed and scale of efficiency gains are noted. These findings are collected in the reference table at the conclusion of the technology overview section.

Permanent Magnet Motors

Permanent magnet (PM) synchronous motors are the most efficient commercially available motors (Goetzler, Sutherland, and Reis 2013). The technology relies on permanent magnets to produce the magnetic field for the rotor, while the architecture of the stator is consistent with that in AC motors. Rare-earth permanent magnets are the key resource input of PM motors and merit some focused discussion.

Rare-earth permanent magnets were developed in the 1960s, with researchers discovering that magnets doped with small amounts of rare-earth metals possessed greater field strength. Small concentrations of rare-earths within a magnet produce dramatic performance changes across a variety of criteria. The three most relevant to motor performance are magnet strength (both field strength and energy density), coercivity (resistance to demagnetization in the presence of external magnetic fields), and Curie temperature (the temperature above which materials lose their permanent magnet properties, which influences operational temperature range).[6]

Theoretically, a variety of rare-earth metals could be doped into ferrite magnets for performance improvements,[7] but the most commonly produced PMs contain some amount of neodymium or dysprosium. Neodymium is the more common element within the Earth’s crust and doping it into ferrite magnets contributes to greater magnetic field strength and energy density. Dysprosium doping into magnets produces a magnet with a higher Curie temperature. Typically, both elements, with a greater proportion of neodymium, will be integrated into a magnet for a resultant high-strength magnet with a broad operating temperature range. A typical PM motor Neodymium Iron Boron (NdFeB) magnet for an application with a conventional NEMA Premium operating temperature range contains 4.2% dysprosium by mass, with the proportion by mass in ultra-high temperature applications as high as 11% (Constantinides 2017). The magnets are manufactured through a sintering process, where fine particles are compressed into a single solid magnet without liquefaction. Magnets of this kind are referred to by their grade, a label which describes their characteristics. A magnet grade is the letter N, denoting that it is a NdFeB magnet, followed by a number representing its magnetic flux/unit volume (a measure of field strength) and concluding with a letter that denotes Curie temperature (e.g., N38M). Within this review, unless otherwise specified, the term “permanent magnet” refers to sintered NdFeB, the type of PM typically used in motor applications. For a more detailed discussion of the global

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[6] Note that neodymium alone reduces curie temperature, which is why NdFeB magnets typically contain dysprosium to improve their temperature performance

[7] Note that samarium-cobalt magnets are manufactured at industrial scale. The NdFeB Magnet Supply section of this review provides a discussion of their substitution with NdFeB magnets.

supply outlook for rare-earth magnets, from the mining of the metals to the manufacture of the magnets, as well as the ongoing research and economic prospects of rare-earth element recycling, see the NdFeB magnet supply review subsection of this report.

High field strength, low coercivity magnets can be used in place of the conventional aluminum rotor cage of the induction design, significantly increasing efficiency (McCoy 2014). Because the field does not require induction, resistive heating losses in the rotor are avoided altogether. The PM rotor design also allows for a more compact, power-dense machine. Because the magnetic field in the rotor is constant, induction winding cannot be used for starting. To properly start and achieve synchronization the motor must be paired with a variable frequency drive (VFD) or dedicated inverter designed specifically to drive PM models (McCoy 2014, Murphy 2012). VFDs comprise a subset of Adjustable Speed Drives (ASD) that employ electronic control (e.g., pulse width modulation of electric current) as opposed to mechanical or other control. While the requirement of a VFD can increase upfront costs, it also means PM motors are inherently capable of variable speed operation. A performance profile relative to conventional AC induction motors can then be established: PM motors are energy efficient, power dense, low maintenance, and capable of variable speed operation and low acoustical noise. The efficiency advantage of PM motors is greatest in small motors operating at variable speeds but present across the entire range of motor sizes and operating profiles. As noted by McCoy (2014), “for small motor sizes, the rated efficiency of the PM motor may increase by 10% to 15% when contrasted with older standard efficiency motors at the same load point.” Comparing a 20 hp PM motor to a NEMA Premium Efficiency baseline in a variable speed application, both driven by a 96% efficient drive, results in a 2.1% energy savings for the PM motor (Washington State University Extension Energy Program n.d. Item 431).

This broad-spectrum performance advantage contributes to a primary disadvantage of PM motors, namely cost. Due to their power density, energy efficiency, durability, and operating temperature range, PM motors are increasingly employed in electric vehicle designs (Desai 2018; Momen et al. 2016; Adams 2018). Wind turbines also incorporate rare-earth magnets in their designs. These demand-side dynamics will be discussed in greater detail in Section 2 (“Supply Chain Analysis”). The primary driver of high upfront costs for PM motors is magnet material cost. While the compact design of PM motors reduces steel and copper costs, the cost of the magnet exceeds these savings. Accordingly, PM motors excel in applications that depend on their robust durability and reliability, high temperature resilience, high power density, and high energy efficiency. Such applications include water pumps, cooling towers, cranes/hoists, fans, compressors, and extruders (Klontz 2017; “Cooling Tower Fans Driven by Less” 2009; Michel et al. 2020).

As PM motors are currently the highest performance motor design, their design optimization pushes the efficiency frontier (Klontz 2017; Huynh and Hsieh 2018). Innovation in PM motors can focus on the magnet. The production process of the magnets can be optimized to reduce waste. Researchers can develop novel magnets less dependent on rare earths. DOE-sponsored research on reducing the amount of rare-earth elements in magnets without sacrificing performance is conducted within the *Developing Substitutes* program at the Critical Materials Institute (CMI), an energy innovation hub led by Ames National Laboratory (Ames National Laboratory n.d.). In Germany, the Fraunhofer Institutes took an interdisciplinary approach in response to rare-earths scarcity. They reduced the input requirements for rare-earths by optimizing sintered magnet production with injection molding. The Fraunhofer Institutes also optimized "(t)he design of the benchmark electric motors… If the motors do not get so hot during operation, magnets with lower temperature stability and thus a lower portion of dysprosium can be used." The institutes also developed a method for rare-earth recycling from e-waste. All these methods combined were able within a lab context to dramatically reduce the newly mined dysprosium and neodymium required to manufacture the magnets without sacrificing motor performance ("Substitution, Efficiency, Recycling: Fraunhofer IMWS" 2018). These tactics for adjusting the makeup of the magnets or the manufacturing process to reduce required rare-earths content are collectively termed "*rare-earth thrifting".*

Automobile manufacturers have responded to the expense of rare-earth magnets with a variety of innovations and thrifting techniques. Honda developed a manufacturing process that resulted in "the first magnet suitable for automotive [applications] that does not require materials like dysprosium or terbium to improve its heat resistance" (Greimel 2016). Toyota developed a magnet that replaced a portion of the neodymium with the more abundant and lower cost lanthanum and cerium (*Reuters* 2018). While none of these innovations have yet entered the market, the research around PM motors will continue toward reducing input costs without sacrificing their best-in-class performance. Further discussion of rare-earth thrifting techniques can be found in the Recycling Rare Earths and Substitutability of NdFeB Magnets subsections of this review.

Reluctance Motors

Reluctance motors operate on the principle of magnetic reluctance, a property in magnetic materials analogous to electrical resistance. As electrical resistance consists of as opposition to an electric current moving through a material, magnetic reluctance is defined as opposition in a material to magnetic flux. This reluctance in a rotor can be employed to apply a torque, which is the core operating principle of reluctance motors. This report will detail two types of reluctance motors, switched and synchronous reluctance motors.

Switched Reluctance Motors

Switched reluctance motors were initially developed in the 19th century, employing primitive mechanical switching technologies. Prior to fast-switching semiconductors, switched reluctance devices could not compete on performance with conventional AC induction models. Even after the introduction of power semiconductors, the technology was not commercial common because of the wide availability of inexpensive induction motors. Not until motor energy efficiency became prominent concern were switched reluctance designs seen as a commercially viable option. They were, however, commonly used in academic settings because they were robust and straightforward, lending themselves to engineering research.

Compared to conventional induction motors, switched reluctance motors enjoy manufacturing advantages. A switched reluctance motor's rotor does not contain magnets, rotor bars, or windings. In essence the rotor is a piece of shaped iron capitalizing on the fact that "forces from a magnetic field on the rotor iron can be many times greater than those on the current carrying conductors" (McCoy 2014). Stator construction also differs from conventional designs:

> "SR stator windings are much simpler than those required for induction motors or permanent-magnet (AC) motors. Each slot in the stator contains windings for only one phase. A winding that emerges from the stator slot needs only to loop back around one slot, rather than around multiple slots as on induction motors. This minimizes the volume of end windings and significantly reduces the risk of a phase-to-phase insulation failure…a switched reluctance motor can be one or two frame sizes smaller than an equivalent induction motor." (Boteler 2012)

The lack of conductors on the rotor results in a lower level of rotor losses compared to conventional induction designs (Boteler 2012). This reduction in rotor losses is greatest during start up. Switched reluctance motors require an electronic power converter or controller that regulates both torque and speed. This controller cannot be substituted with a conventional VFD. Though similar in construction to a conventional VFD, this controller has lower switching losses due to lower carrier frequency. Overall losses are thermal and concentrated within the stator where they are easy to diffuse. The low levels of motor losses ensure the rotating components, including bearings and lubricants, run relatively cool, increasing durability and lifespan.

SR motors are not without drawbacks. Compared to conventional induction motors, as well as other emerging and high efficiency motor technologies, switched reluctance devices produce high levels of acoustical noise. In switched reluctance designs, "powerful radial force between the rotor and stator poles causes the vibration of the stator" (Takayama and Miki 2016). While research is progressing on design improvements to reduce noise levels, some level of this vibration is intrinsic to switched reluctance construction, and mitigation strategies carry trade-offs of reduced efficiency (Correa et al. 2011).

Considering these factors enables a performance comparison with conventional AC induction motors. Due to the necessity of the controller, switched reluctance motors will carry a greater upfront cost than a single-speed induction motor. Due to their intrinsic variable speed operation, a more apt comparison model is an inverter-duty motor with a variable frequency drive. A case study made a comparison for a 100 hp switched reluctance model given a duty cycle of an even split between full speed and load operation (1,800 RPM) and 80% speed (1,428 RPM) against a VFD-driven NEMA Premium baseline. In this case, the switched reluctance system captured 2% greater efficiency compared to the baseline (Washington State University Extension Energy Program n.d. Item 433). Switched reluctance motors are best suited to applications that require variable speed operation and that benefit from their compact design, robust durability and reliability, high temperature resilience, and high power-density. Switched reluctance motors are less suited to applications where physical vibrations, ripple torque, and acoustical noise are significant constraints. Industrial applications well suited to switched reluctance motors include "screw compressors, blowers and high-speed pumps…extruders, conveyors…AC compressors, weaving looms, lab centrifuges, and reverse osmosis pumps" (McCoy 2014). The greatest efficiency gains are captured where variable speed operation is vital. The Western Cooling Efficiency Center at the University of California, Davis, performed a case study evaluating the performance of a switched reluctance motor for an indoor HVAC fan system. They concluded that the switched reluctance motor "operated at a higher efficiency than the baseline over the tested range of load and speed conditions" (Mande and Sevens 2019).

Future developments of the technology are likely to follow application demand, as commercial suppliers of switched reluctance motors are still emerging. A recent factor driving development of the technology is the increasing cost of rare-earth PMs. Within the last decades, there are numerous examples of innovative switched reluctance designs reaching performance and efficiency parity with PM models (Fricke and Bhandari 2019; Jeong, Lee, and Ahn 2017; Tahour and Aissaoui 2017; Husain et al. 2019; Chiba et al. 2011). The architecture of the switched reluctance design is robust, flexible, and inexpensive to manufacture. These designs can be fairly easily translated to fit the required applications and existing manufacturing infrastructure.

