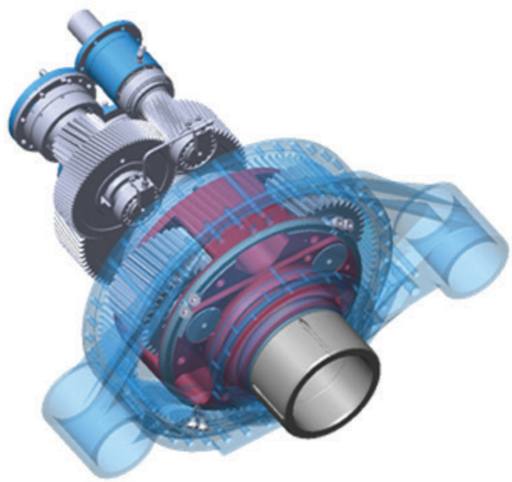
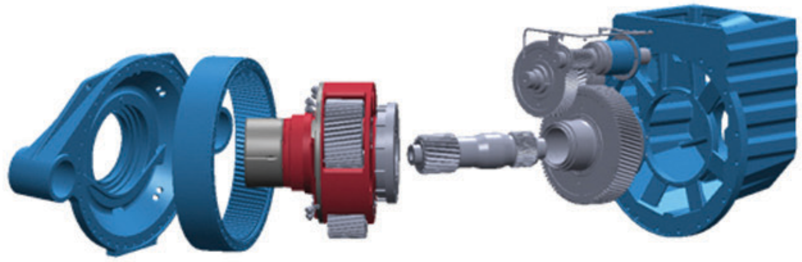
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

WIND AND WATER POWER PROGRAM

Advanced Wind Turbine Drivetrain Concepts: Workshop Report

June 29 – 30, 2010





Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Executive Summary

This report presents key findings from the Department of Energy's Advanced Drivetrain Workshop, held on June 29-30, 2010 in Broomfield, Colorado, to assess different advanced drivetrain technologies, their relative potential to improve the state-of-the-art in wind turbine drivetrains, and the scope of research and development needed for their commercialization in wind turbine applications.

The Advanced Drivetrain Workshop evaluated next-generation technologies to identify those with potential to radically improve the reliability, performance, and capital cost of wind turbine drivetrains beyond the incremental improvements that might be expected for current state-of-the-art technologies. The workshop featured four separate discussion tracks, each focused on a broad category of drivetrain technologies: Superconducting Drivetrains; Advanced Permanent Magnet Generators; Continuously Variable Transmissions and Fluid Drive Systems; and Innovative and Non-Traditional Drivetrain Concepts.

Workshop participants identified major research topics with the potential to improve on the state-of-the-art in wind turbine drivetrains for each of the four broad drivetrain technology categories. The participants also listed the major barriers to the commercialization of these technologies and potential research and development pathways for overcoming those barriers. Those results are summarized in Table 1 below.

Table 1. Benefits, Barriers, and Development Pathways for Advanced Drivetrain Technologies

	Topic	Benefits	Barriers	Pathways
Superconducting Drivetrains	Superconducting Direct Drive Generators	Capital costs; reliability; energy capture; supply chain security	Technical; perception; scaling; IP	Sub-component reliability testing; demonstration project deployment; engage independent third parties
	Next Generation Superconducting Technologies	Energy capture	Technical	Laboratory testing
Permanent Magnet Generators	Advanced Magnetic Materials	Capital costs; reliability; energy capture; safety and serviceability	Technical; commercial; perception; certification	Materials science research; tradeoff analysis; cost/benefit analysis; International Electrotechnical Commission (IEC) standards development
	System Design and Topology	Capital costs; reliability; energy capture; safety and serviceability	Technical; commercial; certification;	Laboratory research; cost/benefit analysis; IEC standards development
	Power Electronics	Capital costs; reliability; performance	Technical; perception; commercial;	Laboratory research; workforce education and training cost/benefit analysis;
	Diagnostics and Maintenance	Reliability;	Reliability; operator training; certification	Reliability research; workforce education and training; IEC standards development

	Topic	Benefits	Barriers	Pathways
Continuously Variable Transmissions	Frictional Contact Drives	Capital costs; reliability; energy capture	Technical; scalability; materials	Cost-benefit analysis; design and modeling tools; demonstration projects; component development and testing
	Fluid Drives	Capital costs; reliability; energy capture; energy storage	Technical; scalability; materials; perception	Cost-benefit analysis; design and modeling tools; component development and testing; demonstration projects
Innovative Concepts	Uptower Direct Current (DC) Generator	Reliability; grid benefits	Technical	Feasibility studies; equipment survey
	Ground-Level Generators	Reliability	Technical	Feasibility studies
	Rim-Drive Turbines	Reliability	Technical	Feasibility studies
	Tandem Generators	Availability; scalability	Commercial	Feasibility studies
	Complete Up-Tower Gearbox Reparability	Reliability	Technical	Feasibility studies
	Other Innovative Drivetrains	Capital costs; reliability	Technical; perception	Design studies

The technologies outlined above can be grouped into three broad categories based on their potential impact on the market for current and next-generation drivetrains. The first category includes concept-stage designs for next-generation wind turbines that offer potentially significant but still uncertain advantages over the state-of-the-art. The second category includes technologies that are currently being considered for incorporation into current wind turbine drivetrain designs. The third category includes technologies that have potentially transformative application in next-generation turbine designs with large nameplate capacities (5+ MW), particularly in offshore wind turbines. The unique challenges facing each category will require different research and development strategies in order to successfully commercialize these technologies.

Table of Contents

List of Tables

List of Figures

1.0 Introduction

This report presents key findings from the Advanced Drivetrain Workshop, which was organized by the U.S. Department of Energy (DOE) Wind and Water Power Program to discuss the next generation of wind turbine drivetrain technologies. The workshop, held on June 29-30, 2010 in Broomfield, Colorado, convened experts from industry, academia, the federal government, and national laboratories. The purpose of the workshop was to assess different advanced drivetrain technologies, their relative potential to improve the state-of-the-art in wind turbine drivetrains, and the scope of research and development needed for their commercialization in wind turbine applications. The Wind and Water Power Program sponsored the workshop as part of its larger efforts to reduce the cost of energy produced by wind turbines.

