



# **An Assessment of U.S. Manufacturing Capability for Next-Generation Wind Turbine Drivetrains**

J. Cotrell and T. Stehly

**NREL is a national laboratory of the U.S. Department of Energy  
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Prepared under Task No. WE11.0620

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# Executive Summary

## Project Objectives

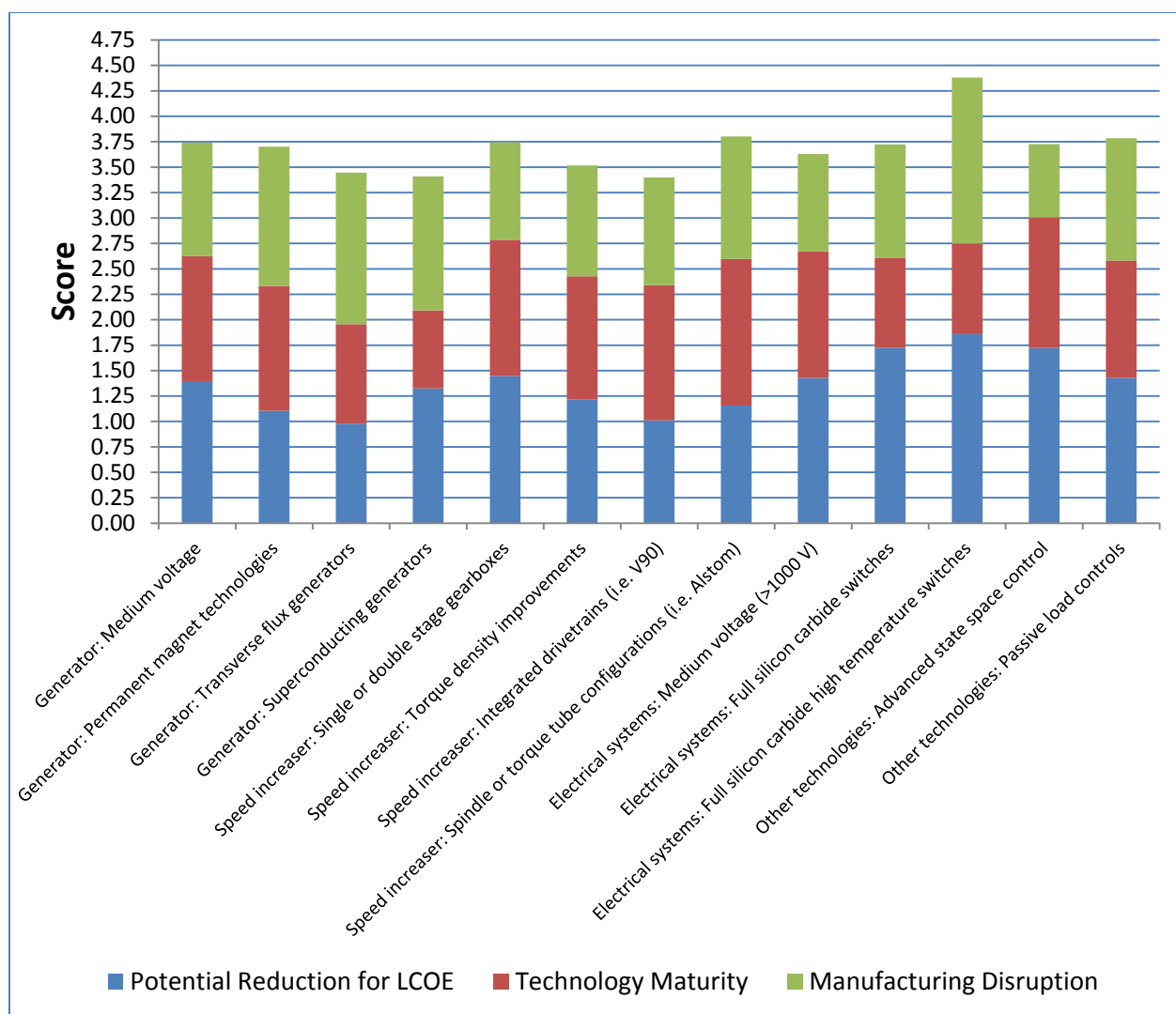
Robust U.S. wind turbine manufacturing capabilities and supply chains are important for the country to reduce the cost of electricity generated from wind turbines; are necessary for the invention and commercialization of new wind turbine technologies; and provide high-quality jobs. The development of advanced drivetrain technologies for wind turbine applications—such as medium-speed and direct-drive generators, silicon-carbide (SiC) insulated gate bipolar transistor (IGBT)-based power electronics, and high-torque-density speed increasers—is advancing the state of the art for drivetrain design by producing higher capacity and operating reliability than conventional drivetrains. However, these advanced technologies require different manufacturing and supply chain capabilities that present both risks and opportunities for U.S. wind turbine manufacturers and the wind industry as a whole.

The primary objective of this project was to assess how advanced drivetrain technologies and trends will affect the U.S. wind turbine manufacturing industry and its supply chains. The U.S. Department of Energy (DOE) and other industry participants will use the information from this study to identify domestic manufacturing gaps, barriers, and opportunities for developing U.S. wind turbine manufacturing capabilities and supply chains for next-generation drivetrain technologies. This report also includes recommendations to help prioritize technology areas for possible investments by public, private, or nonprofit entities, with the intention of reducing the levelized cost of wind-generated electricity.

## Project Approach

National Renewable Energy Laboratory (NREL) researchers performed literature surveys, expert interviews, and manufacturing facility visits to obtain the information and industry perspectives needed to inform the study. NREL also drew upon previous experiences with DOE and industry-funded drivetrain projects to compile a list of technologies for consideration and evaluation. The compiled list contained approximately 80 different drivetrain technologies. NREL engineers then identified three key metrics to assess the technologies, and selected 13 of the highest scoring advanced drivetrain technologies to evaluate in more detail (see Figure ES1).

The project scope was further narrowed by eliminating several technologies that received a particularly low score in one or more of the three metrics. For example, superconducting generators were eliminated from the technologies list because of the particularly low technological maturity score. The remaining technology categories were then consolidated into three categories for additional study.












**Figure ES1. Out of 80 drivetrain technologies identified, NREL researchers reduced the list to 13 using three key metrics**








## Key Findings and Recommendations

Figure ES2 shows the three main drivetrain technology categories selected (generators, speed increasers, and electrical systems) and the authors' overall qualitative scores in each key metric. The red and orange colors indicate a stronger rationale for focusing investments in the designated technology area. The first metric, *Potential Reduction for Levelized Cost of Energy (LCOE)*, describes the relative potential impact of a drivetrain technology to reduce the LCOE through performance and reliability improvements or capital cost reductions. The second metric, *Manufacturing Disruption*, is an indication of the amount of change in the drivetrain manufacturing and supply chain that would be caused by implementing the advanced technology. The third metric, *Existing U.S. Manufacturing Activity and Research and Development (R&D)*, represents the existing U.S. manufacturing and R&D activity and supply chain capabilities for the technology. An example of this third metric can be illustrated by examining the scores for the technologies considered in Figure ES2. The authors found no

companies performing serial manufacturing of permanent-magnet (PM) or medium-voltage (MV) wind turbine generators in the United States (although several companies have the capabilities for this manufacturing), and limited PM generator R&D resulting in an assessment of little or no manufacturing or R&D activity (red). In contrast, domestic manufacturers reported that they have substantially more manufacturing capacity for large wind turbine gearboxes [up to roughly 9 gigawatts (GW) per year capacity for new wind turbine gearboxes], thereby indicating moderate manufacturing and R&D activity (yellow). The extent of manufacturing activity for full SiC switches was also deemed moderate because of the R&D activities conducted by other industries, such as transportation and defense.

