Supplying Advanced Materials & Components for Wind Power Systems

October 2001

Sponsored by

U.S. Department of Energy
Office of Industrial Technologies
Office of Power Technologies

Prepared by

Mark Ellis
Energetics, Inc.

Jack Eisenhauer
Energetics, Inc.

Table of Contents

List of Appendices

Introduction

On August 29, 2001, the U.S. Department of Energy's Office of Industrial Technologies (DOE-OIT) and Office of Power Technologies (DOE-OPT) held a technology forum titled **Supplying Advanced Materials and Components for Wind Power Systems** in conjunction with the Utah 2001 Industry Showcase in Salt Lake City, Utah. The meeting gathered nearly 50 participants from wind turbine and component manufacturers, and material and process industries such as aluminum, composite materials, fiberglass, metal casting, plastics, and steel (See Appendix A for List of Participants). The forum provided a rare opportunity for direct information exchange between the two groups. The primary purpose was to identify existing and emerging materials, technologies, and processes within these manufacturing industries that can improve the performance and lower the costs of both small and large wind power systems.

Forum participants with full-scale small wind turbine.

Several presentations provided overviews of wind system requirements and advanced material options. Denise Swink, Deputy Assistant Secretary for DOE-OIT, identified opportunities for cooperation between manufacturing industries and the wind industry. P.J. Dougherty from DOE-OPT gave an overview of the wind industry and DOE's efforts to promote increased use of wind power generation. Dan Ancona from Princeton Energy Resources International outlined the technology evolution, material needs, and future market projections of the wind industry.

Technical presentations began with wind industry representatives. Kirk Pierce of Enron Wind discussed key material and manufacturing needs characteristic of a large turbine manufacturer. David Jones of Southwest Windpower next presented similar issues from a small turbine manufacturer's perspective. Presentations were given by the following individuals from the plastics, composite materials, steel, and aluminum industries, respectively: John Ciovacco, Cyclics Corporation; Michael Sandlin, Hexcel Composites; Wayne Parcel, The Timken Corporation; and David Williams, Alcoa. Each presenter discussed innovative materials and approaches that could benefit the wind power industry. The forum concluded with a facilitated discussion that identified current barriers, technical needs and opportunities, and potential next steps for action (See Appendix B for the Forum Agenda).

Background

Recent electricity shortages, rising energy prices, and concerns about meeting increasingly stringent air pollution targets have increased interest in alternative energy sources. Wind power in particular has become the fastest growing source of electricity worldwide, and its demand is rapidly increasing; new wind power capacity has grown by more than 30% per year worldwide for the past five years. The American Wind Energy Association estimates new wind installations worldwide will total over 48,000 MW over the next decade, representing more than $40 billion in new wind power systems. Growth exceeding 1,800 MW in U.S. wind energy capacity is expected this year alone.

DOE has established three goals for U.S. wind power:

- Provide 5% of the nation's electricity by 2020 with 10 GW online by 2010 and 80 GW online by 2020
- Increase the number of states with more than 20 MW installed wind power to 16 by 2005 and to 24 by 2010
- Provide 5% of the Federal government's electricity by 2010

Recent technological advances and manufacturing improvements have fueled this growth by driving down the cost of energy (COE) provided by wind power systems. In fact, over the last 20 years, average COE for wind power has declined steadily from approximately $0.40/kWh to less than $0.05/kWh in state-of-the-art wind systems, making wind power more competitive with conventional and other alternative energy sources alike. Continuing reductions in COE are especially critical to sustained growth of the U.S. wind power market, which has a less favorable energy cost structure than its European counterparts. Heavy government subsidization of green power, coupled with higher energy costs for fossil fuel-based energy supplies, have provided a more nurturing, lower-risk atmosphere for wind power utilization throughout Europe. Crucial to achieving these additional cost reductions and realizing DOE's goals is overcoming current barriers to high-volume, low-cost component manufacture for wind power systems.