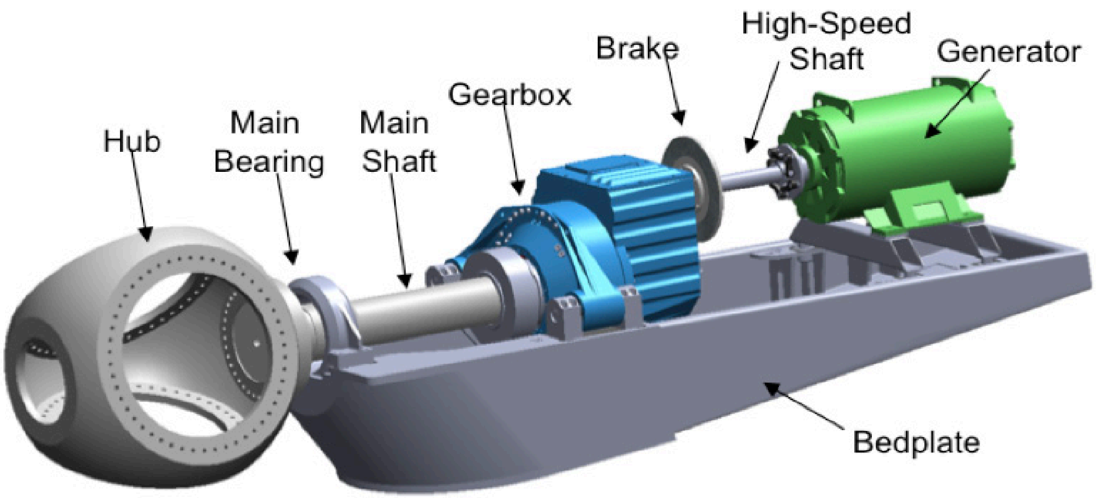


Figure 1. Conventional gearbox drivetrain configuration

The drivetrain of a wind turbine converts the low-speed, high-torque rotation of the turbine's rotor (blades and hub assembly) into electrical energy. The most common drivetrain configuration (Figure 1) consists of a low-speed shaft (also called a main shaft), a gearbox, a high-speed shaft, and a generator (Hau 2006). The low-speed shaft connects to the rotor hub and is supported by the main frame (or bedplate) through one or two main bearings. As a result, the low-speed shaft rotates at a rotational speed of roughly 12-30 revolutions per minute (rpm) for current utility-scale wind turbines. A gearbox connected to the low-speed shaft steps up the rotational speed to 1,200-1,800 rpm via a set of gears in two or three stages, typically consisting of planetary and parallel gear configurations (Hau 2006). A high-speed shaft then transmits mechanical power from the gearbox to a generator, which requires high rotational speeds (1,200-1,800 rpm) in order to economically generate electricity. Generators often use power electronics to allow variable speed operation and to condition the electrical power output of the turbine so that it can be integrated into the power grid easily and efficiently. Some wind turbine configurations forgo a gearbox and instead generate electricity by coupling the low-frequency rotation of the main shaft directly to the generator. Such "direct-drive" configurations typically require large diameter generators and extensive power electronics to allow variable speed operation and to condition the electrical output for the grid.

Drivetrains contribute to the total cost of energy produced by wind turbines in multiple ways. First, the drivetrain includes some of the most expensive components in a wind turbine, namely the gearbox and generator, which account for nearly one half of the turbine's total capital cost (Fingersh, Hand and Laxson 2006). Heavier drivetrains also require more substantial towers to support their weight, further driving up the turbine's overall capital equipment costs. Second, drivetrains represent a significant proportion of the total energy losses within a wind turbine, reducing electrical power output, and thus revenue, of an individual turbine. Finally, conventional drivetrains are not meeting their expected 20-year operating lifetimes primarily due to premature gearbox and bearings failures that necessitate turbine downtime as well as expensive and time-consuming repairs or replacements, often via the deployment of very large and expensive lifting cranes (Musial, Butterfield and McNiff 2007). In addition to the costs of replacement equipment, crane rental, and lost revenue, widespread gearbox failures can lead financiers to demand higher interest rates for project loans due to a higher perceived level of technology risk.

To help lower the cost of wind energy, the Wind and Water Power Program works to improve reliability, increase performance, and decrease capital costs for wind turbine drivetrains. The program funds the Gearbox Reliability Collaborative, a public-private partnership between national laboratories, universities, gearbox and component manufacturers, engineering consultants, and wind turbine manufacturers. The mission of the Gearbox Reliability Collaborative is to gather, analyze, and share data from operational and experimental gearboxes (Figure 2). The goal of this effort is to identify critical design parameters and root causes that are responsible for gearbox failures in the field. The program also funds the development of large dynamometers capable of testing next-generation wind turbine drivetrains – this functionality allows turbine manufacturers to validate and refine new designs before deploying them in the field. In some cases, the program has worked with specific companies to develop new wind turbine designs that incorporate advanced drivetrain technologies, such as multi-generator systems, gearbox component load mitigation, or permanent magnet replacements for wound electromagnets in the generator to reduce system size. Finally, the program funds laboratory research and development on a variety of topics with the potential to improve the reliability and performance of turbine drivetrains. Two key topics are advanced materials that improve the lubrication and wear resistance of drivetrains and drivetrain components, and the use of condition-based health monitoring to reduce equipment failures through predictive maintenance.

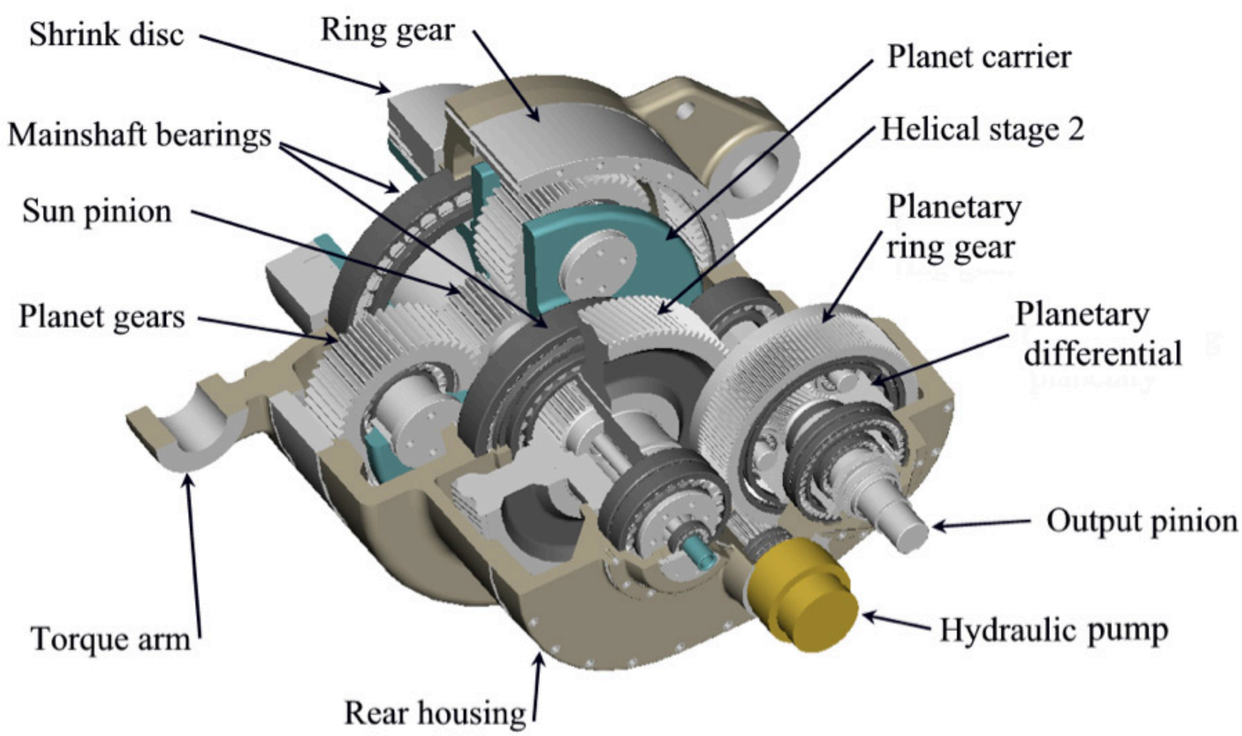


Figure 2. Cutaway of multi-stage gearbox

The Advanced Drivetrain Workshop evaluated next-generation technologies to identify those with potential to radically improve the reliability, performance, and capital cost of wind turbine drivetrains beyond the incremental improvements that might be expected for current state-of-the-art technologies. The workshop began with introductory remarks covering DOE's existing portfolio of drivetrain research and development projects, the current state of the art in drivetrain design configurations, and the purpose and structure of the meeting. The workshop participants then split into four groups to discuss separate technologies: Superconducting Drivetrains; Advanced Permanent Magnet Generators; Continuously Variable Transmissions and Fluid Drive Systems; and Innovative and Non-Traditional Drivetrain Concepts. Over a series of three sessions, the participants provided input on the current state of different advanced drivetrain technologies; described how these technologies could offer an improvement over the state-of-the-art; listed some of the current uses of these technologies and the barriers to commercialization in wind turbine applications; and outlined potential paths to commercialization of these technologies, including estimated development timelines and key areas of research and development. The Workshop concluded with a report-out session in which the four groups presented their key findings to the larger assembly.