	Metric 1	Metric 2	Metric 3	
	Potential Reduction for LCOE	Manufacturing Disruption	Existing U.S. Manufacturing Activity and R&D	Recommended Priority for Drivetrain Investments
<b>Generator: MV &amp; PM Technologies</b>				First Priority
<b>Speed Increaser: High Torque Technologies</b>				Second Priority
<b>Electrical Systems: Full SiC MV Switches</b>				Second Priority

Legend			
	High Potential	High Disruption	Little or No Manf. Activity and R&D
	Medium Potential	Medium Disruption	Low Manf. Activity and R&D
	Low Potential	Low Disruption	Moderate Manf. Activity and R&D
	No Potential	No Disruption	High Manf. Activity and R&D

**Figure ES2. A matrix of qualitative scores summarizes the study results and helps prioritize investments in the three drivetrain technology areas evaluated**

Overall, the authors identified the medium-voltage and permanent-magnet generators drivetrain category as the highest priority for possible investments. This category is perceived to have moderate potential for LCOE reductions, and will disrupt current manufacturing activities by requiring new technologies, process capabilities, and manufacturing facilities. In addition, there is little or no manufacturing and R&D activity in the country for this category compared to the other technology categories.

According to the study results, high-torque speed increaser technologies (such as the use of journal bearings or flex pins in the planetary stages of gearboxes) is also a promising technology area because it has moderate potential for reducing the cost of energy. However, manufacturing

disruption is expected to be small and the existing U.S research and development activity is larger than for medium- and low-speed permanent-magnet generators. As a result, additional investments in high-torque gearbox manufacturing are expected to affect the gearbox supply chain less than investments in medium-voltage and permanent-magnet generator technologies.

Full SiC switch technology, which uses both a SiC switch and SiC diode, is also a promising area for investment although presently expensive to manufacture. The survey of subject matter experts indicated that full SiC switches have the highest potential for LCOE reduction. A leading factor that contributes to the technology being a lower priority recommendation than medium-voltage and PM generators is that several other industries (especially transportation and defense) are already funding R&D in this area. The authors expect that further investments will have a smaller marginal benefit than the other technology areas because of diminishing returns on additional investments.

Table ES1 contains specific recommendations that will foster supply chain development and LCOE reductions in the three advanced drivetrain technology areas explored. In addition to these recommendations, NREL identified a list of key findings from the project that merit emphasis. These findings include the following:

- A stable U.S. market for wind energy is necessary for drivetrain manufacturing and supply chain growth, but it may not be sufficient alone for this growth. Additional investments may be required to compete with the extensive investments in wind turbine drivetrain manufacturing capabilities in regions such as Europe and Asia made over the last decade.
- The U.S. wind energy supply chain and manufacturing capabilities are central to the health of the U.S. wind turbine innovation ecosystem.
- Generally, drivetrain supply chain investments that incentivize smaller, risk-tolerant companies to collaborate with large, risk-adverse companies in technology development and commercialization offer one of the most promising paths to facilitating innovation and strengthening U.S. manufacturing capabilities and supply chains.
- Supply chain and manufacturing status, projections, and interrelationships are dynamic and complex, thereby making generalizations difficult. Therefore, continued study, monitoring, and stakeholder input are recommended to best inform investment decisions over time.



**Table ES1. Summary of Recommendations for Possible Investments in Advanced Wind Turbine Drivetrain Manufacturing and Supply Chains**

Technology	Recommendations
<b>Generators: Medium Voltage and Permanent Magnet</b>	<ol style="list-style-type: none"> <li>1. Fund advanced manufacturing process R&amp;D and equipment investments for medium-speed and direct-drive permanent-magnet generator technologies, such as automated, high-density coil-winding processes and automated magnet magnetizing and placement</li> <li>2. Continue to facilitate commercialization paths for generator innovations via competitive technology solicitations that target collaborations between universities, small companies, and global original equipment manufacturers (OEMs) and target OEM installation of advanced generator technologies in new wind turbines</li> <li>3. Strengthen the generator industrial commons (the R&amp;D, engineering, and manufacturing capabilities needed to turn inventions into commercial products) by: <ul style="list-style-type: none"> <li>• Supporting the development of an institute for manufacturing innovation that focuses on permanent-magnet motors and generators</li> <li>• Issuing drivetrain technology development solicitations</li> <li>• Supporting wind-related magnet R&amp;D at universities and encouraging the development of generator design and analysis professionals through wind turbine manufacturing fellowships</li> <li>• Performing and publishing more detailed U.S. wind turbine drivetrain competitiveness analysis.</li> </ul> </li> </ol>
<b>Speed Increaseers: High Torque</b>	<ol style="list-style-type: none"> <li>1. Continue to facilitate commercialization paths for gearbox innovations via competitive technology solicitations that target collaborations between universities, small U.S. gearbox technology companies, global OEMs, and gearbox refurbishers</li> <li>2. Strengthen the U.S. gearbox industry commons and innovation ecosystem by: <ul style="list-style-type: none"> <li>• Issuing additional advanced drivetrain solicitations that target high-risk innovation</li> <li>• Funding activities like the Gearbox Reliability Collaborative at higher power ratings</li> <li>• Supporting university programs that develop gearbox design and analysis professionals</li> <li>• Encouraging information exchange at events (e.g., a recurring drivetrain technology workshop)</li> </ul> </li> <li>3. Consider policies that increase or stabilize demand for gearboxes manufactured in the United States, such as requiring a minimum amount of domestic content for U.S.-installed wind turbines.</li> </ol>
<b>Electrical Systems: Full SiC Medium-Voltage Switches</b>	<ol style="list-style-type: none"> <li>1. Facilitate commercialization paths for SiC technology innovations by incentivizing the demonstration of hybrid SiC power electronics in a wind turbine and funding collaborations between small U.S. SiC companies and global OEMs</li> <li>2. Monitor full SiC and high-temperature SiC technologies to leverage opportunities and collaborate with other industries</li> <li>3. Provide funding to explore and document the power electronics supply chain in more detail, engage laboratory expertise in wind turbine power converter technologies, or develop the expertise, if necessary.</li> </ol>

## Recommended Future Work

To the authors' knowledge, this report is the first public study of its kind to assess the impact of advanced wind turbine drivetrain technologies on U.S. manufacturing and supply chains.

Recommended work to be considered for the future that was not undertaken during the initial study includes:

- Providing a more in-depth assessment of manufacturing and supply chain issues for power electronics
- Formally vetting the results of the initial study with industry stakeholders
- Developing a strategic plan or vision for wind turbine manufacturing and supply chain activities in the United States.

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# 1 Project Objectives

The development of advanced drivetrain technologies for wind turbine applications—such as medium-speed and direct-drive generators, silicon-carbide (SiC) insulated gate bipolar transistor (IGBT)-based power electronics, and high torque-density speed increasers—is advancing the state of the art for drivetrain design by producing higher capacity and operating reliability than conventional drivetrains. These drivetrain technologies require different manufacturing and supply chain requirements and processes—which present both risks and opportunities for U.S. wind turbine manufacturers and supply chains.

The primary objective of this project was to assess how advanced drivetrain technologies and trends will impact the U.S. wind turbine manufacturing industry and its supply chains. This information can be used to identify domestic manufacturing gaps, barriers, and opportunities for developing U.S. wind manufacturing capabilities and supply chains for next-generation drivetrain technologies. This report includes recommendations to help prioritize technology areas for possible investments by public, private, or nonprofit entities.

## 2 The Importance of U.S. Wind Turbine Manufacturing and Supply Chains

A supply chain can be defined as the network created amongst different companies for producing, handling, and distributing a specific product. A robust supply chain is at the heart of a successful manufacturing industry, and is an important part of reducing the cost of electricity generated from wind turbines, inventing and commercializing new wind turbine technologies, and providing high-quality jobs.

Supply chains also affect technological innovation. As of June 2011, manufacturing companies are responsible for about 70% of industrial research and development (R&D) in the United States and employ 63% of domestic scientists and engineers [1]. Therefore, a decrease in domestic manufacturing could have a direct effect on the innovative capacity of the nation. Locating supply chains and manufacturing facilities near design centers encourages essential communication between production and design. This communication facilitates innovation by enabling the person-to-person contact that is required to transfer the often tacit knowledge underlying emerging technologies [2].

# 3 Identification and Selection of Drivetrain Technologies for Assessment

## 3.1 Identification and Evaluation of Advanced Drivetrain Technologies

A wide variety of advanced drivetrain technologies exists at a range of technology readiness levels. For this report, the National Renewable Energy Laboratory (NREL) drew upon previous experiences with the U.S. Department of Energy (DOE) and industry-funded drivetrain projects to compile a list of technologies for consideration and evaluation. The majority of ideas on the list stemmed from a brainstorming session of six NREL staff members. To improve the comprehensiveness of the list, the authors also reviewed literature, such as DOE’s *Advanced Wind Turbine Drivetrain Concepts Workshop Report* [3].