Many industries offer a wealth of innovative, high-performance materials, technologies, components, and manufacturing techniques that can help U.S. wind power manufacturers to design and build superior wind power systems for both domestic and export markets. However, due to the small size of the U.S. wind power industry, many wind component and turbine manufacturers may be unaware of emerging materials and process technologies in manufacturing sectors such as DOE-OIT's Industries of the Future (IOF) which include aluminum, glass, steel, and metal casting. Sophisticated manufacturing techniques commercialized or under development in IOF and other industries (e.g., plastics and composite materials) may enable wind power producers to improve productivity while lowering manufacturing costs. Partnering with these industries would also provide the U.S. wind industry with greater leveraging power over limited financial resources.

Wind Turbine Materials and Technology

Below is a summary of materials and technology issues important to wind turbine and component manufacture extracted from *Wind Turbine—Materials and Manufacturing Fact Sheet* written by Dan Ancona and Jim McVeigh of Princeton Energy Resources International. The full version of this report can be found in Appendix C.

Reducing the cost of a wind turbine, without sacrificing its reliability and performance, is essential to the continued competitiveness of wind power with other sources of energy.

Currently, one of the most promising opportunities for significantly reduced COE is through the coordinated development of superior low-cost materials using reliable, high-volume component manufacturing techniques. Rotors, usually consisting of two or three blades attached to a hub, represent the highest cost component of a wind turbine despite being less than 15% of its weight. However the rotor and nacelle, including its internal components (e.g., gearbox, drivetrain, generator, etc.), can account for up to 50% of total system mass, with the remaining weight located primarily in the support tower.

Developing lightweight materials for use in rotor blades is particularly important. Cutting blade weight has a dramatic weight-saving effect throughout the rest of the wind turbine. Reduced material needs and new, perhaps less costly, material options elsewhere in the turbine thus become real possibilities. The drivetrain, gearbox, support bearings, and associated components would no longer need to be as robust to operate effectively. Moreover, the tower and other support features then can be designed to less rigorous strength requirements— especially in relation to fatigue—without compromising structural reliability. As with all other components, a careful balance must be achieved between reductions in blade weight and the higher costs typically associated with specialized lightweight materials (e.g., carbon composites).

Photo courtesy of DOE/NREL

A variety of materials are used in today's wind turbines, due largely to differences in desired performance and cost. Each component of a wind turbine experiences unique forces, in turn demanding specific material properties. Turbine manufacturers must pay careful attention to ensure the right materials are in the right component at the right cost. Steel dominates turbine tower and nacelle material use. Glass reinforced plastic (GRP) tonnage exceeds that of steel in rotors, although GRP is used almost exclusively for blades while steel often forms the hub. Significant differences also exist between large and small wind turbines. Small turbines generally consist of lighter weight materials, such as cast aluminum nacelles and carbon filament reinforced plastic (CFRP) blades.

The continued development of high-strength, lightweight materials with low life-cycle costs is critical to the wind industry. Evolutions in turbine design will likely result in the increased use of steel, GRP, and CFRP composites in the rotors. Magnetic materials will become more popular, especially in direct-drive generator technology that will replace traditional step-up gearboxes in some larger machines. Material demands for nacelles and its associated machinery are difficult to predict because of the complexity of its components; greater simplicity is the top goal in this area. Steel is expected to remain the dominant material used to construct towers. However, steel-reinforced concrete towers are expected to rise sharply in use, especially in future European offshore wind applications. Overall, steel will remain the primary construction material used by wind industry manufacturers, yet numerous opportunities exist for new material applications in every part of a wind turbine.

Additional material and technology issues can be found in Wind Turbine--Materials and Manufacturing Fact Sheet, included in Appendix C.

TECHNOLOGY OPPORTUNITIES

Six presentations were given by representatives of the wind power industry and the material and process industries. The order is consistent with that of the presentations given during the workshop:

- Kirk Pierce, Enron Wind Corporation
- David Jones, Southwest Windpower
- John Ciovacco, Cyclics Corporation
- Michael Sandlin, Hexcel Composites
- Wayne Parcel, The Timken Corporation
- David Williams, Alcoa, Incorporated

Complete transcripts of each presentation are included in Appendix D.