2.0 Workshop Results

The following sections describe the major technologies discussed in each of the four technology breakout sections, their potential benefits over the state-of-the-art, and possible pathways for their commercialization.

2.1 Superconducting Drivetrains

This session discussed the potential application of superconducting materials (materials capable of conducting electricity with near-zero direct-current (DC) electrical resistance) in wind turbine generators. Superconducting materials only exhibit their superconducting properties at very low temperatures and are classified by the critical temperature at which they operate. Low temperature superconducting materials typically require temperatures below 20 Kelvin (-253 Celsius), while high temperature superconducting materials operate between approximately 30 and 40 K. Superconducting materials and cooling systems are currently used in many non-wind applications, including Magnetic Resonance Imaging machines, particle accelerators, electrical transmission, and prototype ship propulsion systems. Superconducting generators generally feature superconducting materials in the rotor (Figure 3) and a conventional (non-superconducting) stator, although alternate topologies exist (including homopolar designs, “inside-out” designs in which the rotor encloses the stator, and designs combining permanent magnets and superconducting materials). Future superconducting technologies may make it practical to also use superconducting material in the generator stator; however, with current technologies, the alternating current inherent in the stator results in time-varying magnetic fields that incur substantial losses.

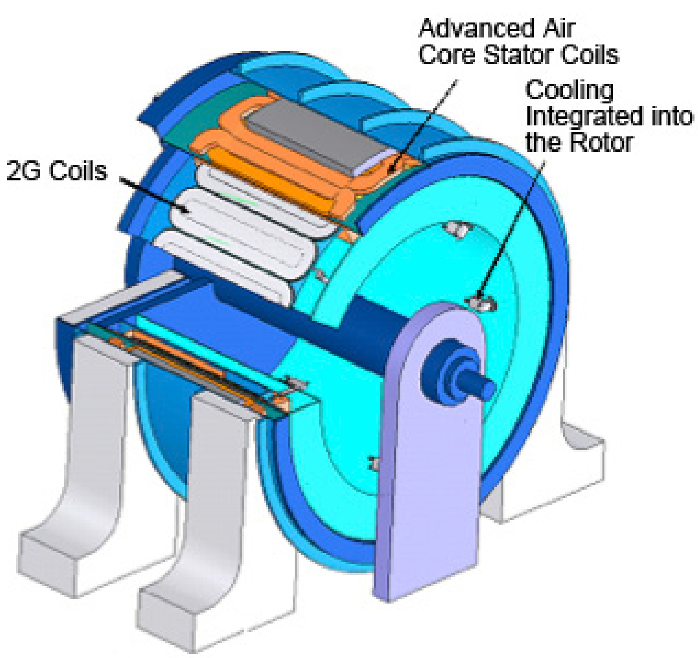


Figure 3. Superconductor coils in vacuum-insulated rotor

Superconducting generators have the potential to offer several cost and reliability improvements over conventional wind turbine drivetrains when scaled up to very high capacities (5 MW and larger) and when used in direct drive systems. Direct drive wind turbines do not require a gearbox, thereby eliminating a major source of reliability failures. Although superconducting generator technology can be used with a gearbox, this session focused on the application of superconducting generators in direct drive wind turbines due to perceived advantages in commercial and economic viability of such designs. Superconducting generators have less mass and require less volume than comparable permanent-magnet direct drive generators, particularly as wind turbine capacity ratings continue to increase (power output tends to scale with volume more quickly in superconducting generators than in conventional direct-drive generators). Lower generator mass and size reduces the capital cost of generator and reduces the loads on the tower, resulting in an overall reduction in turbine capital costs. Cost advantages produced by such weight savings are most likely to be realized initially in large turbines (roughly 5+ MW). In addition to weight savings, superconducting generators have the potential to increase drivetrain reliability by allowing a much larger air gap tolerance between rotor and stator as compared to permanent-magnet direct drive designs. Conventional direct-drive generators must maintain an air gap between rotor and stator of only a few millimeters, making contact between rotor and stator much more difficult to avoid, and ultimately leading to increased weight due to increased structural support requirements (Mueller and McDonald 2008). It can be difficult to manufacture and operate conventional direct-drive generators with such tight tolerances. Superconducting direct-drive generators, with air gaps on the order of several centimeters, can be more easily designed to avoid this mode of failure.

Superconducting direct-drive generators are especially suited for offshore wind applications, because there is an economic incentive to place as large of a turbine as possible on a single foundation to compensate for the high installation costs for offshore wind, and because these designs have the potential to offer greater reliability and require less maintenance than both geared and conventional direct-drive designs.

Table 2 below lists major areas of interest in superconducting direct-drive generator research and development and the potential benefits that these areas of interest offer over the state-of-the-art in wind turbine drivetrains.

Table 2. Benefits of Superconducting Direct Drive Generators

Area of Interest	Description	Benefits
Low-Temperature and High-Temperature Superconducting Direct Drive Generators	*Superconducting direct-drive generators eliminate electrical resistance in rotor coils by super-cooling them, allowing for extremely strong magnetic flux and high torque densities without the need for adding material (larger coils or permanent magnets). As a result, superconducting generators tend to be less massive and much smaller in size than conventional direct drive generators, especially at generating capacities of 5 MW and higher.*	▪ **Reduced Capital Costs**: potentially significant drivetrain mass advantage begins around 5 MW and scales rapidly with generating capacity. The lighter construction and reduced material usage can result in a lower drivetrain cost, decreased tower loading, and easier installation logistics. ▪ **Improved Reliability:** larger air gap between rotor and stator leads to reliability and design benefits compared to permanent-magnet direct-drive designs. This may lead to reductions in unscheduled maintenance. ▪ **Increased Energy Capture:** superconducting direct-drive designs promote scalability to taller and higher generating capacity turbines due to smaller and lighter nacelles. ▪ **Supply Chain Security:** Superconducting direct-drive generator designs use readily available materials to generate magnetic flux, thereby providing an alternative to the rare earth magnet materials, typically mined outside the U.S., used in other direct-drive designs.
Next Generation Superconducting Technologies	*Advances in superconducting technology that were discussed include: superconducting rotor AND stator, linear superconducting generators, and synchronous generators with air cores and copper stators.*	▪ **Increased Energy Capture:** advances in superconducting technology will increase the efficiency of superconducting direct-drive systems; increased efficiency may result in higher magnetic flux densities, lower parasitic losses (currently <~1%), or further design optimization.

The major barriers to incorporating superconducting generators in wind turbine designs are in large part commercial rather than technical in nature. The perception of superconducting generators as overly complex, undeveloped, and high-risk technology is expected to increase the cost of financing projects using this technology. Perceived safety concerns regarding the use of super-cooled nitrogen or hydrogen may also hinder the adoption of this technology, despite its widespread use in common commercial applications such as Magnetic Resonance Imaging (MRI). The lack of a scaling reference or an operating prototype turbine incorporating superconducting direct-drive technology render it difficult to compare the costs and performance of this technology with current drivetrain technologies, though initial testing has been performed on multi-megawatt-scale superconducting motors. In addition to these commercial risks, superconducting generators face potential technical risks related to reliability and durability of superconducting materials, such as wire performance and durability degradation resulting from mechanical and thermal cycling. A further concern is cooling system fatigue and degradation resulting from thermal cycling.

Due to the commercial barriers outlined above, a research and development program to commercialize superconducting generators in wind turbines might focus heavily on the demonstration of these technologies to establish their technical viability and cost and performance advantages. The demonstration of a large-scale prototype turbine with a superconducting generator, leveraging existing, appropriately-sized turbine components such as blades to speed deployment, at a pre-permitted land-based or offshore site could address many of the perception concerns. Existing DOE initiatives, such as the Large Blade and Large Drivetrain Testing Facilities and ongoing certification and standards development, could support the development of this prototype. Component and subcomponent reliability testing would be especially effective in addressing perceptions of high technology risk before a full scale prototype is tested in a turbine.