Synchronous Reluctance Motors

Another reluctance design is the synchronous reluctance motor. The theoretical design for these devices has existed since the 1920s, though the technology was not feasible for practical industrial applications until the advent of modern power electronics. While academic work on synchronous reluctance designs has been robust since the 1970s, the market dominance and performance profile of induction machines resulted in minimal application of the design. When improvements to VFDs and a rising emphasis on motor energy efficiency caused an uptick of interest in the 1990s, this coincided with the rise of PM motors, so once again, commercial development was minimal. Not until the last 15 years did synchronous reluctance designs began to garner genuine commercial interest, with the European firm ABB announcing a launch of a full product line of industrial synchronous reluctance motors in 2012 (Jones 2014).

Technically, synchronous reluctance devices rely upon the principle of magnetic reluctance, the magnetic analog to electrical resistivity, within the rotor. In the presence of the changing magnetic field induced in the stator, the rotor will align itself to minimize this changing magnetic field with respect to its reference frame, generating a torque and rotating the rotor. In switched reluctance devices, on-off switching of phase-shifted coils within the stator generates continuous torque on the rotor. Synchronous reluctance devices in contrast generate continuous torque through non-uniform magnetic reluctance within the rotor. Orthogonally offset regions of high and low magnetic reluctance mean that in the presence of the polyphase induced magnetic fields generated by the stator, continuous torque is applied to the rotor (Donaghy-Spargo 2016).

The synchronous reluctance design carries some performance advantages relative to conventional AC induction design. First, the absence of an electric current within the rotor wholly eliminates rotor I^2R losses. Next, the difference between the rate of stator field rotation and rate of rotor rotation is called slip, and in induction machines motor slip represents a performance concern as it is an efficiency drain and can cause a motor to stall. When slip is reduced to zero a motor is said to be operating at synchronous speed. Synchronous reluctance motors are always operating at synchronous speed, i.e., rotor slip is zero. The lack of rotor losses reduces operating temperature, allowing for less cooling and a smaller form factor while increasing durability. Unlike switched reluctance devices, acoustic noise is not a major concern in synchronous reluctance devices (Donaghy-Spargo 2016). Synchronous reluctance devices require a drive to operate, though unlike switched reluctance devices they can be driven using a conventional VFD. The absence PM components means their upfront costs are lower than PM motors, and there is no risk of demagnetization in synchronous reluctance devices.

Comparing synchronous reluctance motor-drive systems to analogous premium efficiency induction motor-drive systems, manufacturer ABB found that synchronous reluctance systems ranged from ~2-4% more efficient (ABB 2014). While nameplate efficiency can be a limited metric of performance and the source is a manufacturer, ABB's values are consistent with the findings of independent research evaluating a range of realistic use cases (Kärkkäinen et al. 2017). This research found the efficiency disparity between induction and synchronous reluctance motor drive systems ranged from 0% to 5% across loads and speeds, with the efficiency advantage of synchronous reluctance systems being greatest at low speeds and high torque, conditions where slippage is most pronounced in induction systems. Additionally, performance improvements compared to AC induction motors were greatest in variable torque applications, especially those operating at reduced loads.

Synchronous reluctance designs have some performance disadvantages. Compared to PM devices, they possess a lower power factor.[8] While their lower operating temperature reduces their operational wear, design requirements of the rotor result in a system less robust than switched reluctance devices, though still favorable in comparison to induction machines. Finally, the technology is immature, and the rotors can be challenging to manufacture.

A motor design related to synchronous reluctance motors merits brief discussion: permanent magnet-assisted synchronous reluctance motors. These motors are designed to improve upon the comparatively low power factor of synchronous reluctance devices by augmenting the stator magnetic fields with PMs inserted into the motor air gap. This results in a motor with a greater power density and higher torque capability. Both NdFeB PMs and ferrite PMs can be employed in these designs. However, demagnetization of the PM is a significant concern in these motor systems, with demagnetization representing a greater challenge in ferrite systems (Donaghy-Spargo 2016), though this risk can be reduced through design optimization. Systems which employ ferrite magnets as their PMs compare favorably to NdFeB based systems on power factor and energy efficiency depending on the application (Sekerak et al. 2013). The lower field strength of the magnets means ferrite-based designs cannot achieve the same levels of torque (Sanada, Inoue, and Morimoto 2011). Ferrite designs do possess a significant advantage over NdFeB alternatives, namely a dramatically lower up-front cost (Yetiş, Meşe, and Biyikli 2018).

As these designs are something of a middle ground between synchronous reluctance and PM motors, their performance profile is similarly a middle ground. Their potential torque, power factor, and energy efficiency are not as high as the highest quality PM motors but are higher than conventional synchronous reluctance motors (Ibrahim et al. 2020). Conversely, they are heavier and more initially expensive than synchronous reluctance devices, though not as heavy or costly as PM motors. PM-assisted synchronous reluctance motor systems can achieve measured efficiency improvements of 2-3% over a premium efficiency synchronous reluctance motor system (Leuzzi et al. 2017) across a range of speeds and loads. Ongoing development on these motor designs is encouraging, with ferrite-assisted synchronous reluctance motors demonstrating significant promise owing to their competitive performance profile and lower up-front cost.

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[8] Power factor is the ratio of real power (watts) to apparent power (volt-amps)

Motor System Materials and Components

Historically, AC induction motors have improved efficiency through component quality improvement, e.g., the common integration of higher quality materials to reduce eddy current losses. This began with copper and electrical steel, and in the last decade has been accomplished in essence through PMs by substituting them for the magnetic inductor. The permanent magnetic field generated by the PM replaces the induced magnetic fields in AC induction motors. From a systems efficiency perspective, VFDs are a single component of an integrated drive-motor system. There is mounting interest in replacing the conventional silicon-based power electronics in VFDs with wide bandgap power electronics that have the capability to increase efficiency, reduce footprint, and reduce waste heat. The following section overviews the mechanisms by which these high-quality components increase efficiency compared to standard materials and the scale of that efficiency gain.

Copper Rotor Motors

The copper industry in the mid-1990s undertook a project to replace the aluminum squirrel cage in the rotor of electric motors with copper, with the goal of increased efficiency through greater quantities of copper (Peters and Cowie 1999). After overcoming a series of technical barriers to manufacturing this design by developing cost-effective die casting, copper rotors delivered efficiency improvements. This efficiency stems from the lower intrinsic resistivity of the copper, thereby reducing resistive heat losses are. Copper rotor motors, typically marketed as “ultra-efficient,” are now commercially available (McCoy 2014). These motors are rated as NEMA Premium or SuperPremium[9] and incorporate aspects of efficient motor design. Copper rotor motors significantly outperform baseline standard efficiency AC induction models and outperform NEMA Premium aluminum cage motors by 0.6%-3% (Dyess and Agamloh 2007; “Copper Rotor Motors and Energy Efficiency: A Case Study” 2019; “Kienle + Spiess | Copper Rotors” 2020). The lower operating heat of copper cage motors allows them to employ a smaller cooling fan, which allows these motors a smaller, more compact design though their weight is slightly increased. The lower heat also reduces component wear making them more durable. The disadvantages of copper cages are an increased upfront cost due to the higher concentration of premium copper, challenges relating to manufacturing, higher in rush currents and lower slip compared to conventional motors. Lower slip can be a challenge if the motor is driving a pump or fan where the increased motor speed could drive the system faster than desired.

Existing aluminum die-casting facilities cannot be employed to cast copper rotors owing to the 400°C-higher melting point of copper than aluminum (Finley and Hodowanec 2000). In the development of copper rotor motors, this presented a significant technical challenge which the copper industry, DOE, and commercial manufacturers collaborated to address (Brush et al. 2003). Siemens launched a product line based on these die casting innovations in 2006 (Teschler 2009). While now technically achievable, economic factors inhibit further growth of this copper die-cast technology for rotor manufacturing. The extremely high temperatures represent a safety concern with existing die-casting workforce, requiring at the minimum retraining. Additionally, customers are sensitive to the upfront cost of motors, and the high material cost of copper therefore substantially reduces demand. Not only is human capital investment required, but novel

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[9] SuperPremium is a proposed NEMA motor efficiency category denoting elite efficiency models, and it usually refers to advanced or emerging motors technologies.

equipment is also necessary to manufacture these rotors compared to conventional aluminum cages. The strenuous production process also dramatically effects the lifecycle of this equipment, with the nickel alloys necessary to manufacture copper rotors having a lifespan of only 20% of conventional steel tools (Mechler 2010). These factors do not prevent copper rotor motor production altogether, but they do place an upper bound on further adoption. Unless underlying economic conditions change, copper rotors will serve their niche in space-constrained traction and heavy industrial applications extremely sensitive to operating costs (Teschler 2009).

High Performance Conductors

The copper windings in a motor could theoretically be replaced by superconductive material and further improve motor efficiency, though current superconductors require such extreme temperatures and pressures that this application is not commercially viable in the near-term. The principle of decreasing resistive losses through advanced materials is scientifically sound. Carbon nanotubes represent a promising candidate material, as carbon nanotube yarn can achieve three times the practical electrical conductivity of copper. Several motor designs replacing copper wiring with nanotubes have been published or piloted recently (Rallabandi et al. 2016; U.S. Department of Energy 2018; Pyrhönen et al. 2015). Non-zero resistance in motor windings results in a small amount of resistive waste heat within the motor. The dramatically lower intrinsic resistivity of nanotube yarn compared to copper could dramatically reduce stator resistance losses where the yarn is integrated into the current conducting elements of electric motors. Carbon nanotubes are in the earliest stages of commercialization, and production capacity has not yet been practically scaled in a laboratory setting, well short of industrial manufacture. The performance improvement potential of the material is significant enough to warrant further study and investment, but the technology is still too early in its development cycle to justify a more detailed supply chain analysis.

Electrical Steel

During motor operation, the changing magnetic field induces an eddy current and a hysteresis loss in the conductive components of the motor core. These losses are referred to as *core losses* or *iron losses,* in contrast to losses that occur in the copper windings, which are called *copper losses* or *winding losses.* Core losses account for 15%-25% of electric motor losses (McCoy 2014), as indicated in Table 1. These losses dissipate through a combination of I^2R heating and acoustic noise. Electrical steel is steel doped with silicon up to 6% to change the electromagnetic properties of the metal. The grains of silicon can be arranged through further processing to enhance the effects, and the resultant material is referred to as *grain oriented electrical steel.* The silica present in electrical steel raises the resistivity of iron, resulting in a higher level of magnetic permeability and smaller hysteresis area compared to conventional steel.

Thinner sheets and alternative coatings are other methods of improving electrical steel performance, though both introduce greater manufacturing complexity. When used in the construction of motor cores, electrical steel can reduce core losses by up to 5% compared to non-oriented off-the-shelf steel (“Why Electrical Steel Can Make All the Difference in EV Motors” 2017). Grain-oriented electrical steel requires dedicated manufacturing facilities and labor, resulting in significant increases to cost. A more detailed discussion of the electrical steel supply chain is provided in the electrical steel subsection of Section 2 of this report.

Variable Frequency Drives

Stand-alone AC motors are commonly designed to provide a steady output speed based on incoming electrical grid power. About 27% of industrial motor loads and 30% of commercial motor loads require single-speed continuous operations (Rao et al. 2021). All other applications require some intermittency in operation or variation in operating speed or load. Variable frequency drives can be installed to attenuate the frequency and voltage of electricity supplied to the motor, matching motor speed to the required uses. VFDs consist of a rectifier and inverter to adjust the frequency and voltage of current flowing into the motor to the requirements of the application, as well as the sensors and computational equipment to determine the required motor input. They carry significant energy efficiency improvements through the elimination of gears, as well as reducing mechanical wear both through lower operating speeds and gentler startup and stop (Waide and Brunner 2011). Increasingly motors are being manufactured and sold as systems integrated with a drive.