The compiled list contained approximately 80 different advanced drivetrain technologies and the factors (or drivers) that motivate the development of these technologies. The importance of each driver (see Table 1) was determined using a ranking system that is described in Section 3.3.

**Table 1. Two Categories of Advanced Drivetrain Technology Drivers: Primary and Additional**

<b>Primary Drivers</b>	<ul style="list-style-type: none"><li>•Reliability</li><li>•Torque density [kiloNewton meters (kNm)/kilograms (kg)]</li><li>•Material availability</li></ul>
<b>Additional Drivers</b>	<ul style="list-style-type: none"><li>•Power rating</li><li>•Reparability</li><li>•Capital cost</li><li>•Loads reduction</li><li>•Efficiency/performance</li><li>•Transportation and installation/removal costs</li><li>•Intellectual property issues</li><li>•Wind market size for power electronics</li></ul>

The authors organized the numerous drivetrain technologies by creating a drivetrain technology taxonomy with four categories: speed increasers, generators, electrical systems, and other technologies. The taxonomy list of advanced drivetrain technologies for each of the categories is shown in Table 2.

**Table 2. Advanced Drivetrain Taxonomy**

Speed Increaser Technologies	Generator Technologies
<ul style="list-style-type: none"> <li>• <b>Gearboxes</b> <ul style="list-style-type: none"> <li>• Multiple output gearboxes (i.e., multi-duored)</li> <li>• Single- or double-stage gearboxes</li> <li>• Four-stage gearboxes</li> <li>• Lubrication improvements</li> <li>• Torque density improvements                             <ul style="list-style-type: none"> <li>• Journal bearings</li> <li>• Flex pins</li> <li>• Multiple planets</li> <li>• New steels</li> <li>• Coatings and finishes</li> </ul> </li> <li>• Integrated drivetrains (i.e., V90)</li> <li>• Spindle or torque tube configurations (i.e., Alstom)</li> </ul> </li> <li>• <b>Alternative teeth geometries</b></li> <li>• <b>Hydraulic drives</b></li> <li>• <b>Chain drives</b></li> <li>• <b>Continuously variable transmissions</b> <ul style="list-style-type: none"> <li>• Toroidal</li> <li>• Belts</li> <li>• Chains</li> <li>• Friction</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• <b>Medium voltage</b> <ul style="list-style-type: none"> <li>• Insulation materials</li> <li>• Dielectrics                             <ul style="list-style-type: none"> <li>• Nano-technologies</li> <li>• New materials (chemistries)</li> </ul> </li> </ul> </li> <li>• <b>Alternative generator architectures</b> <ul style="list-style-type: none"> <li>• Axial flux generators</li> <li>• Air core generators</li> <li>• Ring generators</li> <li>• Sectional generators</li> <li>• Permanent-magnet technologies                             <ul style="list-style-type: none"> <li>• New materials (nano, dysprosium replacement)</li> <li>• New processes</li> <li>• Nonhomogeneous magnets</li> </ul> </li> <li>• Laminations                             <ul style="list-style-type: none"> <li>• Conventional laminations</li> <li>• Powder core</li> <li>• High-flux density and low core losses</li> </ul> </li> <li>• Transverse flux generators</li> <li>• Reluctance generators</li> <li>• Superconducting generators</li> <li>• Magnetic gearbox</li> <li>• Vernier generator</li> <li>• Variable pole generator (stamping generator)</li> <li>• Homo-polar generator</li> <li>• Variable-speed synchronous generator</li> </ul> </li> </ul>



**Table 2. (Continued)**

Electrical Systems	Other Technologies
<ul style="list-style-type: none"> <li>• <b>Power electronics</b> <ul style="list-style-type: none"> <li>• Medium voltage (&gt;1,000 volts)</li> <li>• Full power conversion</li> <li>• Silicon carbide (SiC) switches <ul style="list-style-type: none"> <li>• Silicon (Si)-SiC hybrid</li> <li>• Full SiC</li> <li>• Full SiC high temperature</li> </ul> </li> <li>• Power factor correction system</li> <li>• Grid tie-in</li> <li>• Converter architecture <ul style="list-style-type: none"> <li>• Matrix converters</li> <li>• Multilevel converters</li> <li>• Resonant converters</li> </ul> </li> </ul> </li> <li>• <b>Transformer</b> <ul style="list-style-type: none"> <li>• Location uptower</li> <li>• High-frequency transformers</li> <li>• Superconducting transformers</li> </ul> </li> <li>• <b>Collection system</b> <ul style="list-style-type: none"> <li>• DC coupling of turbines</li> <li>• AC 60 Hertz (Hz)</li> <li>• AC variable frequency</li> </ul> </li> <li>• <b>Flexible AC transmission system (FACTS)</b> <ul style="list-style-type: none"> <li>• Static VAR compensations</li> <li>• Statcom</li> <li>• Series compensations</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Alternative load path configurations</li> <li>• Load control <ul style="list-style-type: none"> <li>• Mechanical load control</li> <li>• Advanced load control</li> <li>• Passive load control</li> <li>• Active torque control using power electronics</li> </ul> </li> <li>• Condition monitoring</li> <li>• Self-erecting tower and nacelle technologies</li> <li>• Storage (short term and long term)</li> </ul>

### 3.2 Metrics for Analyzing the Drivetrain Technologies

The number of advanced drivetrain technologies identified required down-selection to achieve a manageable scope. The authors used a spreadsheet-based ranking system to aid in the selection of technologies that would most affect the supply chain. Technologies that received low scores overall were eliminated from further consideration. The metrics used to evaluate the advanced drivetrain technologies are as follows.

### ***Potential Reduction for Levelized Cost of Energy***

This first metric describes the potential impact of an individual drivetrain technology (relative to the other technologies listed) to reduce the overall levelized cost of energy (LCOE).

Technologies with a low potential impact received low scores.

### ***Technology Maturity***

Technologies that are less mature (a longer time period until commercialization) generally entail more risk. The expected value of the rate of return for investments in such technologies and the likelihood of commercialization are less. As a result, less mature technologies received a lower score for this metric.