Table 3 below lists major barriers to the commercialization of superconducting direct-drive generator technology and potential research and development pathways for overcoming those challenges.

Table 3. Barriers to Commercializing Superconducting Direct Drive Generators

Area of Interest	Commercialization Barriers	Development Path
Low-Temperature and High-Temperature Superconducting Direct Drive Generators	➢ **Technical Risk**: cooling system reliability, fatigue caused by thermal cycling, and coolant containment are untested in a wind turbine environment.	▪ **Conduct sub-component reliability testing**: accelerated reliability testing could utilize shaker tables to test operating cryo-systems and coil windings under representative wind turbine conditions.
	➢ **Perception Risk**: misperceptions regarding the "newness" of superconducting direct-drive technology, system complexity, and safety uncertainty cause concerns about its implementation in wind turbine systems.	▪ **Conduct reliability testing and deploy demonstration projects:** accelerated reliability testing and deployment of operational demonstration superconducting direct-drive wind turbines would help alleviate misperceptions about this technology.
	➢ **Scaling Risk**: project economics and manufacturing requirements for 10-MW wind turbines have not been demonstrated. There are no 10-MW scale prototype test platforms	▪ **Deploy demonstration projects:** successfully deployed large wind turbines could establish their viability.
	➢ **IP Risk**: superconducting technology owners and developers may be hesitant to collaborate on turbine research, development, and testing.	▪ **Engage independent third parties:** federal or state governments, universities, certification bodies, or other independent organizations could assist in data aggregation and benchmark development.
	➢ **Certification Risk**: wind turbine standards have not been developed for direct-drive or superconducting technologies	▪ **Establish IEC standards for superconducting direct-drive:** support working groups to establish standards language.
Next Generation Superconducting Technologies	➢ **Technical Risk**: advanced superconducting technologies are still in the basic research phase.	▪ **Conduct laboratory testing**: continued research, development, and testing will advance the Technology Readiness Level of advanced superconducting technologies.

2.2 Permanent Magnet Generators

This session discussed advanced permanent-magnet generator topologies for wind turbine applications. These designs use permanent magnets composed of rare-earth mineral alloys in place of induction generators composed of wound electromagnets that require electricity to operate. This session discussed direct-drive designs (a class of drivetrain that does not require a gearbox to step up the rotational speed of the turbine rotor to the high rotational speeds desired for electricity generation) as well as the incorporation of permanent magnet generators (Figure 4) in conventional geared drivetrains. Permanent-magnet generators have been commercialized for wind turbine applications, both in geared and in direct-drive topologies, although opportunities for technology improvements still exist.

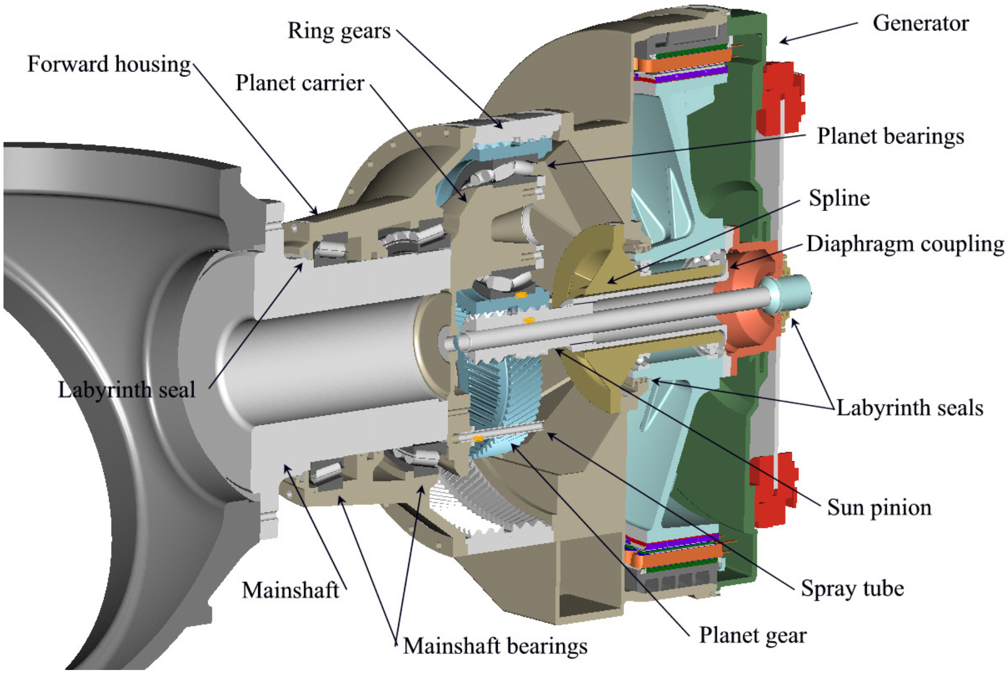


Figure 4. Cutaway view of single-stage permanent magnet drivetrain

Permanent-magnet generators have the potential to offer several cost and reliability benefits over conventional induction generators using wound electromagnets. First, permanent magnet generators have increased power densities over conventional induction generators using wound rotor or squirrel cage designs; permanent-magnet generators thus weigh less and require less space than comparable induction generators. Because permanent-magnet generators do not require electricity to induce a magnetic field in the rotor, they offer performance improvements (lower parasitic energy losses) over induction generators or wound field synchronous generators. In addition, permanent-magnet generators do not require generator brushes and rotor winding insulation, eliminating these components as potential sources of equipment failure. Direct-drive designs with permanent-magnet generators offer additional benefits, most notably the complete elimination of the gearbox from the drivetrain. The gearbox is one of the most expensive components of a wind turbine, requires the most scheduled maintenance and very expensive repairs, and is responsible for a large portion of the turbine's energy losses.

Although direct-drive permanent-magnet generator designs overcome these gearbox issues, they face a separate set of challenges. To generate power from low- speed, high-torque rotational motion, these topologies require large-diameter generators, which increase the size and weight of the drivetrain and use increasing amounts of expensive rare earth magnetic material. Furthermore, these topologies must maintain a very small air gap between rotor and stator (on the order of millimeters) to obtain higher flux densities. This leads to design, manufacturing, and operational challenges in handling the complex loads from the rotor as the generators increase in size. Finally, because direct-drive turbines operate as synchronous generators, they require extensive power electronics to allow variable speed operation and to synchronize their output with the frequency of the power grid.

Table 4 below lists major areas of interest in permanent magnet generator research and development and the potential benefits that these areas of interest offer over the state-of-the-art in wind turbine drivetrains.

Table 4. Benefits of Permanent Magnet Technology Improvements

Area of Interest	Description	Benefits
Advanced Magnetic Materials	*Improved magnetic materials could lead to increased energy densities, which would result in smaller generators and, consequently, lower weight drivetrains. Materials improvements include bulk material property enhancement, nano-structured magnetic materials, and "flexible" magnets that can be magnetized or demagnetized post-installation.*	▪ **Reduced Capital Costs**: lower weight permanent magnets would result in lower weight generators, reducing up-tower weight. ▪ **Improved Reliability:** relaxed air-gap constraints would decrease the incidence of rotor/stator impact, decreasing maintenance costs. ▪ **Increased Energy Capture:** lower nacelle weights may make it cost effective to deploy taller towers with larger rotors. ▪ **Safety and Serviceability:** magnets that are safer to handle during installation and maintenance would reduce the potential for accidents.
System Design and Topology	*Possible system design and topology improvements include:* • *Radial flux (geared or direct drive), transverse flux, Vernier designs, magnet gearing and coreless armatures;* • *Advanced air gap design to improve tolerances and reduce strikes;* • *Designs for in-situ maintenance (handling), such as individually replaceable coils or modularized designs.*	▪ **Reduced Capital Costs**: advanced topologies could result in smaller generators, reducing up-tower weight. ▪ **Improved Reliability:** better designed and tolerance air-gaps would decrease the incidence of rotor/stator impact, decreasing maintenance costs. ▪ **Increased Energy Capture:** lower nacelle weights could make it cost effective to deploy taller towers with larger rotors. ▪ **Safety and Serviceability:** systems that are designed for installation and maintenance would reduce the potential for magnet related accidents.
Power Electronics	*New concepts for power converters include advanced controls, better controlled voltage levels, improved switching, and advanced architectures. Control and protection topologies for permanent magnet generators could influence demagnetization, overvoltage due to loss of load, short circuit prevention, and unbalanced load prevention)*	▪ **Reduced Capital Costs:** technology advances may lead to lower cost power electronics. ▪ **Improved Reliability:** improved power electronics operations and controls would enable wind turbines to avoid reliability problems currently seen in PM generators. ▪ **Improved Performance:** losses due to power electronics may be decreased.