Due to imperfect power electronics, VFDs introduce losses into the system. In applications requiring variable outputs, even with these introduced losses, VFDs still provide significant energy savings compared to full speed operation with a throttling valve, damper, or similar bypass mechanism such as cycling. VFDs also introduce incremental harmonics into the electrical system, the mitigation of which can also drive-up costs. The precise efficiency gains vary depending on application. Indeed, precisely calculating the energy savings of drive integration within an individual case is a nontrivial exercise. Estimated systems energy savings of universal VFD integration are 9% in refrigeration compressors, 9% in fans, 20% in pump applications, and 29% in air compressors. Current penetration in these sectors is 26%, 25%, 25%, and 20%, respectively, as shown in Table 2 (Rao et al. 2021).

Table 2: Current Levels and Potential Savings of Universal VFD integration by Industrial End Use

End Use Application (Industrial and Commercial Sectors)	***Refrigerators (%)***	***Fans (%)***	***Pump (%)***	***Compressors (%)***
Potential Energy Savings of Universal VFD Integration (Percentage of Total Application Energy Use)	9	9	20	29
Current VFD Penetration (Percentage of Applications)	26	25	25	20

Across all motor sizes and applications, current VFD penetration rates are 16% of a facility's connected horsepower for the industrial sector and 4% in the commercial sector (Ibid.). While VFDs provide improved efficiency even for motors that operate continuously at a single speed and non-unity load factor, down-sizing the motor is likely a better energy saving action in these cases. However, as previously mentioned, the system efficiency savings for variable speed applications can be significant and exceed the introduced VFD losses, depending on the system operating characteristics.

While VFDs provide significant efficiency benefits, they increase the floor space footprint of the motor drive system, though this too can be offset by eliminating the need for gears. The precise impact of drive integration on footprint depends on the specifics of the individual system. One area of potential drive innovation is through integration of wide bandgap (WBG) semiconductor devices. WBG power electronics possess a broader energy gap—the energy range where electrons cannot exist. Compared to conventional semiconductors, WBG devices can switch at higher frequencies and operate at higher temperatures (U.S. Department of Energy 2013). This higher operating temperature reduces cooling requirements, further reducing motor footprint. The amount of performance improvement depends on the precise application and model, but case studies and models agree that WBG based drives deliver lower operating temperature, higher switching frequency, and greater energy efficiency (Shirabe et al. 2012; "Eaton Is Working on a Variable Speed Drive with Near-Perfect Efficiency" 2015; Baldwin et al. 2015). Additionally, the higher switching frequency can reduce acoustic noise of the motor drive system. It should be noted that a downside to higher switching frequency is potential to damage windings due to voltage spikes.

The applications that benefit most from WBG drives are large (e.g., medium voltage) or high speed (e.g., >3600 RPM) motors because the non-WBG semiconductors typically used in VFDs (silicon-insulated gate bipolar transistors) cannot operate at the frequencies required by large and/or high-speed motors. Further, VFD's large physical footprint and high thermal losses results result in low levels of adoption for large motors (Morya et al. 2019). For large or high-speed motors, both SiC and GaN based drives improve total system efficiency, reducing drive losses between 5% and 20% over silicon-insulated gate bipolar transistor drives, and increasing total system efficiency by 3% to 5% compared to conventional VFD (Swamy, Kang, and Shirabe 2015; Shirabe et al. 2012). While most industrial applications do not require the high temperature or speeds that constitute the greatest WBG performance improvements (Morya et al. 2017), the compactness of WBG VFDs relieves a significant constraint in HVAC applications These are the most promising applications for WGB VFDs within the scope of our report.

Conclusions

Conventional AC induction motors have increased in efficiency. These efficiency improvements have occurred through the integration of higher quality materials, with more electrically conductive wiring and greater quantities and higher quality electrical steel each reducing resistive losses. There have been efforts to improve AC induction motor efficiency through copper rotors or high-performance conductors, but those have not yet demonstrated widespread economic viability.

With increased emphasis on energy efficiency, other motor technologies – PM and reluctance motors – are expanding from niche uses to more mainstream applications. The most commercially mature are PM designs, though reluctance motors are becoming more widely available. Each of these motor designs is well suited to a variety of industrial applications, though they also each carry some drawbacks.

The changes with the greatest impact on system energy use have been motor right-sizing and greater adoption of variable speed drives. These drives come with some parasitic loses but still yield overall savings. New technologies are being developed to address those loses but are not commercially viable/available yet.

This concludes the technical overview section of the report. The scale of efficiency gains from advanced designs over standard AC induction motors, the marginal effects of integrations of higher quality component materials, and where applicable key end uses of advanced motor technologies are presented in Table 3. Unless otherwise stated, the advanced designs reflect efficiency and performance improvements over AC induction motors. References to premium components compare the performance and efficiency of a motor with the specified component to a conventional AC induction motor.

Table 3: Motor Technology and Component Efficiency Summary

MOTOR TECH AND KEY RESOURCE INPUT	ADVANTAGES	DISADVANTAGES	EFFICIENCY GAINS OVER AC INDUCTION MOTOR SYSTEMS	KEY APP-LICATIONS
PERMANENT MAGNET MOTORS - KEY RESOURCE INPUT: PERMANENT MAGNET	More energy efficient than an AC induction motor, lighter weight, higher reliability	High upfront cost, commodity related price variability (rare-earth supply volatility)	10%-15% more efficient than standard efficiency at small motor sizes (1-10 hp) with smaller gains (~4%) at higher hp ~2% more efficient than a 20 hp NEMA Premium model	Water pumps, cooling towers, cranes/hoists, fans, compressors
SWITCHED RELUCTANCE MOTORS KEY RESOURCE INPUT: NONE	Increased energy efficiency compared to a standard AC induction baseline motor, higher durability, compact design, inexpensive, efficient at varying operating speeds and temperatures, high power density	High acoustic noise and physical vibration, mandatory unique controller, technology not yet fully commercially mature	Individual designs engineered to match performance and efficiency of PM motors, i.e., 4%-15% more efficient than standard efficiency. ~2% more efficient than a NEMA Premium model	Centrifuges, consumer appliances, high speed pumps, conveyors, extruders
SYNCHRONOUS RELUCTANCE MOTOR – KEY RESOURCE INPUT: NONE	Low upfront cost, interoperability with conventional induction rotors and VFDs, High baseline energy efficiency, no slippage	Comparatively low power density, technological immaturity	~2% more efficient than a NEMA premium model. Permanent magnet assisted synchronous motors are ~4% more efficient than NEMA Premium	Pumps, Chillers, HVAC

COPPER SQUIRREL CAGE[10]	Greater efficiency than an AC induction motor with an aluminum squirrel cage, lower operating heat, compact design	High upfront cost, slightly increased weight	~1%-3% overall efficiency gains over NEMA Premium aluminum cage models across a range of operating loads	Extruders, Mills, Extractive Industry
GREATER SILICA GRAIN ELECTRICAL STEEL INTEGRATION	Greater efficiency than motors with non-electrical grade steel, lower operating heat	Greater upfront cost, low availability of the required steel	~1%-1.5% total efficiency gains through reduced core losses	All purpose
WIDE BANDGAP SEMICONDUCTOR INTEGRATION	Lower operating temperature, greater switching frequency in VFDs, lower switching losses in VFDs	Technology still early in development cycle. High upfront cost, durability remains to be seen	WBG semiconductor VFDs up to 3% more efficient than VFDs with conventional silica power electronics	Heat and space constrained speed applications (HVAC), high-switching-speed and high-heat requirements

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[10] Squirrel cage and electrical steel are not technologies per se, but instead premium materials that can be integrated with the existing motors technologies. They are listed on the chart for ease of reference in scaling their impact on motor efficiency.

Section 2: Supply Chain Analysis

Introduction

This section will discuss the supply chains of advanced motor technologies, focusing mostly on key resource inputs. Apart from the rare-earth elements in PM motors, none of the key resource inputs for these high efficiency designs depend on critical materials. This is not to say that sourcing of these resources is trivial; high-grade silica grain steel and copper wiring represent the two pinch points in the electric motor value chain, and both are a key facet of efficiency improvements in advanced motor technologies (Lowe et al. 2010). Copper is a globally competitive commodity subject to price fluctuations. While advanced motor designs (especially copper rotor motors) can be more exposed to this costing constraint, the supply chain is globally diversified and resilient with a robust North American contingent. This stands in contrast to NdFeB magnets, which rely on neodymium and dysprosium, whose global supply chain is exposed to both significant price volatility and potential for supply disruption (Smith Stegen 2015).

The level of publicly available information specifically on stationary industrial motor supply chains is modest. For this reason, this review will draw insight from comparison cases with a greater level of research activity where appropriate. In the case of NdFeB magnet substitution, wind turbines provide an informative case. Significant levels of academic research into substitution of NdFeB magnets in wind turbines occurred in response to rare-earths price shocks (discussed later). Wind turbines present an analogous technological case to PM motors as both are the high upfront cost, high performance design and when NdFeB prices rise alternative designs become more attractive. Additionally, this review will at times draw on the robust literature on traction motor value chains to compare and draw inferences to stationary industrial value chains. That is not to say that stationary industrial and traction motors are the same or that the technological and application differences are trivial. But while operating under different application constraints (weight, operating heat, and power factor holding more central importance to traction motors), the same suite of motor technologies is available in both sectors, informing system-for-system substitution.

The inputs of silica grain electrical steel, permanent magnets, and copper wiring within the motor value chain are characterized by a “Producer-driven supply chain… [with] low interfirm collaboration [and] standardized relationship” (Lowe et al. 2010). While the motors rely heavily on these key resource inputs, motor manufacturing demand represents only a small fraction of the key materials’ total market. Copper and electrical steel are purchased in bulk at market prices. Copper in particular is straightforward to recycle, with recycled copper making up about 38% of U.S. supply in 2020 (United States Geological Survey 2021).

The WBG power electronics-based motor drive value chain is too immature to accurately characterize as either producer-driven or buyer-driven. WBG-enabled VFDs will benefit from the cost of WBG devices dropping (W. Lee et al. 2018; Eden 2016). Within the market for WBG devices, however, the market share that these drives would represent to WBG semiconductors is projected to be modest, with most of the market share growth being driven by electric vehicles and inverter applications.

Understanding the architecture of the value chain (producer-driven versus buyer-driven) is key to understanding the limitations and potential disruptions of the stationary industrial and commercial motor supply, as well as the pace of technological adoption. Figure 1 shows a comparison illustrating the different architectures of buyer-driven and producer-driven value chains. The terms "supply chain" and "value chain" are closely related. In this report, the term *supply chain* will refer to the flow of commodities, goods, and components between firms and their suppliers. The term *value chain* will be employed to describe the broader flow of information, resources, goods, and services between organizations within the supply chain. Value chains describe all the interactions through which firms can add value, which includes but is not limited to, the goods and commodities transfers which make up the supply chain.