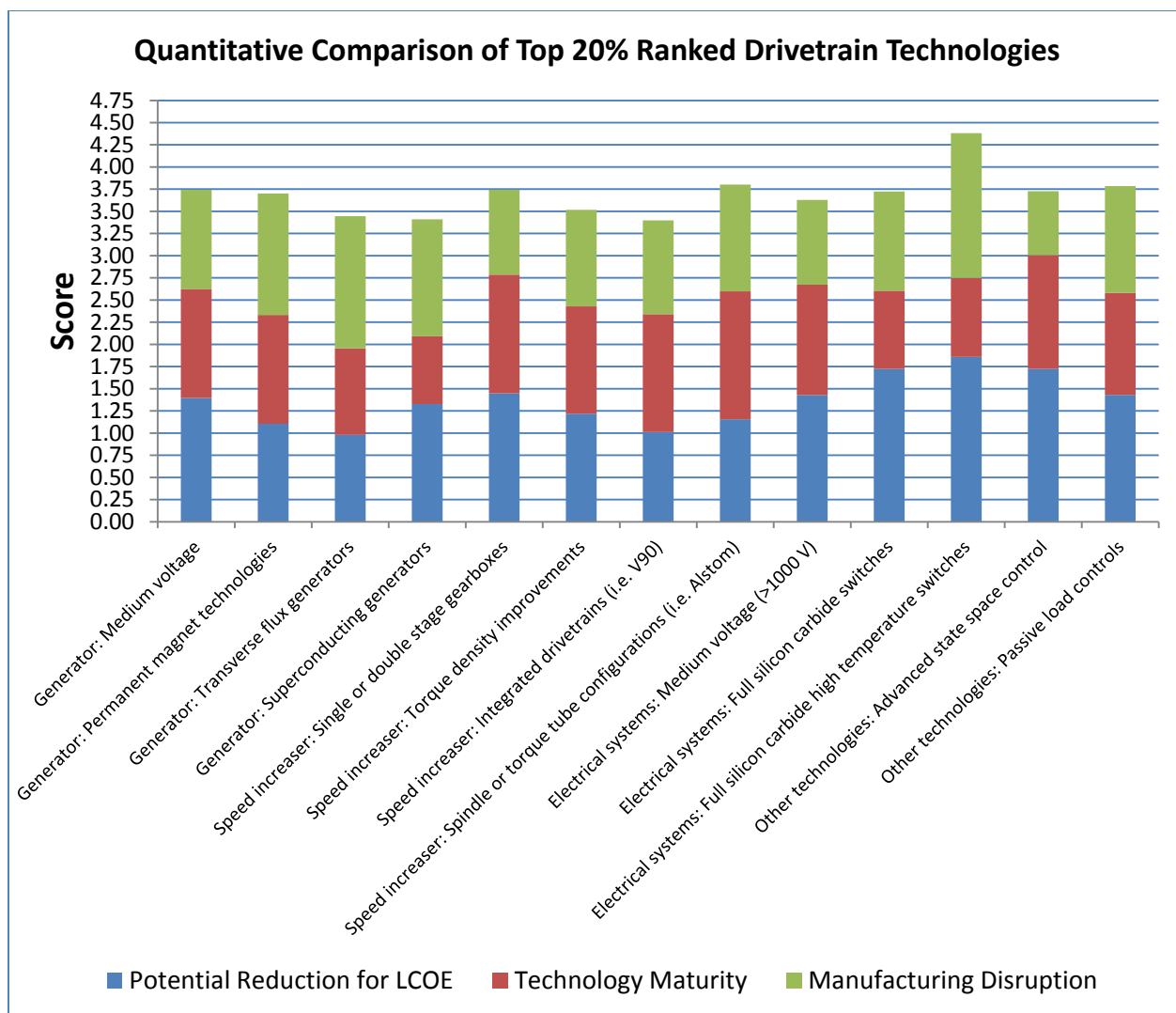
### ***Manufacturing Disruption***

The third metric is a measure of the amount of change in manufacturing machinery, infrastructure, or supply chain if commercialized. Technologies that have more potential to disrupt domestic manufacturing activities received higher scores.

## **3.3 Selection Method for Advanced Drivetrain Technologies**

### ***3.3.1 First Iteration of Technology Down-Selection***

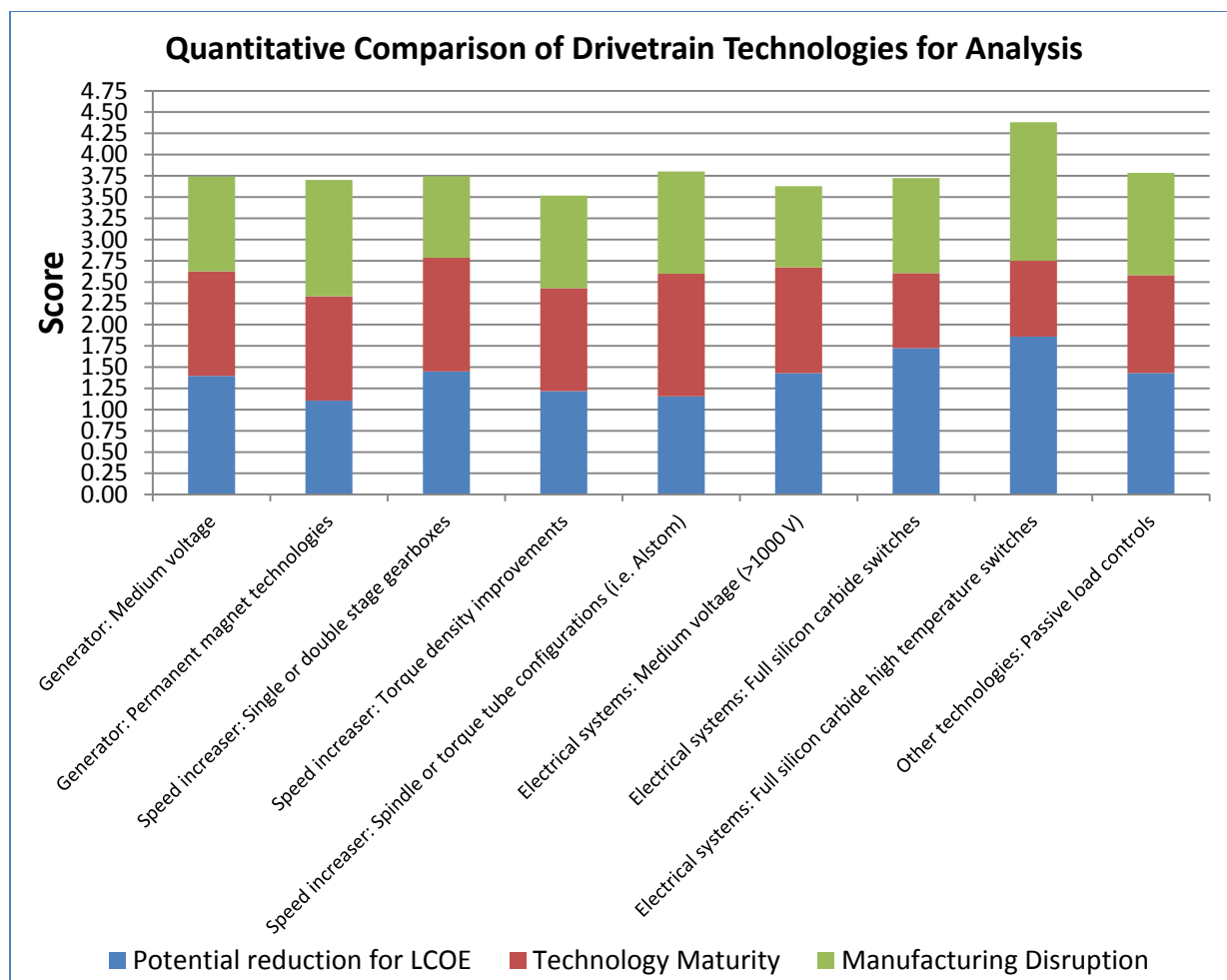
The authors developed a numerical ranking system by assigning a numeric value to each of three metrics applied to the drivetrain technologies and then selecting the highest scored drivetrain technologies for further assessment. Roughly 20% of the highest scoring drivetrain technologies were selected to move forward with the analysis. The selected technologies and their scores are listed in Figure 1.



**Figure 1. Highest scoring drivetrain technologies resulting from the first iteration of quantitative ranking**

### 3.3.2 Second Iteration of Technology Down-Selection

After the first iteration of technology down-selection, the number of technologies for consideration was still too large for the project scope; therefore, researchers implemented a second process for down-selecting the technologies. This process involved a more detailed investigation of each of the technologies shown in Figure 1 and was completed by evaluating the individual scores for each metric. If the score for any of the three metrics was a relatively low value, the technology was not considered for further analysis. One exception to this method was full SiC high-temperature switches, in which a low rating of technology maturity was not eliminated because it had the highest cumulative score relative to the other technologies. The technologies remaining after this second process of elimination are listed in Figure 2.



**Figure 2. Highest scoring drivetrain technologies resulting from the second iteration of quantitative ranking**

The selected technologies in Figure 2 were further condensed into four categories: permanent-magnet medium-voltage generators, medium-speed gearboxes, SiC power electronics, and rotor-stretching technologies. Table 3 lists the final general categorization of the technologies.

**Table 3. General Categorization of the Selected Nine Drivetrain Technologies for Analysis**

<b>SiC Medium-Voltage Power Electronics</b> <ul style="list-style-type: none"> <li>•Electrical systems: Full SiC switches</li> <li>•Electrical systems: Full SiC high-temperature switches</li> </ul>
<b>Rotor-Stretching Technologies</b> <ul style="list-style-type: none"> <li>•Speed increaser: Spindle or torque tube configurations</li> <li>•Other technologies: Passive load controls</li> </ul>
<b>Medium-Speed Gearboxes</b> <ul style="list-style-type: none"> <li>•Speed increaser: Single- or double-stage gearboxes</li> <li>•Speed increaser: Torque density improvements</li> </ul>
<b>Permanent-Magnet Medium-Voltage Generators</b> <ul style="list-style-type: none"> <li>•Generator: Medium voltage</li> <li>•Generator: Permanent-magnet technologies</li> <li>•Electrical systems: Medium voltage (&gt;1,000 volts)</li> </ul>

## 4 Analysis of the Four General Drivetrain Categories

### 4.1 SiC and Medium-Voltage Power Electronics Analysis

Wind turbine power electronic switches can be categorized into three different categories—conventional, hybrid, and full SiC power electronics—depending on the composition of the switch and the junction diode. Conventional insulated-gate bipolar transistor (IGBT)-based power electronic switches use silicon (Si) switch and junction diodes, and are used in wind turbine electrical systems today.