Standards	*There is a market need for PMG standards development, particularly pertaining to testing and measurement.*	▪ **Improved Reliability:** Standards typically lead to more reliable systems or components; this would be true for PMGs as well. ▪ **Reduced Capital Costs:** Future financing costs would decrease as systems become more reliable and can be certified to a standard.
Diagnostics and Maintenance	*Signature analysis utilizing smart sensors allow for advanced diagnostics and predictive maintenance.*	▪ **Improved Reliability:** Operations and maintenance costs decrease as a result of well-scheduled maintenance that minimizes failures and turbine downtime.
Operating Environment	*As wind turbine move offshore (marine environment) and/or are located in more extreme operating environments (extreme temperatures, etc.), new materials and design considerations will be required to ensure successful long-term operations.*	▪ **Improved Reliability:** Extreme operating conditions will have a negative effect on component and system life-time. Technology improvements with this in mind may lead to wind turbines that remain reliable regardless of location.

The session identified several areas of research and development that could lead to improved permanent-magnet generators, including magnetic materials research; development of new generator machine designs; improved power electronics characteristics and power converter architecture; and development of diagnostic methods. The specific sub-topics, benefits, and challenges of each of these research areas are described below.

Magnetic materials research could improve permanent magnets by improving their energy density, creating nano-structured magnets, or by creating materials that can be magnetized or demagnetized post-installation to simplify assembly and maintenance processes. These advances could result in size and weight reductions over current magnets, particularly important for large-diameter direct-drive generators. Development of such magnets would require basic materials science breakthroughs, and the high cost of such materials and lack of market demand could hinder commercialization in wind turbine applications.

Several opportunities exist for new permanent-magnet generator machine designs. Transverse flux permanent magnet topologies and Vernier machine designs could yield increased permanent-magnet generator power densities, resulting in smaller size and lower weight direct drive generators. Commercialization could be hindered by a lack of sufficient manufacturing capabilities and a lack of investor and project operator experience with these technologies. Mitigating the risk of air gap collapse would improve turbine performance and reliability but may cause capital cost increases; the need for and value of such a design have not been quantified. Coreless armature winding designs could improve reliability by removing steel from the generator coils (reducing corrosion risk), could reduce overall generator weight, and could provide better voltage regulation, but these designs would result in larger-diameter generators that increase assembly, transportation, and installation complexity.

Permanent-magnet generator designs that allow in-situ maintenance (without the use of cranes) could lead to increased reliability and availability, decreased operations and maintenance costs, and reduced project risk. However, the need for such designs has not been quantified, and commercial users may not recognize the value of such designs.

Research on the transportation, installation, and support structures of permanent magnet generators could lead to reductions in capital equipment costs, logistics costs, and overall system weight, but certain designs, such as segmentation requiring field assembly, may reduce system efficiency and impact the rest of the system. A related issue is the ongoing competition between modularized and integrated design approaches to permanent magnet direct-drive turbines. The benefits and risks of developing new integrated generator designs that could reduce system weight, cost, and maintenance need to be evaluated in comparison to modular designs that allow turbine manufacturers to retain the expertise of and share risks with dedicated generator manufacturers. Magnetic gearing has the potential to reduce or remove many of the reliability problems associated with conventional gearboxes, but the extra permanent-magnet materials costs, lower power densities, and uncertain efficiency gains of such gearing need to be evaluated in order to determine the potential for commercialization. Finally, development of ruggedized permanent magnet generator designs for cold-weather or marine conditions could increase performance, reliability, and equipment lifetime for turbines operating in these environments, but commercialization is hindered by the lack of relevant codes and standards, the increase costs of implementing such upgrades, materials limitations, and uncertain market demand.

Workshop participants identified two major areas of research to improve power electronics for permanent-magnet generators: new power converter concepts, and improved control and protection topology. New power converter concepts could focus on controls, voltage levels, switching, and converter architecture. Advances in these areas could yield increased efficiency, reliability, and availability, but successful commercialization would have to first overcome the technical limitations of semiconductors, the lack of experience with high-voltage systems on the part of wind turbine designers and operators, and the overall lack of operational experience of these systems. Control and protection topology research could focus on demagnetization, overvoltage, short circuit prevention and management, and unbalanced operation. This research could yield improved performance and energy capture and would require software (rather than hardware) modification. The major barrier to commercialization is the cost of developing commercial products from existing technical papers and results.

Development of diagnostic methods for permanent-magnet generators might feature signature analysis including smart sensors to improve turbine reliability and availability. While deployment of these sensors would increase upfront capital costs, the improvements to reliability, scheduled maintenance, and performance should outweigh these costs. Possible technical barriers include electromagnetic interference with sensors from the permanent magnets, the potential for faulty information, and need for operator training. Lack of industry codes and standards related to sensors and diagnostic methods and the higher upfront costs could limit commercial deployment.

Table 5 below lists major barriers to the commercialization of permanent magnet generator technologies and potential research and development pathways for overcoming those challenges.

Table 5. Barriers to Commercializing Permanent Magnet Technology Improvements

Area of Interest	Commercialization Barriers	Development Path
Advanced Magnetic Materials	➢ **Technical Risk**: basic materials science breakthroughs are required.	▪ **Conduct materials science research**: basic research into novel, low-cost magnetic materials is needed.
	➢ **Commercial Risk**: high cost of permanent magnet materials may increase capital costs.	▪ **Develop tradeoff analysis:** advanced magnet costs may be offset by up-tower weight savings.
	➢ **Perception Risk**: current lack of market demand.	▪ **Develop cost/benefit analysis:** definitive studies showcasing costs and benefits of advanced permanent magnet materials, plus the development of an offshore wind industry, would drive demand.
	➢ **Certification Risk**: wind turbine standards have not been developed for advanced permanent magnet materials.	▪ **Establish IEC standards:** develop working groups to establish standards language for permanent magnet direct-drive.
System Design and Topology	➢ **Technical Risks**: manufacturing process breakthroughs are required to affordably implement advanced designs and topologies.	▪ **Conduct laboratory research: b**asic research into novel permanent magnet topologies may allow for their eventual deployment in the field.
	➢ **Commercial Risk**: the need for such designs has not been quantified; therefore the effect on overall costs is unknown.	▪ **Develop cost/benefit analysis:** definitive studies showcasing costs and benefits of advanced permanent magnet topologies would begin to overcome this area of risk.
	➢ **Certification Risk**: wind turbine standards have not been developed for advanced PMDD technologies.	▪ **Establish IEC standards:** develop working groups to establish standards language.
Power Electronics	➢ **Technical Risk**: limitations of existing semiconductors need to be overcome.	▪ **Conduct laboratory research:** basic research into advanced Power Electronics may allow for their eventual deployment in the field.
	➢ **Perception Risk**: lack of wind industry experience with high-voltage equipment.	▪ **Increase education and training:** education and training programs will increase high-voltage experience.
	➢ **Commercial Risk:** the cost of developing commercial products and lack of operational experience may hamper future power electronics development.	▪ **Develop cost/benefit analysis:** definitive studies showcasing costs and benefits of advanced power electronics may lead to a compelling business case for further development. ▪ **Increase education and training:** education and training programs will increase experience.