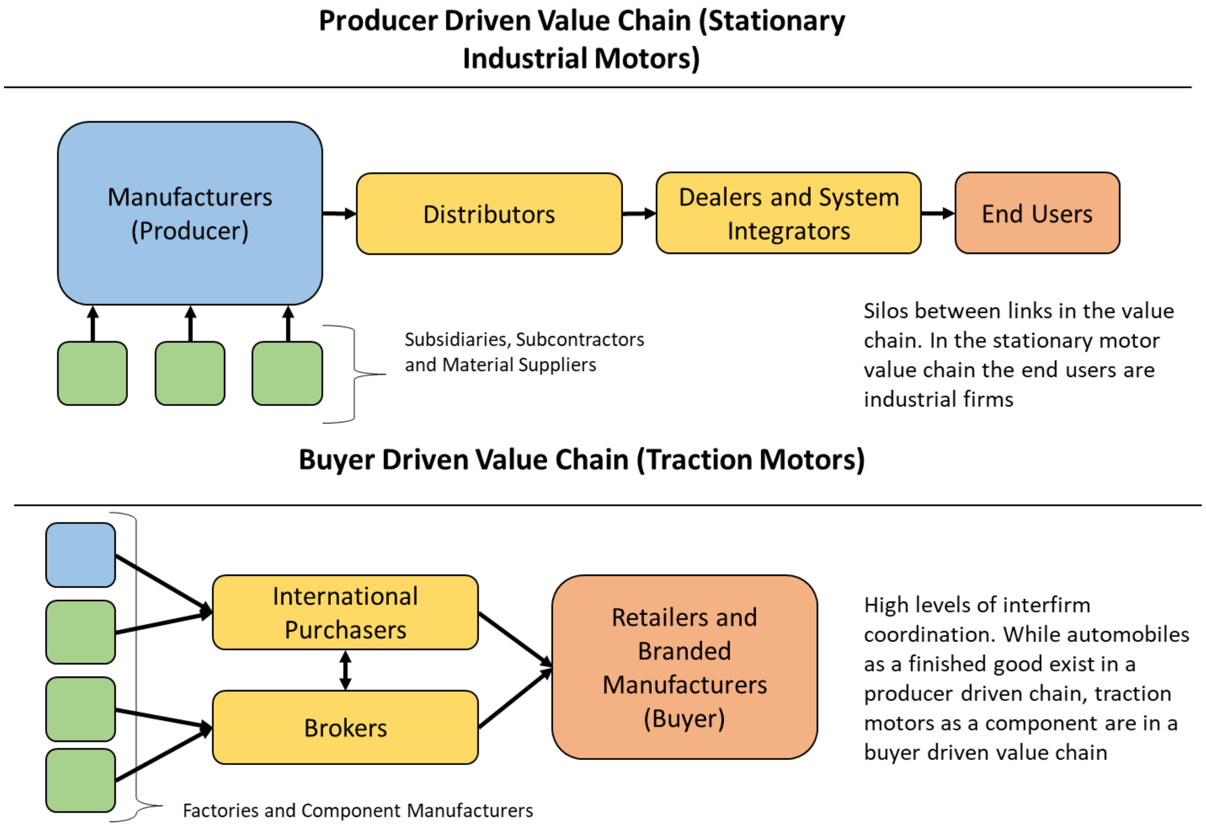

Figure 1: Key features of the producer and buyer-driven value chains are shown. Goods flow in the direction of the arrows, connections between boxes illustrate interfirm interactions, and the relative size of each link denotes level of influence on the behavior of other links in the value chain. For this analysis, the key differentiator is the relationship between firms and their suppliers. Buyer-driven chains have high levels of interfirm collaboration and coordination, while in producer-driven chains, interfirm collaboration and coordination are low. The colors denote the mapping of these concepts onto motor value chains, with green denoting suppliers, yellow intermediaries, blue motor manufacturers, and orange end users of the motor. Adapted from (Lowe et al. 2010)

Producer-driven value chains have low levels of interfirm engagement and are defined by significant exposure to globally competitive commodity pricing. The most powerful actors within the value chain are the product manufacturers (Bramucci et al. 2015). Buyer-driven value chains are characterized by high levels of interfirm collaboration, and the most powerful actor in the value chain is a branded retailer with a sufficient fraction of the end purchases of the manufactured goods to dominate the value chain. Stationary motors for commercial and industrial applications exist within a producer-driven value chain, with characteristics of that value chain affecting the speed of technological adoption and the level of interfirm collaboration (Lowe et al. 2010).

Comparing the stationary motor value chain to the buyer-driven traction motor value chain can illustrate potential efficiencies. While automotive manufacturing is usually characterized as producer-driven, the value chain of the traction motors *within* automotive manufacturing is better understood as a buyer-driven chain. Large, branded institutional buyers (car manufacturers) are the most influential agents, the marker of buyer-driven value chains, as indicated in Figure 1. The buyers in "buyer-driven" value chains are large institutional purchasers, not the car consumers. The following sections present a more detailed review of the stationary industrial motor value chain through this lens, as well as comparisons to vehicle traction motors and their buyer-driven value chain. This review will detail the supply chain of NdFeB magnets, including both mining and recycling efforts, and will then discuss the value chain of PM motors, including a discussion of potential substitution of the NdFeB magnets within them. The value chains of electrical steel, WBG semiconductors, switched reluctance, and synchronous reluctance motors will then be discussed.

NdFeB Magnet Supply Review

Mining Rare Earths

Much analysis has been devoted to the fraught global rare-earths supply. For a more extensive explanation of the challenges of rare-earth extraction and refining see the *U.S. Department of Energy Critical Materials Strategy* (Chu 2011). While moderately abundant in the Earth's crust in the absolute terms, rare earths are not often in concentrations high enough to make them easy to exploit economically (Humphries 2010). Rare earths are sometimes termed "geological vitamins," as small amounts doped into materials can vastly alter their characteristics. The refining process can be hazardous; rare-earth bearing ore is often laced with radioactive thorium, and the separation of the relevant rare earths requires solvents that pose a groundwater contamination risk (Hsu 2019). Historically rare-earth production was headlined by the United States out of the Mountain Pass mine in California. Beginning in 1980s China, where 36% of the world's reserves are located, began to scale production, accounting for 90% of the world's commercial heavy rare-earths[11] production by 2010. The terms *rare-earths oxide* or *rare-earths oxide equivalent* are employed in assessments of rare-earths deposits and mining. Rare-earths oxide refers to rare earths that have been processed, purified, and powdered for sale. Rare-earths oxide equivalent is a deposit's projected rare-earths oxide yield.

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[11] The designations of rare earth elements as either "heavy" or "light" refers to their atomic number. Commonly rare-earth elements with atomic numbers between 57 and 61 referred to as light and those with atomic numbers 62 and above are referred to as heavy, though these designations are not universally applied.

NdFeB magnets are the primary end use of these heavy rare earths in electric motors. It is estimated that more than 99% of global dysprosium consumption from 2013-2017 was for permanent magnets (Castilloux 2018). Beginning in September 2010, due in part to tensions relating to a border conflict with Japan, China restricted rare-earth exports, sending significant price shocks through the market. These shocks lasted until 2012, with prices increasing on certain heavy rare-earth oxides by factors of 10 (Hayes-Labruto et al. 2013). In response, global supply has diversified, and in topline terms, according to the United States Geological Survey (USGS), China now accounts for only two-thirds of global production of heavy rare-earth oxide equivalent, as shown in Figure 2 (United States Geological Survey 2021).

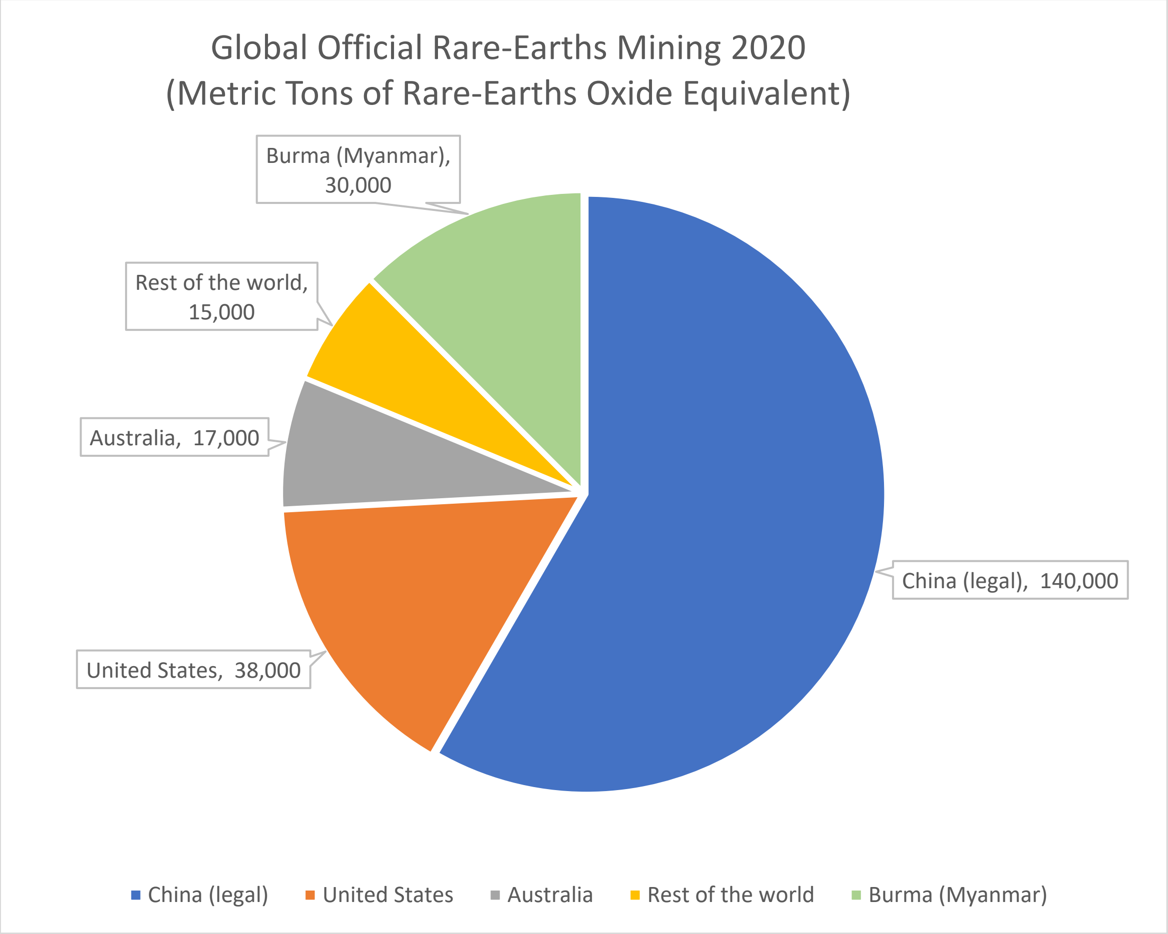

Figure 2: Reported global rare-earths production by point of origin. These are official reported totals and does not include illegally mined or refined rare earths. Thus, China's total is only their officially reported production. Data source: (United States Geological Survey 2021)

These topline numbers do not however reflect the significant influence of illegally mined and refined Chinese rare earths. As the USGS noted in its 2019 rare earths commodity report, based on magnet material production, illegal and black-market rare earths accounted for at least 60,000 tons of production in 2018. This lower bound estimate of illegal production in China was equivalent in scale to 50% of Chinese legal production in 2018 (United States Geological Survey 2019). China has since reduced the amount of illegal rare earths production through stricter enforcement. The financial advisory firm Hallgarten & Co. estimated that illegal production in China had dropped from 2018 peak levels by 50% as of 2020 (Cotting and Barich 2019). With these values for Chinese illegal production, we can construct a more accurate global estimate of production by metric tonnage (Figure 3).