Hybrid IGBT switches use a Si switch and SiC diode (Si-SiC), in which the advanced SiC junction barrier schottky (JBS) diode takes the place of the silicon-based planar positive doped and negative doped (p-n) junction diodes. Hybrid SiC, a type of wide-band gap power electronics, is available today in production ranges of tens to hundreds for engineering applications in research and development.

A third category of power electronics—referred to as full SiC power switches—uses both a SiC switch and SiC diode. Full SiC power switches can be subdivided into low-temperature and high-temperature SiC. Low-temperature SiC is approximately 5 to 10 years away from commercialization and the time frame for high-temperature SiC commercialization is unknown.

Switching losses dominate the efficiency of the inverter. SiC technologies provide efficiency increases by substituting the SiC junction barrier schottky diodes in place of Si-based planar p-n junction diodes. The SiC diode is a majority carrier device and exhibits minimal or no reverse recovery charge. By eliminating the reverse recovery charge from the diode, two loss mechanisms are significantly reduced. First, the turn-off energy associated with the diode is essentially eliminated. Equally important, the reverse recovery current, which must be carried by the commutating IGBT, is also essentially eliminated. The substitution of the SiC diode for the silicon p-n diode reduces the total loss of the converter by roughly 50% [4]. The performance of the JBS diode offers an ideal low- and medium-voltage alternative to conventional silicon p-n diodes because of minimal reverse recovery charge, positive temperature coefficient of forward voltage drop, low reverse leakage at elevated temperature, and robust reliability [5].

In general, SiC switches have many potential benefits for the next-generation wind turbine electrical power systems, including enabling higher power electronic and generator voltages, improving efficiency, and reducing the mass of the filters (“the magnetics”) used to compensate for harmonics caused by slow switching frequencies. The result is a substantial increase in electrical power efficiencies because of the higher voltage and a reduction in electrical component mass and size (due to increased switching frequency).

NREL provided approximate estimates for the possible mass reduction and converter size reduction for each switch technology compared to the conventional Si switch technology shown in Table 4. The NREL subject matter experts ranked SiC switch technology advancements with very high scores, but high-temperature full SiC switches as having the highest overall score. In addition, NREL expects that the commercialization of this technology will substantially impact manufacturing and supply chains because of the new manufacturing processes and knowledge required to manufacture and package the switches.

**Table 4. Wind Turbine Power Electronics Switch Technology Characteristic Comparison for Conventional, Advanced Hybrid, and Full SiC Switch Technologies**

Switch Technology	Voltage (V)	Switching Frequency [kilohertz (kHz)]	Magnetics (Filters) Mass Reduction (%)	Converter Size Reduction (%)	Technology Readiness
Si	1,700	3	-	-	Conventional Technology
Si-SiC (hybrid)	6,000	3	53	-	Prototype
Full SiC Low-Temperature	10,000	20	87	33	5–10 years
Full SiC High-Temperature	10,000	20	87	67	Undetermined

#### **4.1.1 Specific Recommendations for SiC Switch and Medium-Voltage Power Electronics**

The recommendations for SiC switches and medium-voltage power electronics are:

- Facilitate commercialization paths for SiC technology innovations by incentivizing the demonstration of hybrid SiC power electronics in a wind turbine and funding collaborations between small U.S. SiC companies and global original equipment manufacturers (OEMs)
- Monitor full SiC and high-temperature SiC technologies to leverage opportunities and collaborations with other industries
- Provide funding to explore and document the power electronics supply chain in more detail and engage laboratory expertise in wind turbine power converter technologies or develop the expertise, if necessary.

Full SiC switch technology has many benefits for power electronics for wind power generation. However, this technology is at a low technology readiness level. Incentivizing collaborations between smaller U.S. SiC switch companies and global OEMs with competitive technology development and demonstration solicitations will help establish commercialization paths between smaller, more risk-tolerant companies, and larger companies.

The use of SiC switch technology will benefit a variety of industries. For example, the automotive industry is interested in using this technology in electric vehicles for similar reasons that benefit wind turbines (e.g., power quality and small size), and because it could eliminate a separate coolant loop for the power electronics in hybrid vehicles. The wind industry may be able to take advantage of this broader interest. In addition, DOE's recently announced financial opportunity for an Innovation Institute on Wide Bandgap Semiconductors could provide avenues for collaboration. The authors recommend monitoring these opportunities, especially for full SiC low- and high-temperature technologies. Furthermore, the power electronic manufacturing and supply chain should be explored more fully beyond the cursory survey performed in this study.

## 4.2 Rotor-Stretching Technologies Analysis

Rotor-stretching technologies, such as advanced controls and passive load reduction techniques (e.g., flap-twist coupled blades), are not specific elements of the drivetrain. However, these technologies do affect the drivetrain by decreasing the amount of nontorque loads that are transferred to the drivetrain. As a result, larger rotors can be used on the wind turbine that impart larger torque loads to the drivetrain. Because these loads are important design parameters for drivetrains, the NREL subject matter experts scored rotor-stretching technologies as having a significant indirect impact on wind turbine drivetrains. Accordingly, these technologies were considered for comprehensiveness and consistency. However, the authors believe that rotor-stretching technologies will have little direct impact on the drivetrain supply chain. For this reason, the authors recommend focusing drivetrain supply chain investments on drivetrain component technologies to increase the torque density of the wind turbine drivetrain rather than on the rotor-stretching technologies.

## 4.3 Advanced Drivetrain Medium-Speed Gearbox Analysis

### 4.3.1 *Medium-Speed Gearbox Technology Drivers*

Although emerging direct-drive technologies, such as permanent-magnet and superconducting machines, may have the potential to reduce LCOE, the geared, medium-speed drivetrain solution avoids some of the risks associated with newer direct-drive technologies. An overview of the medium-speed technology drivers that motivate the use of medium-speed gearboxes are listed in Table 5.



**Table 5. Overview of Medium-Speed Gearbox Technology Drivers**

Medium-Speed Gearbox Technology Drivers	Driver Explanation
Torque Density	A medium-speed drivetrain configuration is projected to have a 22% increase in torque density compared to a 5-megawatt (MW) high-speed gearbox configuration [4].
Reliability	Gearboxes are a primary cause of wind turbine downtime and operation and maintenance expenses. Medium-speed gearboxes have fewer components than high-speed gearboxes, thereby leading to potential increases in reliability.
Material Availability	Medium-speed-gearbed drivetrains have a substantial reduction in rare earth elements compared to permanent-magnet direct-drive drivetrains.
Efficiency	A medium-speed gearbox typically has a 1%–2% greater efficiency than a high-speed gearbox.

#### ***4.3.2 Primary Technical Challenges and Medium-Speed Gearbox Technologies***

For medium-speed gearboxes (and large wind turbine gearboxes in general), there are three primary technical challenges: 1) reliability of bearings, 2) manufacturability of the large diameter ring and bull gears, and 3) ability to handle the higher torque loads generated by larger turbines. A summary of these challenges are shown in Table 6. To help mitigate these technology challenges, researchers are investigating advanced next-generation drivetrain technologies, such as gearbox flex pins, journal bearings, and premium steels.

**Table 6. Summary of Medium-Speed Gearbox Technology Challenges**

Medium-Speed Gearbox Technology Challenges	Challenge Description
Reliability	There are a high number of failures associated with gearbox bearings. Failures in the gearbox are generally not repairable uptower and require special equipment to complete the repair.
Manufacturability	Medium-speed gearboxes typically have a large diameter ring gear (inside diameter tooth form) or bull gear (outside diameter tooth form), and are difficult to manufacture. These components are on the order of 2 to 3 meters and require extremely tight machining
High Torque Density	As wind turbine power ratings continue to increase, gearbox torque requirements will continue to increase exponentially, as rotor tip speed is constrained. These large gear elements are heavy and difficult to manufacture.

#### **4.3.3 Capabilities and Status of the U.S. Gearbox Industry**

NREL performed an assessment of the capabilities and status of the U.S. gearbox industry using the results of a literature review and by conducting industry interviews. Table 7 lists wind turbine gearbox manufacturing companies in the United States and their capacity to manufacture new gearboxes. Table 9 provides information on the gearbox refurbishment companies.