Improved Diagnostics and Maintenance	➢ **Reliability Risk:** electromagnetic interference may increase the potential for faulty information.	▪ **Conduct research:** laboratory and field research may help overcome electromagnetic interference issues.
	➢ **Operator Training Risk:** operators without proper training may add to permanent magnet-related operations & maintenance costs.	▪ **Increase education and training:** Education and training programs will increase operations & maintenance reliability.
	➢ **Certification Risk**: wind turbine standards have not been developed for advanced permanent magnet technologies.	▪ **Establish IEC standards:** develop working groups to establish standards language for permanent magnet diagnostics and maintenance.

2.3 Continuously Variable Transmissions

This session discussed the use of continuously variable transmissions, including fluid drive systems, in wind turbine applications. Continuously variable transmissions can shift smoothly between an infinite number of effective gear ratios within a range, as opposed to conventional geared systems that offer a limited number of fixed gear ratios (Cotrell 2004). In wind turbine applications, these transmissions can vary their gear ratio seamlessly to ensure that the low-speed rotation of the turbine's rotor, which changes with the incoming wind speed, is always stepped up to the exact high-speed rotation required for electricity generation. These transmissions allow wind turbines to operate at higher aerodynamic efficiencies over a larger range of wind speeds. Conventional wind turbines manage variable-speed operation through the use of power electronics, whereas continuously variable transmissions manage variable-speed operation mechanically. Continuously variable transmissions can also mitigate rotor loads by allowing the rotor to accelerate during wind gusts; this load mitigation reduces required rotor and drivetrain structural strength and therefore cost.

The session examined two major categories of continuously variable transmissions: designs that use frictional contact between components to vary the effective gear ratio, and hydraulic designs that use a fluid to vary the ratio. Frictional designs include rolling traction systems; belt or chain drives; variable diameter gears; and differential planetary drives. Rolling traction systems vary the degree or angle of physical contact between transmission components (usually spheres, torroids, discs, or cones) to change the effective gear ratio. Belt- or chain-drive systems feature two variable diameter pulleys connected by a belt or chain; varying the diameter of the input and output pulley(s) changes the gear ratio. Variable-diameter gears can change their diameter while engaged to alter the gear ratio. Differential epicyclical drives, also called differential planetary drives, control the effective gear ratio by rotating the annulus (outer ring) of a planetary gearbox.

Hydraulic systems include hydrodynamic drives and hydrostatic drives. Hydrodynamic drives use the inertia of the fluid to transmit power, while hydrostatic drives use only static pressure. Hydrodynamic drives feature an impeller on the input shaft and a turbine on the output shaft; the impeller and turbine are coupled via a hydraulic fluid so that torque can be transmitted. This concept is also called a hydraulic torque converter. Hydrostatic drives convert mechanical rotation into fluid flow using a pump and then back into mechanical motion using a hydraulic motor; the variable speed management is achieved by changing the displacement of the pump or motor.

Continuously variable transmissions may offer an improvement over current wind turbine designs that use constant-ratio transmissions. These transmissions could allow turbines to operate at a higher aerodynamic efficiency over a larger range of wind speeds than do conventional designs. This performance improvement would increase the amount of energy produced by the turbine, ultimately decreasing the cost of energy. These systems also have the ability to absorb rotor torque from sudden wind gusts, thus alleviating fatigue loading and improving overall turbine reliability. Finally, continuously variable transmissions reduce the need for power electronics for power conditioning and variable-speed operations purposes (see Camm et al. for a detailed description of doubly-fed induction generators in variable-speed wind turbines). A reduced role for power electronics could lower overall turbine capital cost, reduce power losses due to power electronics inefficiencies, and improve reliability by eliminating the need for maintenance-prone slip rings (Cotrell 2004). Finally, some hydrostatic drive configurations offer the possibility of energy storage through hydraulic fluid accumulators, potentially smoothing the integration of wind turbine energy output into the electrical grid.

Table 6 below lists major areas of interest in continually variable transmission research and development and the potential benefits that these areas of interest offer over the state-of-the-art in wind turbine drivetrains.

Table 6. Benefits of Continuously Variable Transmissions

Area of Interest	Description	Benefits
Frictional Contact Drives	*These designs change the physical contact between components to vary the effective gear ratio. Physical contact designs include rolling traction systems; belt or chain drives; variable diameter gears; and differential planetary drives.*	▪ **Reduced Capital Costs**: these systems reduce the need for power electronics. ▪ **Improved Reliability:** these systems can absorb rotor torque from sudden gusts, thereby alleviating fatigue loading. These designs could also improve reliability by eliminating generator slip rings. ▪ **Increased Energy Capture:** these designs increase turbine energy production by allowing turbines to operate at a higher aerodynamic efficiency over a larger range of wind speeds.
Fluid Drives	*These designs use pressurized hydraulic fluid to vary the effective gear ratio. Designs include hydrostatic and hydrodynamic (or hydraulic torque converter) designs.*	▪ **Reduced Capital Costs**: these systems reduce the need for power electronics. ▪ **Improved Reliability:** these systems can absorb rotor torque from sudden gusts, thereby alleviating fatigue loading. These designs could also improve reliability by eliminating generator slip rings. ▪ **Increased Energy Capture:** these designs increase turbine energy production by allowing turbines to operate at a higher aerodynamic efficiency over a larger range of wind speeds. ▪ **Energy Storage**: hydrostatic drives offer the possibility of energy storage by means of hydraulic fluid accumulators.

The session identified a number of technical and commercial challenges to the commercialization of continuously variable transmissions for wind turbine applications. First, these technologies may introduce new cost and reliability challenges because their application in wind turbines is currently untested. Incorporating new components and systems into the turbine could increase operations and maintenance costs and introduce new avenues of reliability failure. Second, the scalability of these components and materials has not been established. Certain design approaches, such as rolling contact designs and belt drives, may not scale to the high torque produced by megawatt-scale wind turbine rotors. Third, materials constraints may limit the commercialization of these technologies; hydraulic drive systems may need research and development of environmentally benign fluids, while certain frictional contact drive designs could require new high-friction materials in order to effectively transfer power between components. Finally, the perception of continuously variable transmissions as complex and undeveloped technologies may limit the commercial adoption of these technologies.

A research and development effort to facilitate the commercialization of continuously variable transmissions would focus on analyzing, proving, and demonstrating the benefits of the respective designs and technologies within this larger category. The overall gains in turbine performance, reliability, and cost need to be modeled and analyzed for different continuously variable transmission designs and in comparison to conventional variable-speed turbine designs. Part of this effort could include the development of specialized design, modeling, and analysis tools. Engineering work to prove and improve the reliability of continuously variable transmission components and materials in wind turbine applications is also needed. Finally, the demonstration of different continuously variable transmission designs in turbine test platforms could help establish the costs, benefits, and reliability impacts of these technologies.

Table 7 below lists major barriers to the commercialization of continuously variable transmission technologies and potential research and development pathways for overcoming those challenges.