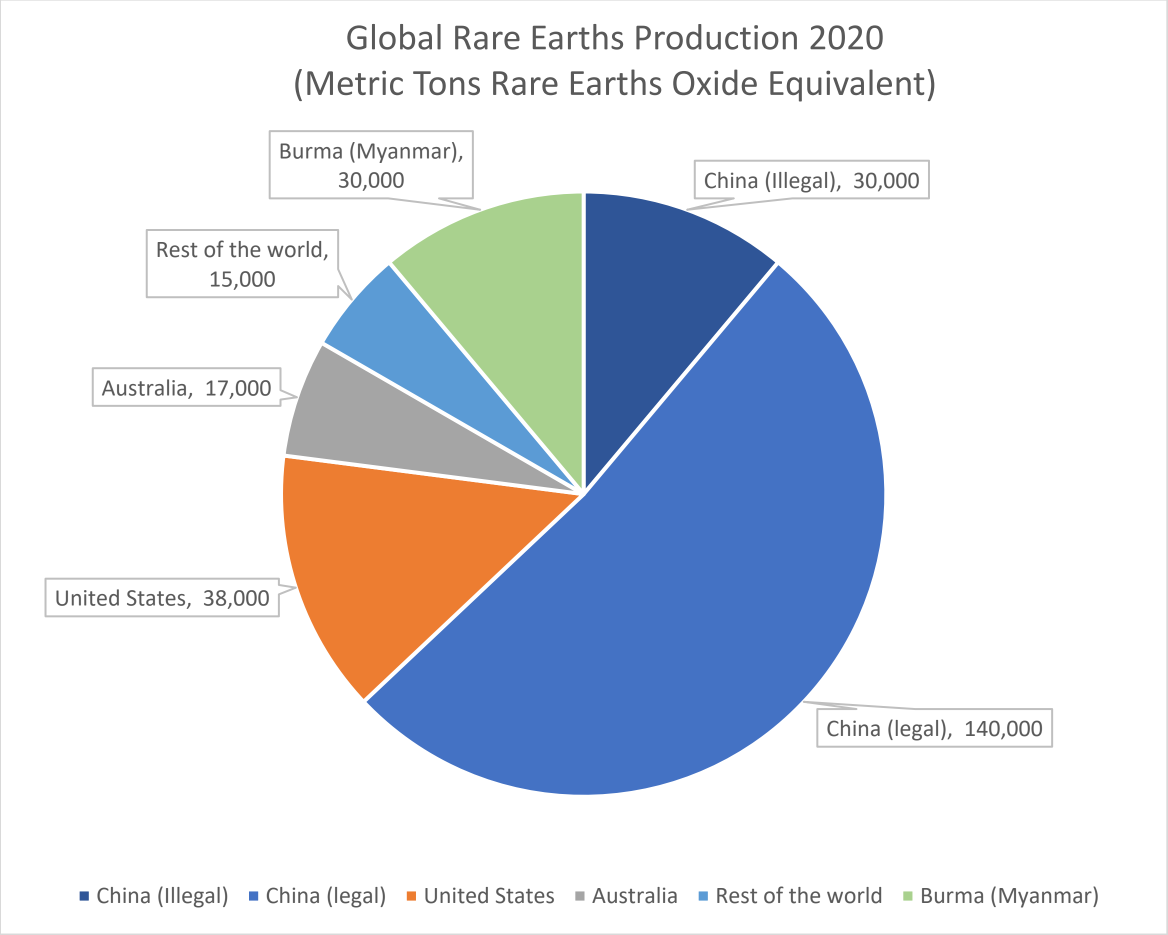

Figure 3 Global rare-earths production by point of origin, including estimates of Chinese unsanctioned production. Illegal Chinese mining and refining was estimated by USGS based on exports of rare-earths derived products, including magnets in 2018 and industry analysis of reduction in illegal production. Data sources: United States Geological Survey 2021, United States Geological Survey 2019, Cotting and Barich 2019.

In addition to their significant domestic mineral reserves, China is where the overwhelming majority of global heavy rare earths are processed. Raw heavy rare-earth ores are chemically treated to produce first ore concentrates and then pure rare-earth element oxides (Hsu 2019). According to industry analysis firms, China accounts for 70%-80% of global neodymium processing capacity (Castilloux 2018), and as high as 99% of global dysprosium processing (Vukovich 2019). The United States does retain a small amount of light rare-earths processing activity, typically as a byproduct of aluminum refining, and a series of rare-earths projects are currently receiving U.S. Army funding to build up domestic refining capability (Scheyder 2019). In response to supply chain disruptions relating to the Covid-19 pandemic, the U.S. Department of Defense awarded $30.4 million under the Defense Production Act Title III to Lynas Rare Earths Ltd. in February 2021 for further development of domestic light rare-earths processing (Department of Defense 2021). The United States, Australia, and Japan announced an initiative in March of 2021 to jointly develop heavy rare-earths processing capabilities (Decena 2021).

While there is clear governmental support for developing domestic processing, as of the writing of this report, no heavy rare earths are processed in the United States.

After ceasing operations in 2002, the Mountain Pass mine in California was purchased by Molycorp Minerals LLC in 2008 with an intent to reopen and expand the mine. After five years and the construction of a processing plant, Molycorp filed for Chapter 11 bankruptcy protection, resulting in a restructuring that separated the Mountain Pass mine from other assets. The mine was purchased in 2017 by a conglomerate of American investment groups and Shenghe Resources Holding Co., a Chinese rare-earths processing firm. An ownership stake in the mine is held by MP Materials, the operator of the mine. Mining resumed in 2018, but the raw heavy rare earths are exported to Chinese processors (Ernest Scheyder 2019; Green 2019). While the government support and investment in processing projects shows promise, none have yet begun construction, let alone operation.

In response to trade and supply related shocks, the mineral extraction of rare-earth bearing ores has diversified in the last decade. Australia and the United States both possess proven extractive capabilities. There has not, however, been significant diversification of processing capacity, and in the short to medium-term, this is unlikely to change due to a lack of facility capacity outside of China and the specter of price competition from already established low-cost Chinese plants, as well as the concerns of health and environmental risks from processing (*Reuters* 2019). While some projects outside of China are in the introductory stages of development, none have yet moved the needle of global processing. This has prompted investigation into an alternative path to rare earths through recycling.

Recycling Rare-Earths

Beginning in earnest after the Chinese rare-earths export restrictions of 2011, basic research and development ramped up around closed-loop supply chains for rare-earth elements. The greatest enthusiasm emerged around recycling. The Japanese government announced it would develop a recycling program to extract rare earths from scrap (Tanaka et al. 2013). The European Union (EU) funded a variety of efforts around rare-earth element recycling, including a multifaceted Fraunhofer Institutes project ("Substitution, Efficiency, Recycling: Fraunhofer IMWS" 2018). The U.S. DOE funded efforts at universities and national labs (Brewer et al. 2019). While challenging, these pathways are technically feasible and could serve as a path toward increased recycling above current levels (near zero) "if recycling became mandated or very high prices of rare-earth elements made recycling [economical]" (Goonan 2011).

The research into rare-earth element recycling can be sorted into two categories: preconsumer recycling and postconsumer or end-of-life recycling. Preconsumer recycling uses byproducts, scrap, and slag from rare-earths processing as secondary sources of rare-earth oxides. End-of-life recycling refers to the extraction and refinement of the rare earths from products at the end of their life cycle. Preconsumer recycling occurs commercially through two main processes: melting/strip casting and acid leaching. These recycling practices reprocess scrap from shaping and manufacturing defects, and account for between 1%-2% and 10%-20% of total production, respectively (Sprecher et al. 2017). Until very recently, there was no commercial end-of-life NdFeB recycling (Rademaker, Kleijn, and Yang 2013; Yang et al. 2017). In 2020, the Urban Mining Company began production of NdFeB magnets using end-of-life electronic waste recycling as their rare-earth element feedstock, though they have not yet achieved commercial scale (Vinoski 2020). In response to the Covid-19 pandemic, the Department of Defense bolstered these efforts with a $28.8 million award to Urban Mining Co. under Title III of the Defense Production Act, allowing further development of production capabilities even during the workforce disruption of the pandemic (Department of Defense 2020). The historical context of low rare-earth element prices meant there was little to no incentive for commercial development of recycling efforts. The greatest level of research activity into postconsumer recycling has occurred in regions without feasible mineral reserves to mine, namely Japan and the EU. For these actors, postconsumer electronics and wind turbines constitute a potential urban mine (Smith Stegen 2015).

DOE-sponsored research on rare-earth element recycling includes the *Driving Reuse and Recycling* research effort by the CMI (Ames National Laboratory n.d.). This research investigates both preconsumer and postconsumer recycling, with a recent example including the development of an acid-free leaching regime for the extraction of rare-earth elements from electronic waste (Prodius et al. 2020). The Ames National Laboratory also received a Small Business Technology Transfer grant to collaborate with TdVib LLC on commercializing less environmentally hazardous recycling solvents ("TdVib Receives $200,000 STTR Award from US Department of Energy to Develop Innovative Critical Materials Recycling Method" 2020). Momentum Technology licensed a recycling patent from the CMI with applications in both lithium-ion batteries and rare earth permanent magnets, and several postconsumer recycling pilots and technology commercialization demonstrations are underway (U.S. Department of Energy 2020).

Several major barriers impede *magnet-to-magnet recycling*, the mechanical reprocessing of postconsumer magnets into magnets without chemical breakdown into their constituent components. These barriers include oxidation sealing, labor costs, and grade purity of the input materials (Sprecher et al. 2017). NdFeB magnets easily oxidize and are usually sealed to stabilize them. This makes recovery more difficult, increasing the cost of harvest. Compounding this challenge, the size of the magnet is so small in much of the electronic waste stream as to make harvest labor cost prohibitive. Finally, if the NdFeB magnets being recycled are not uniform in magnet grade, they must instead be broken down into their base components, increasing the technical and economic challenge in recycling (Smith and Eggert 2018). This is especially relevant when considering the recycling of the magnets in PM motors, as the grade of the magnets varies between manufacturers and units. Simple objects (such as beverage cans) are economically recyclable, even if the commodity in question is low cost, as the material being recycled is straightforward to separate, requiring minimal processing. As the complexity of the object being recycled and its "material mixity" increases, recycling only occurs when the recovered materials have a proportionally higher value (Dahmus and Gutowski 2007). Rare earths "tend to be used in small quantities, in complex devices…the [costs associated with] collecting scrapped objects that contain rare earths, and separating the rare earths from the other materials, is often larger than the value of the materials that they contain" (King, Eggert, and Gschneidner 2016).

Direct reuse of end-of-life NdFeB magnets represents another potential avenue to a closed loop supply chain. The potential for reuse of magnets in wind turbines is an illustrative contrast to magnet reuse in stationary motors. The major difference between the magnets in these applications is scale: NdFeB magnet content ranges in mass from a less than a gram in a cell phone, to ~1 kilogram in a traction motor, to 1-2 metric tons in a modern offshore wind turbine (Yang et al. 2017). This large scale makes the magnets in offshore wind turbines economically viable to recycle, but even more attractive to reuse (Fishman and Graedel 2019). Like postconsumer recycling, reuse harvests magnets from end-of-life products. Unlike postconsumer recycling, reuse uses the recovered objects as is without reprocessing. Reuse is most effective when the harvested products are standardized and high cost. Offshore wind would adapt well to NdFeB reuse because the comparatively few offshore turbines make magnet grade standardization and harvest feasible, and the scale of the magnet makes harvest economically competitive with new manufacture.

Neither of these characteristics, component standardization nor excessive component costs, are present in stationary motors, meaning recycling and reuse face significant economic headwind. Closed-loop rare-earth supply chains more generally face a scale constraint on the demand side. Rare earths are essential inputs for the magnets in wind turbines, traction motors for electric vehicles, solar inverters, and advanced batteries. All these end uses are projected to grow globally in the coming decades, while also increasing the product lifetime. Chinese projected domestic NdFeB consumption growth alone is expected to outpace their legal rare-earth oxide production quotas by 2025 (Castilloux 2018). Even under the most optimistic recycling and reuse scenarios, sectoral growth means closed-loop supply chains are insufficient to meet demand. With overall NdFeB demand and lifespan increasing, the quantity of rare-earth magnets at end-of-life cannot meet projected needs, regardless of recycling or reuse efficiency.