##### **4.3.3.1 New Gearbox Industry**

According to the American Wind Energy Association, the United States installed 6.8 gigawatts (GW) of wind power in 2011 [6]. Assuming that 90% of wind turbines installed in the United States utilize a gearbox in the drivetrain, an approximate demand for new domestic wind turbine gearbox manufacturing is more than 6 GW per year. Accumulation of theoretical annual capacity for the U.S.-based gearbox manufacturers reflects a manufacturing and/or assembly capacity of 9.5 GW annually. These results indicate ample U.S. gearbox manufacturing or assembly capacity (tier 1 suppliers), with the ability to support the majority of new wind plants installed domestically. However, the price of new gearboxes has dropped over the past few years by nearly 40%. In addition, large gearbox manufacturers are building new capacity in Brazil in order to meet domestic content requirements. There also appears to be no remaining independent U.S. suppliers providing gears and other components to the gearbox manufacturers and assemblers (tier 2 suppliers). Tier 2 suppliers cited two reasons for exiting the wind industry: 1) wind turbine market uncertainty, and 2) loss of their primary domestic customers (e.g., Clipper Windpower).

**Table 7. Status and Capabilities of the U.S. New Wind Turbine Gearbox Manufacturing Industry**

Note: Gearbox manufacturers that have recently stopped producing new gearboxes for the wind industry are indicated by text that has been stricken through.

U.S.-Based New Gearbox Manufacturer	Tier Classification	U.S. Manufacturing Facility Location	Product Size (MW)	Annual Facility Capacity (MW/Year)
Winergy Drive Systems Corporation	Tier 1	Elgin, Illinois	Up to 6.5	600 MW in the United States [7]
ZF	Tier 1	Gainesville, Georgia	Up to 6.2 (2 U.S.)	2,000 MW in the United States [8] (12,000 MW worldwide)
Brevini	Tier 1	Muncie, Indiana	Up to 4.5 MW (depending on geometry)	4,500 MW in the United States [9]
Moventas	Tier 1	Portland, Oregon	Up to 2.0	Can assemble up to 2,400 MW in the United States [10]
<del>Clipper Windpower</del>	<del>OEM/Tier 1</del>	<del>Cedar Rapids, Iowa</del>	<del>Up to 2.5</del>	<del>1,000 MW (in 2006) [11]</del>
<del>GE Drivetrain Technologies (a division of GE Transportation)</del>	<del>Tier 1</del>	<del>Erie, Pennsylvania</del>	<del>Up to 2.5</del>	<del>Estimated 2,000 MW</del>
Brad Foote	Tier 2	Cicero, Illinois	Up to 5.8	2,000 MW

The authors expect domestic gearbox manufacturers/assemblers to have the highest probability of remaining engaged in the U.S. wind industry relative to manufacturers of other drivetrain components. Table 8 summarizes the rationale for this assessment.

**Table 8. U.S.-Based Tier 1 Gearbox Industry Assessment**

U.S. Tier 1 Gearbox Industry Assessment	U.S. Tier 1 Gearbox Industry Assessment Details
Ample Existing Manufacturing Capability	The U.S. tier 1 gearbox suppliers have a theoretic capability to supply gearboxes for 9.5 GW of installed wind power. This leaves 2.7 GW of potential additional capacity when considering the 6.8 GW of total installed wind power in 2011. Gearbox prices have dropped and new capacity is being constructed in countries such as Brazil to meet domestic content requirements.
Access to Europe’s Industry Commons	The U.S.-based wind turbine gearbox industry has access to the well-established industry commons in Europe that provide cost-effective gearbox manufacturing and shipping.
Access to Capital for Necessary Expansion	Most tier 1 gearbox suppliers are in a position for additional capital if manufacturing facility and tooling expansion is necessary.
Barriers to Exit	Many gearbox manufacturing companies have large stranded U.S. manufacturing assets or “trapped capacity.”
Domestic Logistical Advantages	A U.S.-based gearbox manufacturing facility mitigates the strict OEM gearbox shipping requirements (e.g., gearbox rotation while being shipped) and shipping costs (i.e., specialty storage containers on boat or rail).

#### **4.3.3.2 Refurbishment/Repair Gearbox Industry**

Another important market to consider in the wind industry is the gearbox refurbishment/repair market. The knowledge and experience contained in the gearbox refurbishment/repair industry is a sizeable component of the gearbox industry commons. Additionally, the industry players in this market have the potential to expand into tier 1 suppliers or assemblers, as well as contribute to gearbox innovations and reliability improvements.

Gearboxes have a history of being one of the most problematic drivetrain components and typically require repairs before the end of their design life. This repair time frame, often between 5–7 years of operation, creates a large and generally consistent refurbish/repair market for gearboxes. In fact, several gearbox tier 1 suppliers are capitalizing on this. The demand for gearbox refurbishment is relatively stable compared to new gearbox demand. A summary of the status and capabilities of the U.S. refurbishment/repair market is shown in Table 9.

**Table 9. Status and Capabilities of the U.S. Refurbishment/Repair Wind Turbine Gearbox Manufacturing Industry**

U.S.-Based Gearbox Refurbishment/Repair Company	Wind Industry Work Description	U.S. Gearbox Facility Location	Facility Capabilities and Capacity
Eickhoff	<ul style="list-style-type: none"> <li>Gearbox inspection, repair, rebuilds, and overhauls</li> </ul>	Pittsburgh, Pennsylvania	<ul style="list-style-type: none"> <li>Up to 2.5 MW gearboxes [12]</li> <li>Throughput capacity unknown</li> </ul>
Gearbox Express	<ul style="list-style-type: none"> <li>Remanufactured gearboxes and down-tower services</li> </ul>	Mukwonago, Wisconsin	<ul style="list-style-type: none"> <li>45,000 sq ft facility</li> <li>3.1 MW test stand</li> <li>Throughput capacity unknown [13]</li> </ul>
Moventas	<ul style="list-style-type: none"> <li>Overhaul and maintenance</li> </ul>	Portland, Oregon	<ul style="list-style-type: none"> <li>Assemble 100 to 150 gearboxes annually</li> <li>Turbines up to 2 MW [14]</li> </ul>
Winergy	<ul style="list-style-type: none"> <li>Workshop service, repairs, and upgrades</li> </ul>	Elgin, Illinois	-
Broadwind Energy Maintenance Service (EMS)	<ul style="list-style-type: none"> <li>Manufacture gearbox parts as needed for repairs/remanufacturing</li> </ul>	Abilene, Texas	<ul style="list-style-type: none"> <li>500 MW of annual throughput capacity</li> <li>3 MW full-load gearbox testing [15]</li> </ul>
Bosch Rexroth Hydraulics	<ul style="list-style-type: none"> <li>Gearbox repairs</li> </ul>	Lake Zurich, Illinois	<ul style="list-style-type: none"> <li>Repair capabilities of 100 gearboxes annually</li> <li>Repair up to 3 MW gearbox [16]</li> </ul>
ZF Services	<ul style="list-style-type: none"> <li>Remanufacturing and parts distribution</li> <li>Complete repair of gearbox and main shaft</li> <li>Engineering upgrades and uptower services</li> </ul>	Vernon Hills, Illinois	<ul style="list-style-type: none"> <li>2.5-MW load test bench</li> <li>200 annual gearbox repairs [17]</li> <li>30-ton crane capacity</li> </ul>
The Gear Works	<ul style="list-style-type: none"> <li>Repair work</li> </ul>	Seattle, Washington	<ul style="list-style-type: none"> <li>Repair up to 1.5-MW gearbox</li> <li>Currently repair 100 gearboxes/year</li> </ul>
David Brown [16]	<ul style="list-style-type: none"> <li>Gearbox service</li> </ul>	Kentucky [18]	-
NextEra Generation Repair Services (GRS) [19]	<ul style="list-style-type: none"> <li>Overhaul and repair</li> <li>Parts and supplies storage facility</li> </ul>	Story City, Iowa	-

#### **4.3.4 Specific Recommendations for Medium-Speed Gearbox Supply Chain**

NREL has developed the following specific recommendations to support a more robust U.S. advanced gearbox supply chain:

- Continue to facilitate commercialization paths for gearbox innovations via competitive technology solicitations that target collaborations between universities, small U.S. gearbox technology companies, global OEMs, and gearbox refurbishers.
- Strengthen the U.S. gearbox industry commons and innovation ecosystem by:
  - Supporting university programs that develop gearbox design and analysis professionals
  - Issuing additional advanced drivetrain solicitations
  - Funding activities like the Gearbox Reliability Collaborative at higher power ratings
  - Encouraging information exchange at events such as a recurring drivetrain technology workshop
- Consider policies that increase or stabilize demand for gearboxes manufactured in the United States, such as requiring a minimum amount of domestic content for U.S.-installed wind turbines.