Table 7. Barriers to Commercializing Continuously Variable Transmissions

Area of Interest	Commercialization Barriers	Development Path
Frictional Contact Drives	➢ **Technical Risk**: these technologies may introduce new cost and reliability challenges or increase operations and maintenance costs.	▪ **Undertake cost-benefit analysis**: model and analyze the gains in turbine performance, reliability, and cost over conventional designs. ▪ **Design and modeling tools**: develop tools for designing, modeling, and analyzing continuously variable transmission turbine concepts.
	➢ **Scalability Risk**: scalability of these components and materials has not been established for high-torque applications.	▪ **Demonstration**: deploy continuously-variable transmissions in turbine test platforms to establish benefits.
	➢ **Materials Risk**: could require new high-friction materials in order to effectively transfer power between components.	▪ **Component development and testing**: optimize components, materials, and designs through testing.
Fluid Drives	➢ **Technical Risk**: may introduce new cost and reliability challenges or increase operations and maintenance; fluid cleanliness requirements.	▪ **Undertake cost-benefit analysis**: model and analyze the gains in turbine performance, reliability, and cost over conventional designs. ▪ **Design and modeling tools**: develop tools for designing, modeling, and analyzing continuously variable transmission turbine concepts.
	➢ **Scalability Risk**: scalability of these components and materials has not been established for high-torque applications.	▪ **Demonstration**: deploy continuously-variable transmissions in turbine test platforms to establish benefits.
	➢ **Materials Risk**: may need research and development of environmental fluids.	▪ **Component development and testing**: optimize components, materials, and designs through testing.
	➢ **Perception Risk**: these technologies could be perceived as complex and undeveloped, limiting commercial adoption.	▪ **Demonstration**: deploy continuously-variable transmissions in turbine test platforms to establish benefits.

2.4 Innovative Concepts

This session discussed a variety of novel concepts, design approaches, components, and technologies that could be deployed in wind turbine drivetrains. The major concepts discussed were uptower direct current generators; innovative drivetrain topologies; ground-level generators; traction- or rim-drive turbine designs; tandem generators; and complete uptower gearbox reparability. These technologies are at different stages of readiness, from concept studies to field deployment in wind turbines, and each offers its own benefits over the state-of-the-art as well as commercialization challenges. Session participants also discussed belt drives, variable diameter gears, hydrodynamic torque converters, magnetic gears, magnetic bearings, hydrostatic bearings, fluid drives, and the use of advanced materials in drivetrains. To avoid duplication, the findings of the Innovative Concepts session with respect to these technologies have been incorporated in the preceding sections 2.1 through 2.3. Finally, although not strictly an 'innovative' concept, session participants identified research and development to overcome the gearbox failures afflicting current turbine designs as a crucial effort.

Table 8 below lists major areas of interest in innovative drivetrain concept research and development and the potential benefits that these areas of interest offer over the state-of-the-art in wind turbine drivetrains.

Table 8. Benefits of Innovative Drivetrain Concepts

Area of Interest	Description	Benefits
Uptower Direct Current (DC) Generator	*This concept would incorporate DC generators into turbine nacelles, feeding into a plant-wide DC collection system.*	▪ **Improved Reliability**: reduced need for transistors for AC-DC-AC conversion. ▪ **Grid Benefits**: energy storage potential; improved fault ride-through capabilities.
Ground-Level Generators	*This design would place the generator at the base of the tower; the main shaft in the nacelle would connect to a vertical driveshaft with a bevel gear.*	▪ **Improved Reliability**: generator at ground level may be easier to service and replace.
Rim-Drive Turbines	*An outer rim would enclose the turbine's rotor; generators embedded along that rim would produce power.*	▪ **Improved Reliability**: potentially eliminates the need for a gearbox.
Tandem Generators	*These designs would stack multiple permanent-magnet direct drive generators in tandem along the same horizontal-axis driveshaft.*	▪ **Improved Availability**: turbine can continue to produce power if one generator is taken out of service. ▪ **Scalability**: concept may scale well to larger generating capacities.
Complete Uptower Gearbox Reparability	*Development of gearboxes and drivetrains that can be repaired in situ without requiring external cranes*	▪ **Improved Reliability:** repairs can be completed more quickly without requiring cranes or wholesale gearbox replacement.
Other Potential Innovative Drivetrain Topologies	*This concept refers to the wholesale reevaluation of turbine drivetrain layouts.*	▪ **Reduced Capital Costs**: potential for improvement, but needs to be demonstrated. ▪ **Improved Reliability:** potential for improvement, but needs to be demonstrated.

Uptower direct current (DC) generators would enable a wind power plant-wide DC collection system, designed around the DC bus. Such a system could increase reliability by reducing the number of transistors for AC to DC to AC conversion. The system could also improve fault ride-through capabilities, increase transmission efficiency, especially for offshore wind systems, and provide opportunities for energy storage through capacitors and batteries. The major technical barriers to such a system are the design of the collection system and the need for extensive design work on control systems and power electronics. A potential research and development approach might include system design and cost studies to determine the potential benefits and costs of a plant-wide DC collection system and to review the available high-voltage DC hardware needed to build such as system.

Ground-level generator configurations would reduce weight in the turbine nacelle by placing the generator at the base of the turbine, potentially with gearbox stages to step up the driveshaft's rotational speed. These designs would incorporate a bevel gear in the nacelle to connect the horizontal low-speed shaft to a vertical driveshaft running the length of the tower. This layout would reduce nacelle weight, thereby reducing the structural requirements of the tower, and would allow for easier maintenance and replacement of the generator. However, such a layout would be mechanically complex; specific technical challenges include maintaining alignment in the vertical driveshaft, transferring high torque rotation through right-angle gearing, and developing suitable components such as a light-weight vertical shaft. Initial research efforts could focus on analyzing the feasibility, costs, and benefits of such as system.

Traction- or rim-drive turbine designs represent a radical departure from current common drivetrain configurations. As the name implies, these designs enclose the turbine's rotor within an outer rim; generators embedded along that rim would produce power as the rotor moves. Similar designs have been developed by the marine and hydrokinetic energy industry to produce power from tides and ocean currents. While such designs would reduce or eliminate the need for a gearbox, they would be technically challenging to design and construct. Research is needed to determine the technical feasibility of the concept and any potential benefits over existing technology.

Stacking multiple permanent-magnet direct drive generators in tandem along the same horizontal-axis driveshaft could improve overall turbine reliability and availability by creating redundancy. If one of the generators were to fail, the turbine could continue to produce power (albeit at a lower output) while that unit was repaired. Scalability of this concept is another major benefit, especially for offshore wind applications. However, adding components, weight, and expensive permanent-magnet materials to the turbine could drive up capital costs. Feasibility studies would be needed to evaluate the trade-offs between added capital costs and improved reliability and reparability.

Innovative drivetrain topology concepts refer to the wholesale reevaluation of turbine drivetrain layouts to see if entirely new component configurations may improve on the current state-of-the-art by reducing weight and costs and improving reliability. Such work involves substantial technology risk, since these new configurations have not been tested and could create new problems. Research and development of these concepts would likely take the form of extensive concept studies to develop new design configurations. Should new configurations appear to offer improvements to the state-of-the-art, research efforts might expand to include design validation, optimization, and testing.

Complete uptower gearbox reparability refers to the development of gearboxes and drivetrains that can be maintained and repaired in situ without requiring external cranes to hoist equipment. Such a gearbox would improve turbine availability and reduce maintenance and replacement costs by eliminating the need for expensive crane rentals. Such designs would likely require additional facilities uptower to lay out parts, built-in handling fixtures and tools, and extensive condition monitoring systems to determine which particular part or component has failed. Feasibility studies would be needed to demonstrate the cost-competitiveness of such concepts with costs of replacing or rebuilding conventional gearboxes.

Table 9 below lists major barriers to the commercialization of innovative drivetrain concepts and potential research and development pathways for overcoming those challenges.