This is not to discount the potential for recycling and reuse efforts to significantly contribute to global rare-earths supplies in the future. Future development of grade standardization to allow for more straightforward recycling or end-of-life reuse in PM motors could ensure a more resilient supply chain, but it would carry trade-offs in price and performance flexibility. Within the short term, the direct impact of end-of-life recycling on the supply chain for permanent magnet motors remains small.

Magnet and Motor Manufacturing

The global landscape of permanent magnet manufacturing is similar to rare-earths processing with respect to the prominence of China. China is the largest global producer of sintered NdFeB permanent magnets. The second largest producer is Japan, with the EU and the rest of the world comprising the remainder. The breakdown of global supply by origin is shown in Figure 4.

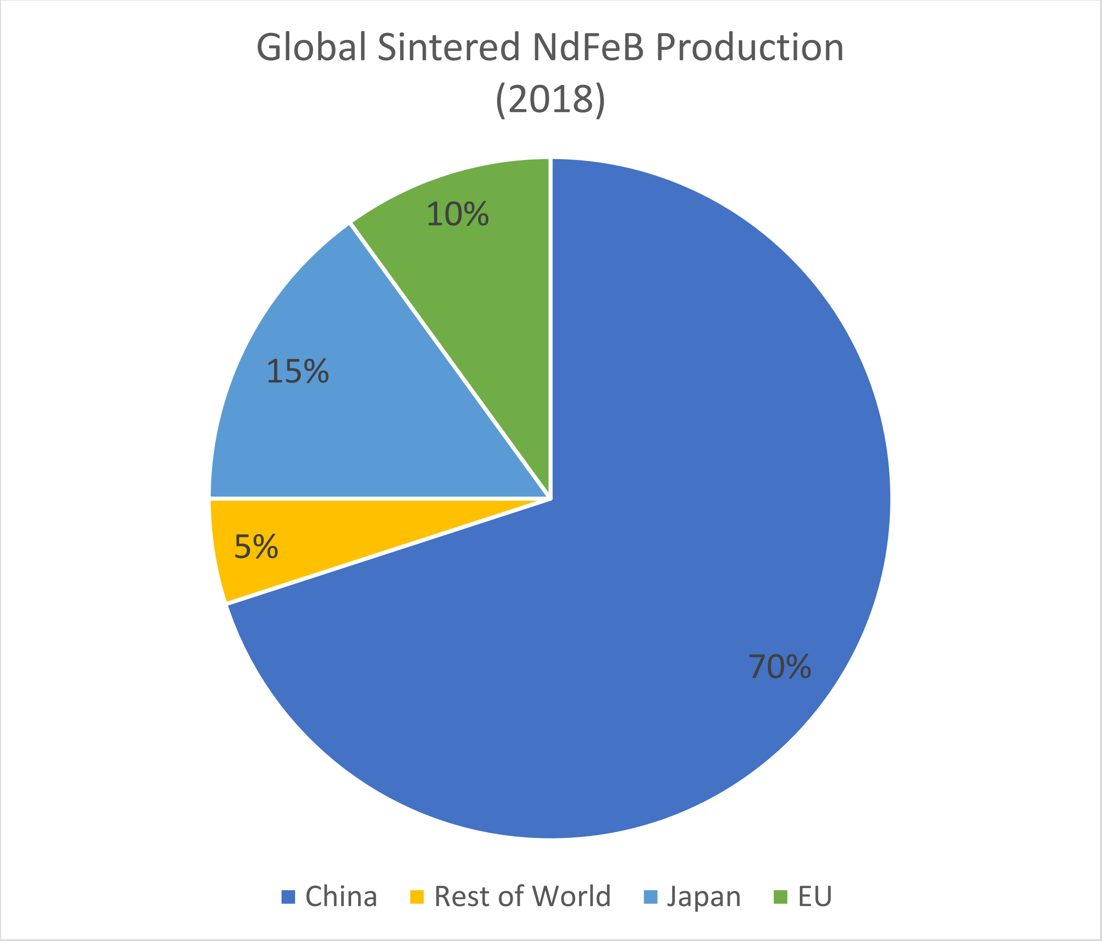

Figure 4:National and regional sintered NdFeB production as a proportion of the global total. Note that at the time these data were reported, the United Kingdom had not formally exited the European Union. These data do not differentiate by magnet grade or production technique. Data source: Vukovich 2019

More than 200 Chinese state-owned companies engage in rare-earths mining, processing, and magnet manufacturing. There are reports of a strategic shift by the Chinese government toward consolidation, combining these companies into fewer, larger organizations. This primarily internal organizational change is intended to reduce bureaucratic bloat and streamline management (Argus Media 2020). The Japanese magnet producers are characterized by proprietary intellectual property relating to the sintering process. Hitachi is the holder of more than 600 patents related to sintered rare-earth magnets, and Japanese domestic production is dominated by Hitachi and firms they will license to: TDK and Shin-Etsu. The only United States sintered NdFeB industrial scale manufacturing facility was until recently owned by Hitachi. Constructed in 2011 in North Carolina, production at the plant ceased in 2015 following the resolution of the 2010-2012 rare-earth element price shock. The magnet manufacturing equipment from this plant was sold to USA Rare Earths LLC in April 2020 (Shane 2020). While Urban Mining Co. is still developing their production capacity, they are the only NdFeB producer located in the United States (Staub 2020). The 2010-2012 price shock arose in part in response to a patent licensing dispute between Japan and China. At that time Hitachi would only license its intellectual property to eight firms in China. While this licensing dispute is ongoing, it is worth examining the Japanese supply chain around traction motors for potential insights into how to strengthen the stationary motors value chain.

While technically similar to stationary motors, electric vehicle (EV) traction motors differ in their value chain architecture. The electric motors and any accompanying key resource input are each components of a holistic buyer-driven EV value chain, resulting in a greater degree of interfirm cooperation, and more robust systems level design architecture around efficiency and process optimization (Lowe et al. 2010). In Japanese electric vehicle manufacturing the "companies producing these magnets are not simply suppliers. They often collaborate with OEMs such as Toyota to customize their motors to reduce the amounts of rare-earth element required, as well as catering to other specific needs" (Kiggins 2015). Despite accounting for only a small fraction of global rare-earth magnet production, "Hitachi Metals, Shin-Etsu Chemical and TDK are the dominant suppliers of [premium quality permanent magnets] …The Japanese car industry buy[s] only from these three firms in order to maintain its technological superiority" (Kiggins 2015). This dominance in vehicle applications is not only domestic; Japanese firms accounted for 77% of all production of EV traction motors from 2011-2015, with the EU accounting for 9% (Johnson, Hanratty, and Holcomb 2016). The domestic U.S. traction motor value chain is defined by a lack of strategic investment and key resource input manufacturing capacity (Johnson, Hanratty, and Holcomb 2016, 10).

The Japanese firms that dominate production of traction motors are close collaborators across their entire value chain and are then able to respond to disruptions more nimbly. The dominance of the buyer in the buyer-driven value chains means there is a single influential firm that benefits from systems efficiency and technological innovation. In producer-driven value chains such as the stationary industrial motor value chain, the distant relationship between motor manufacturers and industrial end users results in no individual actor being responsible for process optimization. Manufacturers reduce the variety of motors they produce to a minimum to cut down on manufacturing capital expenditure, producing a generalized, mass market product for the widest possible suite of applications (Bilgin, Jiang, and Emadi 2019). No individual end user is important enough to merit a significant relationship with the manufacturers, let alone to meaningfully influence manufacturer strategy. This relational distance also contributes to technical stagnation. End users stand to benefit most from adoption of emerging, more efficient technologies, but no individual end user is significant enough to the manufacturers where the prospect of a long-term contract outweighs the risk of manufacturing a less proven technology. This technological conservatism results in motor manufacturers "spending more effort and capital to reduce the costs of production of existing technologies than in designing new technologies which could change the game" (Bilgin, Jiang, and Emadi 2019).

Buyers' reaction to this value chain relationship compounds these effects. Industrial end users view their electric motors as an equipment fixed cost in their production, often keeping multiple backup units on hand to avoid interruption of critical applications (Waide and Brunner 2011). This inventory of old motors then depresses adoption of emerging technologies, both by displacing end-of-life replacements by newer motors and compounding the technological conservatism of operations and maintenance firms by locking in their services to older designs. System integrators focus on upfront cost rather than life-cycle efficiency. There is a collective action problem within these producer-driven value chains, as there is no actor with sole ownership of these system efficiency optimizations that holds the greatest potential for energy savings: namely, end-operator systems efficiency, VFD integration, and motor right-sizing (Almeida, Ferreira, and Both 2003). The lack of strategic coordination in producer-driven value chains makes them more vulnerable to supply disruptions of their key resource inputs. In a buyer-driven value chain, buyers can respond to a price shock by adjusting strategy and shifting to a more secure resource or substitute technology and coordinating that shift up the value chain as we saw occur in traction motors. In response to a shift in strategy by the dominant buyer, supplier firms made capital investment to align themselves with this strategic shift. Each individual producer within a producer-driven value chain will respond to disruption in their key resource inputs according to their individual price incentives. For an in-depth illustration of how producer-driven value chains react to such shocks, consult the substitutability of NdFeB Magnets subsection of this report.

Stationary PM motors constitute the greatest current demand driver for permanent magnets. Based on growth projections, vehicle traction motors are expected to become the largest end use by 2025 (Castilloux 2018). Within current motors, industrial and HVAC applications combine to form the largest global end use (Ormerod 2019), accounting for 57% of PM motor applications (Benecki 2016).

Substitutability of NdFeB Magnets

The rare-earth element price shock of 2010-2012 provides an informative case to review the substitutability of NdFeB magnets in stationary motors. *Substitutability* refers to the extent which an input resource or component can be substituted for an alternative. In the case of NdFeB magnets, five types of substitution are identified in the literature: (1) element-for-element, (2) technology-for-element, (3) grade-for-grade, (4) magnet-for-magnet, and (5) system-for-system substitution (Smith and Eggert 2016). As defined by Smith and Eggert*, element-for-element* substitution is the reduction of a chemical element in the magnet without a change in magnet grade by replacing it with another element. *Technology-for-element* is the reduction in an element through manufacturing process change within a magnet grade. *Grade-for-grade* is the ability of an intermediate producer to use a different magnet grade of a constant magnet type in place of another. *Magnet-for-magnet* substitution refers to the usage of an entirely different type of magnet in place of the NdFeB magnet. Finally, *system-for-system* substitution is the ability to substitute between different systems altogether, i.e., an alternative technological design to achieve the same output.

The research focusing specifically on NdFeB substitution in stationary motors for industrial applications is minimal. Industries with similar dependency on NdFeB magnets will serve as sources of insight. The most relevant comparison industries for stationary PM motors are other clean energy technologies whose growth will drive the increasing consumption of NdFeB magnets in the coming decades: wind turbines and traction motors. Like stationary industrial motors, wind turbines are a manufactured product within a globally competitive producer-driven value chain (Hansen 2018). The use of wind turbines and power and stationary industrial motors is projected to grow as the economy decarbonizes, and both require NdFeB magnets as a key resource input. Traction motors represent a useful point of comparison because of their technical similarity to stationary motors; the same motor designs and accompanying resource constraints exist in each. Comparing the substitutability of PMs in these end uses with stationary motors both informs the likely supply environment of these magnets in the future and provides insights into how manufacturers and consumers responded to the 2010-2012 rare-earth element price shock.