#### **4.4 Advanced Drivetrain Permanent-Magnet Generator Analysis**

During this study, NREL researchers focused on two types of generator technologies: medium-speed permanent-magnet and direct-drive permanent-magnet.

##### **4.4.1 Wind Turbine Generator Technology Trends**

As the wind turbine sizes and ratings for offshore and land-based machines continue to grow, the torque and power requirements for wind turbine drivetrains increase. Medium-voltage systems are attractive because of the decrease in material and mass that are a result of reductions in electrical current. Medium-voltage generators use less copper in the windings for a given power. They need more insulation, but the increase in insulation thickness is less than the decrease in copper size. The result is a lower mass generator overall, which is especially important for direct-drive generators and, to a lesser degree, medium-speed generators. In addition, the higher-voltage ratings of the generator help facilitate nacelle-mounted power electronics and transformers because of associated mass reductions. In addition, smaller and lighter power cables can be run down the tower.

Although this report focuses on the benefits, manufacturing challenges, and supply chain opportunities for medium-speed and direct-drive generators, an important trend in land-based wind turbine generators is a return to the use of doubly-fed induction generators (DFIG). This renewed interest and use of DFIG machines will potentially delay the development and deployment of permanent-magnet generators for land-based and possibly offshore machines.

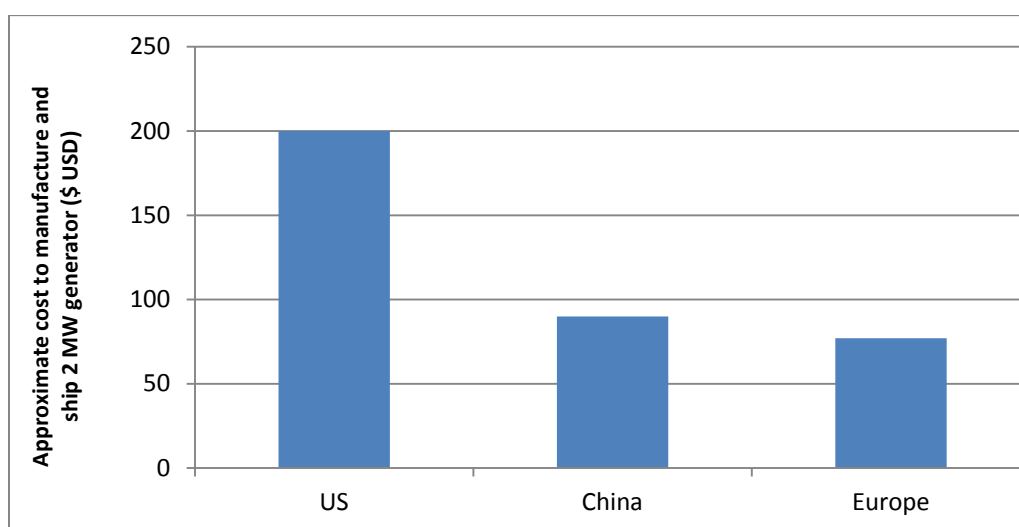
Evidence of this trend includes GE's announcement that it will be returning to DFIG generators for its latest generation of wind turbines. Additionally, the Spanish generator manufacturer Ingeteam invested \$21 million (including facility equipment) in a U.S. generator manufacturing facility equipped to primarily produce DFIG generators [20].

DFIG technology is less capital-intensive than permanent-magnet generator technology because it only requires a partial power converter with 20%–35% of rated capacity [21]. However, the DFIG technology for the GE 2.X series turbines was abandoned roughly 10 years ago, with the expectation that DFIG generators in the 1.5 MW series would not be able to meet future grid connection codes. Recently, substantial progress has been made with DFIG power electronics technologies that allow DFIGs to meet the latest grid codes. Additionally, GE cites the benefit that DFIGs enable a single generator model for both 50 hertz (Hz) and 60 Hz wind markets.

Another factor encouraging the return of DFIG technology is the price volatility of permanent-magnet materials. The price variability and supply assurance for the rare earth materials neodymium and dysprosium introduce cost uncertainties for permanent-magnet generators.

#### **4.4.2 Primary Wind Turbine Generator Manufacturing Challenges**

Generator manufacturing is inherently a high-volume, low-margin business that requires a large amount of capital to be competitive. For example, Europe, particularly Spain, was viewed as the manufacturing market leader of wind turbine generators. Their position is, in part, due to extensive generator manufacturing investments that were provided during the formative years of the wind industry market. These early investments offered “first mover” advantages in the generator market that led to the development of a supply chain that supports a global wind market. One data point collected from a wind turbine generator manufacturer indicates that DFIG generators can be produced and shipped from Europe to the United States at less than half the cost of manufacturing the generator domestically. However, the reasons for Europe’s apparent advantage are not completely clear.



**Figure 3. A comparison of the approximate cost to manufacture and ship a 2-MW generator within Texas and from China and Europe to Texas**

Another challenge for the U.S. generator supply chain described by industry is the nonrecurring engineering costs associated with generators. Typically, each wind turbine OEM has different drivetrain system requirements that make investments difficult, and are further exacerbated by the variability in demand for wind turbines and changing generator designs.

#### 4.4.3 Capabilities and Status of the U.S. Wind Turbine Generator Industry

NREL investigated the capabilities and status of the U.S. generator industry using available literature, generator manufacturing facility site visits to Ingeteam, Danotek, and Swiger Coil Systems, and interviews with four wind turbine OEMs and assemblers. Table 10 and Table 11 summarize the U.S. generator manufacturing companies and capabilities based on facility size.

**Table 10. Known Capabilities of Large, U.S.-Based, Utility-Scale Wind Turbine Generator Manufacturers**

U.S.-Based Large Generator Manufacturer	Tier Classification	Manufacturing Facility Location	Product Size (MW)	Facility Capabilities and Capacities
Ingeteam	Tier 1	Milwaukee, Wisconsin	Up to 8	3,000 generators per year MV and PM manufacturing capabilities
TECO Westinghouse	Tier 1	Round Rock, Texas	Up to 3	Currently not producing wind turbine generators, but has capability

Of the two large U.S.-based generator manufacturing facilities visited, only the tier 1 generator supplier, Ingeteam, reported manufacturing wind turbine generators. The other, TECO Westinghouse, reported having only the capability and capacity to manufacture wind turbine generators.



**Table 11. Known Capabilities and Status of Small and Midsized U.S.-Based Utility-Scale Wind Turbine Generator Manufacturers**

Note: Companies that are no longer producing generators for the wind industry are represented by text that has been stricken through.

U.S.-Based Small/ Midsized Generator Manufacturer	Tier Classification	Wind Industry Work Description	Manufacturing Facility Location	Product Size (MW)	Facility Capabilities and Capacity
<b>Northern Power Systems</b>	OEM/Tier 1	Developer of direct-drive permanent-magnet wind turbines	Barre, Vermont	2.3	-
<del><b>Danotek Motion Technologies</b></del>	Tier 1	Customer-specific generator designs	<del>Canton, Michigan</del>	<del>Power outputs up to 10.0</del>	<del>4,000 generators per year [22]</del>
<b>Boulder Wind Power</b>	Tier 1	Development of axial gap, air core, permanent-magnet direct-drive generators	Louisville, Colorado	3.0 (expected in 2013-2014 timeframe)	Unknown (in product testing phase)
<b>Swiger Coil Systems</b>	Tier 2	Generator coil repairs and complete wound generators for OEMs and tier 1 suppliers	Cleveland, Ohio	-	-










#### 4.4.4 Specific Recommendations for the U.S. Permanent-Magnet Generator Manufacturing and Supply Chain

To support the growth and success of the U.S. manufacturing and supply chain for the wind turbine generator industry, NREL researchers developed the following recommendations:








- Fund advanced manufacturing process R&D and equipment investments for medium-speed and direct-drive permanent-magnet generator technologies—especially targeting automated high-density coil-winding processes
- Continue to facilitate commercialization paths for generator innovations via competitive technology solicitations that target collaborations between universities, small companies, and global OEMs
- Strengthen the generator industry commons by:
  - Supporting the development of an institute for manufacturing innovation that focuses on permanent-magnet motors and generators
  - Issuing drivetrain technology development solicitations
  - Supporting wind-related magnet R&D at universities and encouraging generator design and analysis professionals using wind turbine manufacturing fellowships
  - Performing and publishing more detailed U.S. wind turbine drivetrain competitiveness analysis.