Table 9. Barriers to Commercializing Innovative Drivetrain Concepts

Area of Interest	Commercialization Barriers	Development Path
Up-tower Direct Current (DC) Generator	➢ **Technical Risk**: design of the DC collection system; need to maintain variable-speed control on a DC generator.	▪ **Feasibility Studies**: system design and cost studies would determine the potential benefits and costs of a plant-wide DC collection system. ▪ **Equipment Survey:** review the available high-voltage DC hardware needed to build system.
Ground-Level Generators	➢ **Technical Risk:** maintaining vertical driveshaft; transferring high torque rotation through right-angle gearing; component development.	▪ **Feasibility Studies**: analyze the feasibility, costs, and benefits of such as system.
Rim-Drive Turbines	➢ **Technical Risk**: extremely technically challenging to design and construct.	▪ **Feasibility Studies**: analyze the feasibility, costs, and benefits of such as system.
Tandem Generators	➢ **Commercial Risk:** adding components, weight, and permanent-magnets could drive up capital costs.	▪ **Feasibility Studies:** evaluate the trade-offs between added capital costs and improved reparability.
Complete Up-tower Gearbox Reparability	➢ **Technical Risk:** may introduce new reliability challenges; would require additional up-tower facilities; requires extensive condition-based health monitoring systems.	▪ **Feasibility Studies:** analyze cost-competitiveness of concepts versus costs of replacing conventional gearboxes.
Other Potential Innovative Drivetrain Topologies	➢ **Technical Risk**: new configurations have not been tested and could create new cost & reliability challenges. ➢ **Perception Risk**: designs have not been tested, developed, or deployed.	▪ **Design Studies**: extensive concept studies to develop new design configurations.

3.0 Summary

Participants at the Advanced Drivetrains Workshop discussed a wide range of technologies, system design concepts, components, and strategies that offer the potential to improve the state-of-the-art in wind turbine drivetrains. These areas of interest can be grouped into three broad categories based on their potential impact on the market for current and next-generation drivetrains.

The first area of interest includes concept-stage designs for next-generation wind turbines; these concepts offer potentially significant but still uncertain advantages over the state-of-the-art. These technologies require analysis to evaluate and quantify the benefits they offer over conventional drivetrains, as well as feasibility studies to determine their overall technical viability. In many cases, these technologies were already studied extensively in the 1970s and 1980s and were determined to be not as commercially viable as the drivetrains that ended up in today's modern wind turbine designs, which essentially won out during the 1990's as the optimum configuration. However, given advances over the past thirty years in fields such as materials science, fluid dynamics, and computational design tools, there may be opportunities that present themselves upon reexamining innovative drivetrain concepts from the past, as well as more recent designs and ideas.

The second area of interest includes technologies that are currently being explored by wind turbine manufacturers and third parties for the current generation of wind turbine drivetrain designs. These technologies, some of which have been successfully commercialized in aerospace, automotive, marine propulsion, and industrial machinery applications, require applied research and development to optimize designs, test components in wind turbine applications, and address potential reliability and scalability issues. Novel designs in this category may lead to incremental improvements in wind turbine reliability, performance, or capital costs.

The third area of interest includes technologies that have potentially transformative application in next-generation turbine designs with large nameplate capacities (5+ MW), particularly in offshore wind turbines. Many of these technologies have been successfully commercialized in other industries and in different applications, such as magnetic resonance imaging (MRI), naval vessels, and civil transportation. These technologies require applied research, development, and demonstration programs to facilitate their operational deployment, and research programs in this area should have a multi-year perspective on the requirements of future wind turbines.

4.0 References

Cotrell, J. *Motion Technologies CRADA CRD-03-130: Assessing the Potential of a Mechanical Continuously Variable Transmission.* Technical Report, Golden: National Renewable Energy Laboratory, 2004.

E.H. Camm, M. R. Behnke, O. Bolado, M. Bollen, M. Bradt, C. Brooks, W. Dilling,M. Edds, W. J. Hejdak, D. Houseman, S. Klein, F. Li, J. Li, P. Maibach, T. Nicolai, J. Patiño, S. V. Pasupulati,N. Samaan, S. Saylors, T. Siebert, T. Smith, M. Starke, R. Walli. “Characteristics of Wind Turbine Generators for Wind Power Plants.” *IEEE Power & Energy Society General Meeting.* Calgary: IEEE, 2009. 5.

Fingersh, L., M. Hand, and A. Laxson. *Wind Turbine Design Cost and Scaling Model.* Technical report, Golden: National Renewable Energy Laboratory, 2006.

Hau, E. *Wind Turbines: Fundamentals, Technologies, Application, Economics.* 2nd Edition. New York: Springer, 2006.

Mueller, M., and A. McDonald. “A lightweight low speed permanent magnet electrical generator for direct-drive wind turbines.” *Proceedings of the 2008 European Wind Energy Conference & Exhibition .* Brussels: European Wind Energy Conference, 2008. 19.

Musial, W., S. Butterfield, and B. McNiff. *Improving Wind Turbine Gearbox Reliability.* Conference paper, Golden: National Renewable Energy Laboratory, 2007.

Poore, R., and T. Lettenmaier. *Alternative Design Study Report: WindPACT Advanced Wind Turbine Drive Train Designs.* Golden: National Renewable Energy Laboratory, 2003.

Ragheb, A., and M. Ragheb. “Wind Turbine Gearbox Technologies.” *Proceedings of the 1st International Nuclear and Renewable Energy Conference (INREC10).* Amman, Jordan, 2010. 8.

5.0 Appendix: Workshop Agenda

DAY ONE: June 29, 2010

11:00 am	**Registration and lunch**
12:00 pm	**Opening remarks and overview of DOE Wind Program** *Jacques Beaudry-Losique, Program Manager for DOE Wind and Water Power Program*
12:10 pm	**DOE's drivetrain research and development activities** *Mark Higgins, Turbine R&D Team Leader for DOE Wind and Water Power Program*
12:20 pm	**ARPA-E's perspective on innovative drivetrain development** *Mark Hartney, Program Director, ARPA-E*
12:35 pm	**Wind turbine drivetrain state-of-the-art** *Dr. Fort Felker, Director, National Wind Technology Center*
12:55 pm	**Breakout session instructions** *Mark Higgins*
1:00 pm	**Breakout sessions – technology status & benefits** *Four working groups: Superconducting Drivetrains, Advanced Permanent Magnet Topologies, Continuously Variable Transmissions, and Innovative and Non-Traditional Drivetrain Concepts.* 1. *What is the current state of this technology?* 2. *How does this technology offer an improvement over the state-of-the-art?*
3:00 pm	**BREAK**
3:30 pm	**Breakout sessions – barriers to commercialization** *(Same working groups as before)* 1. *What are the barriers to the commercialization of this technology in wind turbine applications?*
5:00 pm	**ADJOURN**

DAY TWO: June 30, 2010

8:00 am **Breakfast**

8:30 am **Day One recap and instructions**
Mark Higgins

8:45 am **Breakfast sessions – path to commercialization**

8:45 am **Breakout sessions – path to commercialization**
(Same working groups as before)

1. *What is the best way to commercialize this technology for wind turbine applications?*
2. *How would an R&D effort address the barriers to commercialization?*
3. *What key technical milestones or breakthroughs would be needed?*
4. *Describe a realistic timeline for commercialization.*
5. *How much would a successful R&D effort cost?*
6. *What might constitute appropriate levels of government, industry, and academic involvement?*
7. *How can we measure the success of any DOE-sponsored projects in this area?*

11:15 am **BREAK**

11:30 am **Breakout sessions – consolidating results**
Each working group will read through their notes with the facilitator to ensure accuracy, and will prepare their key finding to present to the larger workshop audience.

12:30 pm **LUNCH**

1:00 pm **Presentation of breakout session findings**
Each group has 20 minutes to present their major findings, including Q&A.

2:40 pm **Conclusion and wrap-up**
Mark Higgins

3:00 pm **ADJOURN**

U.S. DEPARTMENT OF
ENERGY

Energy Efficiency &
Renewable Energy

EERE Information Center
1-877-EERE-INFO (1-877-337-3463)
www.eere.energy.gov/informationcenter

DOE/GO-102010-3198 • December 2010
Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 10% post consumer waste.