Element-for-element and technology-for-element are magnet manufacturer driven, contributing to input commodity price on motor manufactures but not driven by their behavior (Smith and Eggert 2018). While a common substitution strategy during the rare-earth element price shock, they were covered in the earlier discussions of preconsumer recycling and rare-earths thrifting sections of this review.

Magnet-for-magnet substitution did not occur at a large-scale in wind turbines, as this substitution strategy was rated by industry participants as the least important substitution response (Smith and Eggert 2018). While there exist alternatives to NdFeB magnets with similar characteristics in samarium-cobalt (SmCo) magnets, their lower energy product (a measure of flux density and field strength) means that no major wind turbine design employs them (Smith and Eggert 2016). Where SmCo magnets possess a performance advantage compared to NdFeB magnets is in their higher Curie temperature, which has led to their common use in aerospace applications. SmCo magnets are not without their drawbacks, not least of which is cost; these magnets rely on a heavy rare-earth element in samarium as well as a costly critical material in cobalt, so they are subject to the same lack of supply diversity and price disruption potential as NdFeB magnets. They cost as much or more than NdFeB magnets, and further, their costs are interrelated due to their status as substitutes, though notably there is domestic manufacturing of SmCo magnets. A major NdFeB manufacturer interviewed by Sprecher et al. estimated “±10% of their customers substituted NdFeB [with] samarium–cobalt magnets and were not aware of any other types of material substitution among their customer base” in response to the 2010-2012 price shock (Sprecher et al. 2017). This same analysis reported a ~10% price increase in SmCo magnets following the NdFeB price increase. SmCo-for-NdFeB substitution in stationary industrial applications is limited by their lower power density, equal or greater cost, and advantage of higher operating temperature being less relevant to many of these applications. Dysprosium doped NdFeB magnets possess a maximum operating temperature of ~230°C, whereas SmCo magnets can operate at temperatures as high as 500°C. Individual cases will vary in their requirements, but NEMA Premium motors typically possess grade F insulation rated for operation at temperatures up to 155°C, indicating their expected operational range (“NEMA Insulation Classes for Motors” 2017). While the extreme temperature requirements of aerospace applications have resulted in extensive use of SmCo magnets, few commercial or industrial applications require such extreme temperatures, limiting their substitution potential.

The substitution of ferrite magnets for NdFeB magnets in PM devices within stationary industrial applications is more promising. Ferrite magnet-based PM designs are a common fixture of the research literature, with investigation accelerating in response to the NdFeB price shock. While typically individual performance characteristics of these motors are competitive with an NdFeB baseline (Drives and Controls Magazine 2014), there is some performance sacrifice. The lower field strength either means a larger magnet to compensate or lower efficiency and power density. A meta-analysis found ferrite substitution in PM designs tended to increase weight by 20-30% and reduce peak energy efficiency by 1-2% (Ma, El-Refaie, and Lequesne 2019). The primary advantage of ferrite substitution is in cost, as ferrite magnets are straightforward to produce and contain commonly available materials making them dramatically cheaper than NdFeB magnets.

Much of the available substitution literature examines wind and traction applications. Ferrite substitution tends to receive little discussion in substitutability analyses in wind applications. In traction applications, ferrite magnet designs are often more novel technologies such as PM assisted synchronous reluctance motors or Varnier machines, making them more accurately understood as system-for-system substitution (Ma, El-Refaie, and Lequesne 2019). Ferrite magnet-for-magnet substitution is a poor fit for both wind and traction applications. Each are especially sensitive to a performance disadvantage of ferrite magnets compared to NdFeB: field strength in the case of wind turbines, and weight and size constraints in the case of traction. Stationary industrial applications are less sensitive to these weight and footprint constraints. Accordingly, we should expect a larger amount of ferrite magnet-for-magnet substitution in industrial and commercial applications. This was confirmed both by conversations with industry (Boteler 2020), as well as by what academic literature is available on the topic (Ding 2014; Eggert et al. 2016). In contrast to the better studied substitution cases, stationary industrial applications are more capable of substituting ferrite in PM designs and accepting the weight and footprint tradeoffs.

Grade-for-grade substitution (also termed *grade optimization*) occurred at a moderate level in wind turbines in response to the 2010-2012 rare-earth element price shock. Grade optimization was driven by two major behaviors: overspecification correction and performance sacrifice. As their key resource input increased in price, wind turbine manufacturers determined that some existing turbine designs had been over specified (designed with a higher quality magnet than was required to reach the performance specifications) and adjusted the grades of their magnets down accordingly (Smith and Eggert 2018). Some producers opted for a lower grade, lower rare-earth element content, lower cost magnet, accepting the accompanying performance downgrade. This substitution strategy is difficult to research “since grade optimization may negatively affect performance and/or lifetime of the final product, there is almost no publishable data available on the topic” (Sprecher et al. 2017). There is a lower bound on how much the quality of the component magnet can degrade in stationary motor design due to industry ratings and manufacturing efficiency standards.

System-for-system substitution was a commonplace response to the 2010-2012 rare-earth element price shock in both wind and traction motor industries. While permanent magnet synchronous generators (PMSG) represent one premium design of wind turbines, there are technically developed alternatives, such as squirrel cage induction generators. Some major manufacturers, such as Siemens, maintain parallel product lines for different turbine designs. In response to price hikes in rare earths, wind installation developers shifted to these alternatives in appropriate projects, typically onshore farms. Like wind turbine manufacturers, stationary motor suppliers will select a technology based on the end use case performance needs.

A key driver of technological risk aversion in the wind energy sector is debt financing. The scale of investment for utility scale wind installations makes lenders highly technologically risk averse, depressing the deployment of recent innovations (Arapogianni et al. 2013). A similar role is played in stationary motor applications by drive manufacturers, whose technological conservatism slows the uptake of emerging motor technologies (Pavel et al. 2017). In traction applications, the rare earths price shock prompted some manufacturers to shift to existing alternatives (asynchronous motors), as well as to begin prototyping development on less commercialized designs (ferrite magnet induction and switched reluctance motors (Arapogianni et al. 2013). The same dynamics were at play in stationary application, with the adoption of emerging technologies accelerating in response to the shock.

These substitutability analyses are dependent on a variety of economic and technological factors. A novel NdFeB magnet manufacturing process, a breakthrough in recycling, effective thrifting techniques, or innovative system designs all could affect the usage of PM motors in stationary applications. These innovations are themselves sensitive to rare-earth element price conditions, as the last major wave of research in these areas began in response to the price shock of 2010-2012. The adoption of this innovation is another matter, as most of the actual technological substitution in both the wind and traction motor sectors was a shift to already available fully commercialized technologies (Smith and Eggert 2018; Sprecher et al. 2017). On the magnet manufacturer side, these shifts have persisted even after rare-earth element costs have fallen to pre-shock levels, as they have now made the capital investments necessary to improve the yield of their production methods so the gains persist. This fact presents a significant opportunity for motor manufacturers to increase their resilience with the development of technical alternatives. Collaboration between stationery and traction motor manufacturers on the development of a low-noise switched reluctance design could dramatically affect the levels of system substitution, for example. The risk scale of purchasers of stationary motors, as well as the availability of technically developed alternatives, would inform the behavior of firms in the event of another rare-earth element price increase.

How is the global value chain for stationary PM motors likely to evolve? In the event of a trade, disaster, or pandemic related disruption, offshore wind growth will be most inelastic, as there are fewer appropriate substitutes to PM in offshore turbines. While PM motors are a high efficiency and high-performance technology, system substitutes are available. In an environment of scarce PM supply, reluctance and copper cage designs represent increasingly competitive alternatives to PM. In an environment of rare-earths abundance, the more highly developed manufacturing value chain of PM motors will allow the technology to retain its market share. In an intermediate case, permanent magnet designs will continue to be the most common advanced motor design in stationary commercial and industrial applications, but their market share will fall as other designs scale up (Bilgin et al. 2020).

Electrical Steel

High-grade grain-oriented silicon electrical steel is a material input which can be incorporated into motor designs to increase their efficiency. Increasing the quality of the steel in the motor can reduce core losses, with a resultant efficiency improvement of ~1%-1.5% (McCoy 2014). Unlike permanent magnets, there are no critical material inputs for electrical steel; chemically it is an iron-carbon alloy doped with up to 6.5% silicon. There are a small number of firms which produce electrical steel, and they are concentrated in the United States, Europe, and Japan (Lowe et al. 2010). Key producers include ARMCO, AK Steel, ATI Allegheny Ludlum, Bao Steel, British Steel Corporation, China Steel Corp, Cogent Surahammars Bruk, Eurotranciatura, Hitachi, JFE Steel, Kawasaki Steel, Nippon Steel, Posco, Tata Steel, and ThyssenKrupp.

Silicon and iron are not themselves a key resource input for electrical steel, the sourcing challenge comes from capital investment and workforce development constraints. Electrical steel "requires a very specific manufacturing pattern/process – [it is] not possible to transition from motor laminated steel to Si-steel in the same plant without an extensive recapitalization effort." (Johnson, Hanratty, and Holcomb 2016). Electrical steel production equipment requires 12 to 24 months to install, and that does not include the human capital development required to retrain or hire a new workforce proficient in the electrical steel manufacturing process.

The market for electrical steel is growing, meaning there is some movement into novel production. The domestic supply chain remains brittle, however; capital investment and time-to-revenue barriers are sufficiently steep that only a limited number of firms are in a financially flexible enough position to develop novel or transition existing production infrastructure for manufacturing electrical steel. The limited intrafirm cooperation between motor manufacturers and their material suppliers, and the relatively small fraction of total demand accounted for by these manufacturers, ensures a limited supply stream. Greater capacity is being developed in response to demand from the larger EV and power infrastructure (high voltage transformer) sectors. Traction motors are an application of electrical steel within EVs, but there are a diverse series of applications for the electrical steel within electric vehicles. The exact grade and thickness of steel used in EV applications differs from stationary motors, but the underlying steel manufacturing infrastructure is the same. The rising EV tide could potentially manifest a more robust and diversified electrical steel sourcing ecosystem for stationary motors manufacturers.

Switched Reluctance Motors

The supply chain of switched reluctance motors represents an interesting case in our analysis, as they are an entire motor design archetype without significant key resource input insecurity. As noted in the switched reluctance motor subsection of the technical overview, their power density, operational temperature range, durability and robustness, and energy efficiency performance are all competitive with or superior to PM or induction motors. They do not require permanent magnets, and their manufacturing process is less expensive and challenging compared to copper die-casted induction machines (Bilgin, Jiang, and Emadi 2019). The component of switched reluctance systems that is presently the most challenging to source is their power electronics. Superficially similar to a drive for a conventional AC design, switched reluctance devices employ a less common form of power converter, known as an *asymmetric half bridge converter*. While currently less widely available than conventional power electronics, this is not due to resource constraint but to lack of existing demand, as their manufacture is straightforward. When compared to other motor designs with costs of VFD included, switched reluctance devices combined with the costs of their power electronics are already at cost parity or advantage (Fricke and Bhandari 2019; Bilgin, Jiang, and Emadi 2019). Integration of WBG power electronics into these converters increases system efficiency, with designs in the technical demonstration phase (Ahmad, Urabinahatti, and Narayanan 2020).

Acoustic noise is a significant downside of switched reluctance motors. There is a steady stream of design case studies and ongoing research into reducing noise in switched reluctance devices, but the noise cannot be eliminated, only mitigated (Bayless et al. 2016; Gan et al. 2018; K. Kiyota et al. 2016). As noted in switched reluctance application guides, low noise, low torque ripple, low temperature rise, and high efficiency all must be balanced and traded off, depending on the needs of the application and end use.