Enron Wind Corporation is a global company with manufacturing facilities in the United States, Germany, Spain, and the Netherlands. Despite being one of the world's largest wind turbine manufacturers, Enron employs just 1,400 people, indicative of the relatively small size of the wind industry. Enron Wind specializes in the manufacture of utility-scale wind turbines, ranging in power from 900 kW to 1.5 MW. These large turbines are extremely robust and impose significant material demands, as indicated by the following component weights:

- Tower: 60,000-140,000 kg
- Blade: 4,000-6,000 kg
- Nacelle: 30,000-80,000 kg
- Hub: 10,000-20,000 kg

Photo courtesy of Green Mountain Power and DOE/NREL

Four design criteria determine Enron's materials and manufacturing needs: cost, reliability, fatigue, and environment. All components must be able to withstand rigorous fatigue stress cycles upwards of 2×10^8 in magnitude. Depending upon turbine location, temperature, lightening, and turbulence may also factor strongly into design requirements.

Southwest Windpower manufactures small, 0.4 to 3.0 kW wind turbines, many of which are used in telecommunication, sailboat, rural electrification, and distributed generation applications. Southwest Windpower is a small company that employs approximately 50 individuals and has two U.S. facilities. In the last seven years, Southwest Windpower has produced more than 45,000 wind turbines. As demand for their products increases, the use of rapid and reliable processing techniques becomes exceedingly important. Consequently, Southwest representatives plan on multiple visits to high-volume manufacturing plants to refine their own manufacturing techniques. Southwest Windpower is strongly pursuing the development of low cost, easy-to-install, freestanding towers to support their machines. Optimizing the balance between turbine size and value is also a top priority.

Cyclics Corporation produces a unique, high-performance plastic known as CBT that combines the advantages of thermosets and thermoplastics, most notably fast processing, superior toughness, strong bonding characteristics, and high temperature and chemical resistance. Due for commercial introduction in 2002, CBT provides the added environmental benefits of high-recyclability and zero toxic emissions during its processing. CBT can be produced using conventional fabrication processes and is available in powder, pastille, and pellet forms, in addition to intermediate forms such as prepreg fabrics. Both its glass- and carbon-reinforced CBT exceed Germanischer Lloyd (GL) standards for tensile strength, tensile modulus, and other mechanical properties; Cyclics is targeting full GL certification of its CBT products. Fatigue properties of these advanced materials are being evaluated as Cyclics continues to refine its CBT products for the wind market. Cyclics plans to field-test CBT in complete wind systems.


Photo courtesy of DOE/NREL

Hexcel Composites employs over 6,000 employees in more than 20 manufacturing sites throughout the United States and Europe. Hexcel was the first supplier of prepregs for wind turbine blades, and has sold over 12,000 tons of composites to the wind turbine manufacturers during its 10 year relationship with the industry. Its reinforcement product offerings include woven and unidirectional reinforcements in glass, carbon, aramid, and hybrid continuous fibers; multiaxial non-crimp fabrics; and specialty products such as spiral weaves and socks. In addition, Hexcel also manufactures an extensive range of epoxy prepregs, epoxy resins, gel coats, and aluminum honeycomb materials. Hexcel is developing an innovative manufacturing process, called HexFit™, capable of consolidating different material combinations to fit specific end-design criteria. Hexcel is prepared to invest in cost-shared development efforts to help commercialize low-cost product solutions for the wind market.

Timken Corporation has historically produced alloy heat-treated tubing for support tower applications and has been a long time supplier of bearings for wind power applications. More recently, Timken has taken particular interest in the development of micro-alloyed steels called MicroTec™. Incorporating small amounts of certain added elements, MicroTec™ offers improved strength characteristics in both rolled and forged forms while providing a low-cost alternative to heat-treated steels. High fatigue resistance, uniform hardness, and improved machinability are additional advantages offered by this unique steel alloy. Typical yield strengths of MicroTec™ steel range from 60 to 95 KSI with surface hardness up to 62 HRC. MicroTec's™ proven success in HDTV towers, driveshafts, and other uses lends itself naturally to wind power applications.