## 5 Investment Prioritization and Summary of Recommendations

This section provides recommendations for prioritizing technology areas for possible investments by public, private, or nonprofit entities that will reduce the levelized cost of wind-generated electricity, foster opportunities to invent and commercialize new wind turbine technologies, and provide high-quality jobs in the United States. Figure 4 shows a summary of the analyzed technologies, selection metrics, and prioritization of the study results. The red and orange colors indicate stronger rationale for focusing investments in the designated technology area that will achieve these objectives.

	Potential Reduction for LCOE	Manufacturing Disruption	Existing U.S. Manufacturing Activity and R&D	Recommended Priority for Drivetrain Investments
<b>Generator: MV &amp; PM Technologies</b>				First Priority
<b>Speed Increaser: High Torque Technologies</b>				Second Priority
<b>Electrical Systems: Full SiC MV Switches</b>				Second Priority

<b>Legend</b>			
	High Potential	High Disruption	Little or No Manf. Activity and R&D
	Medium Potential	Medium Disruption	Low Manf. Activity and R&D
	Low Potential	Low Disruption	Moderate Manf. Activity and R&D
	No Potential	No Disruption	High Manf. Activity and R&D

**Figure 4. The authors used a matrix of qualitative scores to summarize the results and help prioritize investments in the three drivetrain technology areas evaluated**

The authors identified medium-voltage and permanent-magnet generators as the highest priority drivetrain category for possible investments. In general, such investments are expected to enable relatively high reductions in LCOE, but they require new technologies, processes, and manufacturing facilities to produce, and there is relatively little U.S. manufacturing activity, capabilities, and R&D occurring in this area. Overall, public investments in this technology area are expected to have the most impact in positioning U.S. manufacturers for new manufacturing opportunities.

Full SiC switch technologies are also promising areas for investments. The survey of NREL subject matter experts indicated that full SiC switches have the highest potential for LCOE

reduction. A leading factor that contributes to the technology being a lower priority recommendation than medium-voltage and permanent-magnet generators is that several other industries (especially transportation and defense) are already funding R&D in this area. The authors expect that further investments will have less marginal benefit than the other technology areas because of the diminishing returns on additional investments.

High-torque speed increaser technologies (such as the use of journal bearings in the planetary stages of gearboxes) have good potential for reducing cost of energy. However, the manufacturing disruption is expected to be small and the relative amount of existing wind turbine gearbox manufacturing investments and activities in the United States is large compared to medium- and low-speed permanent-magnet generators. For these reasons, the marginal improvements and U.S. supply chain opportunities resulting from investments in high-torque gearbox manufacturing are expected to be smaller than for medium- and high-speed generators.

Table 12 contains specific recommendations that will foster supply chain development and LCOE reductions in the three advanced drivetrain technology areas explored. In addition to these recommendations, NREL researchers identified the following list of key findings from the project:

- A stable U.S. market for wind energy is necessary for domestic wind turbine drivetrain manufacturing and supply chain growth, but may not be sufficient alone for this growth. Additional investments may be required to compete with the extensive investments in wind turbine drivetrain manufacturing capabilities in regions such as Europe and Asia.
- Wind energy supply chain and manufacturing capabilities are central to the health of the U.S. wind turbine innovation ecosystem.
- Generally, DOE drivetrain supply chain investments that incentivize smaller, risk-tolerant companies to collaborate with large, risk-adverse companies in technology development and commercialization are one of the most promising paths to facilitating LCOE reductions and strengthening U.S. manufacturing capabilities and supply chains.
- Supply chain and manufacturing status, projections, and interrelationships are dynamic and complex, thereby making generalizations difficult. Continued study, monitoring, and stakeholder input is recommended to best inform investment decisions over time.

**Table 12. Summary of Recommendations for Possible Investments in Advanced Wind Turbine Drivetrain Manufacturing and Supply Chains**

Technology	Recommendations
<b>Generator: Medium Voltage and Permanent Magnet</b>	<ol style="list-style-type: none"> <li>1. Fund advanced manufacturing process R&amp;D and equipment investments for medium-speed and direct-drive permanent-magnet generator technologies—especially targeting automated high-density coil-winding processes</li> <li>2. Continue to facilitate commercialization paths for generator innovations via competitive technology solicitations that target collaborations between universities, small companies, and global OEMs and target OEM installation of advanced generator technologies in new wind turbines</li> <li>3. Strengthen the generator industry commons by: <ul style="list-style-type: none"> <li>• Supporting the development of an institute for manufacturing innovation that focuses on permanent-magnet motors and generators</li> <li>• Issuing drivetrain technology development solicitations</li> <li>• Supporting wind-related magnet R&amp;D at universities and encouraging the development of generator design and analysis professionals through wind turbine manufacturing fellowships</li> <li>• Performing and publishing more detailed U.S. wind turbine drivetrain competitiveness analysis</li> </ul> </li> </ol>
<b>Speed Increaser: High Torque</b>	<ol style="list-style-type: none"> <li>1. Continue to facilitate commercialization paths for gearbox innovations via competitive technology solicitations that target collaborations between universities, small U.S. gearbox technology companies, global OEMs, and gearbox refurbishers</li> <li>2. Strengthen the U.S. gearbox industry commons and innovation ecosystem by: <ul style="list-style-type: none"> <li>• Supporting university programs that develop gearbox design and analysis professionals</li> <li>• Issuing additional advanced drivetrain solicitations</li> <li>• Funding activities like the Gearbox Reliability Collaborative at higher power ratings</li> <li>• Encouraging information exchange at events, such as a recurring drivetrain technology workshop</li> </ul> </li> <li>3. Consider policies that increase or stabilize demand for gearboxes manufactured in the United States, such as requiring a minimum amount of domestic content for U.S.-installed wind turbines.</li> </ol>
<b>Electrical Systems: Full SiC MV Switches</b>	<ol style="list-style-type: none"> <li>1. Facilitate commercialization paths for SiC technology innovations by incentivizing the demonstration of hybrid SiC power electronics in a wind turbine and funding collaborations between small U.S. SiC companies and global OEMs</li> <li>2. Monitor full-SiC and high temperature SiC technologies for leveraged opportunities and collaborations with other industries</li> <li>3. Provide funding to explore and document the power electronics supply chain in more detail and engage laboratory expertise in wind turbine power converter technologies or develop the expertise if necessary.</li> </ol>

## 6 Future Work

To the authors' knowledge, this study is the first of its kind to assess the impact of advanced wind turbine drivetrain technologies on U.S. manufacturing and supply chains. Recommended work to be considered for the future that was not undertaken during the initial study includes the following.

### **Provide a More In-Depth Assessment of Manufacturing and Supply Chain Issues for Power Electronics**

Of the four advanced drivetrain categories analyzed—SiC power electronics, rotor-stretching technologies, medium-voltage permanent-magnet generators, and medium-speed gearboxes—SiC was explored the least. A better understanding of these supply chain issues for power electronics focusing on SiC is warranted. Assistance from generator and power electronics industry experts and consultants should also be considered.

### **Formally Vet Project Results with Industry Stakeholders**

The results of this project relied primarily on the experience, perspectives, and interpretations of industry information by the authors. A formal vetting process by stakeholders and industry experts will help ensure that the findings and recommendations are consistent across the wind industry.

### **Develop a Strategic Plan or Vision for Wind Turbine Manufacturing and Supply Chain Activities in the United States**

Supply chain and manufacturing status, projections, and interrelationships are dynamic and complex, thereby making generalizations difficult. Therefore, a long-term strategic plan will help provide the coordination and consistency necessary to address the gaps in the U.S. supply chain and position the country's wind industry to take advantage of manufacturing opportunities. Continued study, monitoring, and stakeholder input is recommended to best inform the strategic plan and investment decisions over time.

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