The simple, robust design of switched reluctance motors can be feasibly manufactured using existing electric motor infrastructure. Motor manufacturers that currently possess "the supply chain to manufacture permanent magnet or induction machines, can easily make switched reluctance machines with much lower cost" (Bilgin, Jiang, and Emadi 2019). One application area that switched reluctance devices would most naturally lend themselves to is commercial HVAC provided the noise is mitigated or insulated. As of 2012, high efficiency variable speed motors accounted for 34% of the residential furnace blower fan drive systems, mostly using the permanent magnet design. Switched reluctance motors are an ideal candidate for these applications due to their low production cost, their robust design, and their ability to operate continuously in high or low temperature conditions.

Given their competitive performance across a variety of metrics, their lack of key resource inputs, and their simplicity to construct and repair, why have switched reluctance devices represented such a small fraction of installed devices? There are some historical drivers of the low switched reluctance uptake. While the design has existed in theory for over a century, mechanical switches were a debilitating performance constraint. It is only with the advent of modern electronic semiconductor switching devices that switched reluctance motors were a viable option for industrial and commercial applications. As a performance competitive design has only been feasible for ~50 years, there is a significant legacy of induction motor technological lock-in. Despite accounting for the greatest proportion of life-cycle cost, system energy consumption has not historically been considered by buyers as important as upfront cost (Lowe et al. 2010). As operating efficiency rose in priority, there was initially low hanging fruit of significant efficiency gains by increasing the amount of copper and electrical steel in the motor design. More recently, there has been an analogous shift to permanent magnet devices. Motor and drive manufacturers preferred the more straightforward improvement of materials to a fundamental design shift, especially one that carried the drawback of high levels of acoustic noise and an unfamiliar power converter.

Switched reluctance motors both historically and currently hold a meager share of the global electric motor market (Bilgin, Jiang, and Emadi 2019). Comparing the sales of switched reluctance and PM devices globally, switched reluctance motors represent ~2% of the size of PM motor sales. The major producers of switched reluctance devices include Nidec Corporation, AMETEK, VS Technology, US Motors, Emotron, Maccon, Control Engineering, and Shandong Kehui Power Automation Co. With critical materials likely to become increasingly scarce, there is potential for growth in the uptake of switched reluctance devices and designs that mitigate noise concerns, especially in HVAC applications (Kasprzak 2017).

Synchronous Reluctance Motors

The value chain of synchronous reluctance motor systems possesses advantages and disadvantages. The most glaring issue in the value chain is immaturity. This is on both the technical and commercial level. The technology is still in an early stage of performance and production optimization, major commercial production reached the marketplace in 2012. While more manufacturers than ABB have entered the market, producers are nowhere near as diversified as for other motor technologies. The rotors themselves can be challenging to manufacture. The performance of the motor depends on the thinness of the iron which connects the flux bridges to one another. At high operating speeds, these connectors can represent a structural weakness in the rotor, meaning that careful design and balancing of these considerations is required (Villani 2020). This is not a technically prohibitive barrier to manufacture, but it does make rotor manufacturing challenging (Lehikoinen 2018). The current major producers of synchronous reluctance motor systems include: ABB, Mark Elektriks, Danfoss, Siemens, Relaoto, KSB (REEL), Oemer Motors, Bonfiglioli, Nidec Leroy-Somer.

These challenges are offset by significant advantages. There is no unique material key resource input to synchronous reluctance designs. The material costs of synchronous reluctance rotors range from 10-20% lower than analogous AC induction rotors (Ozcelik et al. 2019). Where the synchronous reluctance value chain holds a significant advantage over other emerging motor technologies is in interoperability with existing suppliers. While the rotors in synchronous reluctance designs are novel, the stators are identical to three-phase induction models. In fact, most research comparisons of synchronous reluctance motors to AC induction motors employ the same exact stator, only interchanging the rotor. This allows for easy retrofit and for existing induction stator stock and manufacturing capacity to serve synchronous reluctance devices. Relatedly, synchronous reluctance motors can be driven with conventional VFDs. While it is not technically prohibitive to manufacture the asymmetric half bridge converters using existing VFD manufacturing infrastructure, the fact remains that few are manufactured making sourcing challenging. In contrast, synchronous reluctance devices can use existing drives, though it is worth noting that owing to their lower power factor, drives should be selected for a motor based on rated current, not power (ABB 2017).

The synchronous reluctance value chain is currently in the early stage of development but is poised to expand. The lack of unique key resource inputs represents one advantage. Note that in PM assisted designs, the magnets can represent a key resource input, so accordingly the most robust and inexpensive value chain exists for the ferrite variant. The interoperability of existing stator and VFD stock lowers barriers to adoption, both for end users and for maintenance and installation professionals. This is an emerging motor technology which could see significant adoption if the technology and rotor manufacturing capacity matures.

Wide Bandgap Power Electronics

A significant portion of the end-use applications of stationary motors would benefit from variable speed operation. Most conventional AC-induction motors are not designed with integrated drives, meaning separate adjustable-speed-drives (most typically VFD) should be integrated. While VFDs significantly improve motor system energy efficiency, they can increase floor space footprint unless they eliminate the need for gears. This constraint is not typically challenging for manufacturing applications, but it reduces VFD penetration in heavy industrial (e.g., oil and gas, mining) and commercial HVAC applications. The cooling requirements of the semiconductors within VFDs is one factor leading to this bulk. Wide Bandgap (WBG) semiconductors, more advanced power electronics compared to conventional silicon semiconductors, would allow for more compact VFDs, with an estimated reduction in heat sink size for a 10 hp motor up to 66% (Hull 2013). In high voltage and frequency applications, drives are not widely deployed due to the high losses and large footprint of conventional power electronics for these applications. The more compact, cooler operating WBG based drives represent a promising path to drive integration in these applications. The semiconductor industry is one of the paradigmatic examples of a producer-driven value chain, characterized by globally competitive, vertically integrated manufacturers. Resultantly, there is currently little interfirm collaboration between drive developers and their power electronics suppliers. Interestingly, the technological competitiveness of the industry has shifted these dynamics somewhat, with interfirm collaboration being driven by the foundry system for the manufacture of WBG devices. This shift of scale could result in a less aggregated industry, building a more diverse network of suppliers and manufacturers. Presently however, WBG devices are early enough along the development curve that production scale and cost lowering are still required for commercial sale.

Two types of WBG designs are nearest to full commercialization: gallium-nitride (GaN) devices and silicon-carbide (SiC) devices. While both are still quite expensive, SiC devices have begun commercializing more rapidly driven by demand from the EV sector. In low voltage applications, however, GaN devices possess a performance advantage due to their higher switching frequency, so there is potential for that technology to overtake SiC in low voltage applications moving forward (Eden 2013). The wide bandgap power electronics market is immature relative to conventional silicon-based power electronics. Wide bandgap devices have only recently begun commercializing (~15 years). The major domestic SiC manufacturers include Cree/Wolfspeed and GeneSiC, with more players (Infineon, Fuji) abroad. There are fewer GaN manufacturers, as the technology is less mature, with Texas Instruments and Transphorm representing the major domestic players. The manufacturing of GaN devices needs to develop significantly before the performance potential of the technology can render it competitive with SiC, let alone cost competitive with conventional silicon devices. As noted in *Wide bandgap Semiconductor Opportunities in Power Electronics* (Das, Marlino, and Armstrong 2018):

> Most GaN devices sold today are on Si substrates (due to their low cost and availability) and are lateral devices, meaning current does not flow vertically though the device like most Power electronics devices, resulting in large area devices, low voltage capabilities, and poor thermal handling. Vertical GaN holds potential for higher breakdown voltages, but requires GaN substrates, which are much less mature than Si or SiC, with material issues (e.g., high defect densities) and high costs, though this is improving.

Until these materials are manufactured to a consistent level of quality, at a competitive price point, GaN devices will remain prohibitively expensive.

Upfront cost is the most consistently cited barrier to WBG adoption, as currently SiC diodes cost 10 times as much up front as conventional Si diodes. However, depending on the application, WBG devices are sometimes already life-cycle cost competitive due to reduced cooling costs and increased efficiency, so WBG devices may not need to achieve full upfront cost parity with Si devices to see widespread adoption. Presently, the cost differences are a contributing factor to slowing uptake (Agarwal et al. 2016).

There is significant ongoing research and development in WBG power electronics, with the PowerAmerica Institute providing research and cosponsoring SiC foundry and the national labs ecosystem providing research and institutional support. Additionally, the EU is financing commercialization of SiC semiconductor manufacturing through its Horizon Project, with several pilots launched from a variety of research and industry partners (European Union n.d.; Bieniek et al. 2019).

Turning to the question of WBG based motor drives specifically, the market is immature; not yet commercialized. There was no estimated revenue for motor drives incorporating WBG as of 2018 (Das, Marlino, and Armstrong 2018). VFD manufacturers currently add value through close relationships and collaboration with local end users; in contrast semiconductors are manufactured a globally competitive producer-driven value chain. It remains to be seen whether the increased sale of combined motor-drive systems disrupts this relationship. For a more detailed modelling of SiC VFD growth and cost scenarios, consult *A Manufacturing Cost and Supply Chain Analysis of SiC power Electronics Applicable to Medium-Voltage Motor Drives* (Horowitz, Remo, and Reese 2017).

Conclusions

As stationary industrial and commercial electric motors account for a large fraction of U.S. electrical energy use, efficiency improvements to this sector dramatically impact overall grid efficiency and resiliency. The historical path of increasing efficiency in conventional AC induction motors has been driven primarily through the integration of higher quality material components (analogous to grade-for-grade substitution), though these improvements may be nearing the point of diminishing returns. Some advanced motor designs do possess critical materials constraints, namely rare-earth permanent magnets. This report summarizes the impact of premium component integration and technology type on total unit efficiency. As premium components and permanent magnets are commodities in high demand, this allows stakeholders to most efficiently allocate their resources as conditions evolve.

A deeper understanding of the supply chains of premium efficiency motor technologies is vital to increasing the resiliency and efficiency of manufacturers. The constraints, strengths, and weaknesses of each of these supply chains are distinct. In the case of permanent magnet motors, the supply chain is defined by the critical material inputs; where rare earths are being mined and processed. In contrast, the silica steel supply chain is defined by capital investment; few firms producing globally competitive commodities possess the financial flexibility to develop a completely new labor force and production infrastructure.

While both switched reluctance and synchronous reluctance motors have no key resource inputs, meaning each are feasible system-for-system substitutes, synchronous reluctance motors possess the significant advantage of conventional stators. Not only does this allow manufacturers to take advantage of existing facilities and capacity, but operations and maintenance firms can employ existing stator stock. The straightforwardness of retrofits and the ability to capitalize on already produced stators positions this technology for quick adoption.

Conventional induction motors operating at constant speed are highly efficient at full load. This is not the case in variable speed applications. A significant share of sub-100 hp commercial and industrial motors are for variable speed applications. As permanent magnet, synchronous reluctance, and switched reluctance motors are each variable speed operable, these applications represent the strongest candidates for increased integration of these emerging motor technologies.

The small- to mid-sized stationary motor value chain can be characterized as producer-driven value chain with low interfirm collaboration. Electric motors for transit applications represent a technically similar product with a vastly different, buyer-driven value chain. As a cog in the larger machine of an integrated, differentiated product, electric motors in these sectors will be optimized for their key resource inputs, efficiency, and performance more quickly than their stationary industrial counterparts. Accordingly, the applications where traction and stationary electric motors most closely align will be the quickest to see gains from this traction motor dividend.

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