Photo courtesy of DOE/NREL

Alcoa, Incorporated produces a comprehensive range of aluminum products to meet the needs of many applications. All major aluminum products are made of aluminum alloys. The inclusion of specific alloying elements (e.g., Mg, Cu, Ag, etc.) gives aluminum distinctive properties with regard to strength, corrosion resistance, durability, and others. Most properties can be further refined through subsequent thermo-mechanical processing of semi-fabricated products such as sheet, plate, extrusions, forgings, and castings. Trade-offs must be made between different properties to achieve a specific end-result without exceeding the physical limits of aluminum alloys. Aluminum alloys offer significant advantages in relation to weight reduction, recyclability, and reduced life-cycle costs. Turbine components in which aluminum may prove beneficial include towers, nacelles, generators, and even blades. The importance of industry working with OEMs to develop competitive material and manufacturing solutions was also emphasized.

NEXT STEPS

The key findings from the facilitated session are summarized below and detailed in Exhibit 1.

The wind industry must perform a focused review of wind power system components to prioritize its research and development needs, paying close attention to cutting costs (both upfront capital costs and long-term operations and maintenance costs) and speeding production rates. Products must also be designed for manufacturability and assembly. Of particular concern is exploring innovative materials that can be fabricated using conventional technologies and concurrently investigating methods to use existing materials in new ways. Often such research spawns near-term solutions that accelerate future technological innovation. There was strong support for continued planning efforts, which could take the form of development paths, industry workshops, strategic plans, and similar initiatives, to more thoroughly examine collaborative technological opportunities.

Promising opportunities exist for the collaboration of wind industry and material and process industry partners, perhaps as far as creating a unified wind power manufacturing organization. Establishing integrated design teams will promote the rapid cross-fertilization of information across industries, while simultaneously pooling increased resource-leveraging power. Optimized product design requires the strategic integration of expertise in product-specific design requirements, OEM manufacturing processes, and material processing and properties. To achieve this goal, each group must actively seek participation with the other—manufacturing industries must make wind turbine and component producers aware of their capabilities and interest, and conversely the wind industry must actively seek material and process industry support. Soliciting utility involvement in the research and development process is also exceedingly important.

In addition to providing funding, testing facilities at national labs, and demonstration sites, the Federal government—primarily DOE-OIT and DOE-OPT—can provide a neutral forum for collaboration and technology planning to facilitate the development of multi-industry manufacturing organizations. Programs such as the Partnership for a New Generation of Vehicles (PNGV) have proven invaluable to other market sectors and should be used as a model for forming strategic partnerships between the wind industry, material and process industries, government, and academia. DOE should market the value of wind energy to other sectors of the Federal government, including Congress, to increase its subsidization. Participants also felt DOE should help to both coordinate utility cooperation with the wind industry and organize the above strategic planning efforts.

Aside from the focus on emerging technologies, processing techniques, and innovative materials utilization to lower costs and speed production, participants discussed additional barriers of important note. Inconsistent standards for different size turbines combined with the lack of agreement between U.S. and international specifications often translate into prohibitively expensive testing and certification expenses that may exceed product development costs. Such discrepancies also limit international market penetration and technology commercialization. Uncertainty regarding government wind power subsidization in the United States further confounds the cost issue. Regardless, the U.S. wind industry must play a larger role in building investor confidence in its companies to obtain vital funding.

Once components have been fabricated, the transportation of these materials creates an additional cost hurdle, particularly for large turbine components (e.g., blades and towers for utility-scale turbines). New manufacturing methods and turbine designs are needed to better accommodate transportation. Developing more robust and reliable onsite turbine fabrication technologies presents one possible solution to the transportation cost dilemma.

EXHIBIT 1. ADVANCED MATERIALS AND COMPONENTS FOR WIND POWER SYSTEMS

Key Technical Needs and Barriers	Taking Advantage of Opportunities	How Can Government Help Partnerships?	Next Steps
• Develop free-standing towers for small turbines • Different standards for different size turbines • Lack of agreement between U.S. and international standards • Expensive testing and certification procedures to allow for domestic and international acceptance – Costs for certification often exceeds those for development • Uncertainty regarding government wind power subsidization in U.S. • Less wind power subsidization in U.S. than in Europe • High transportation cost of large components • Limited tower fabrication capabilities • Difficulty commercializing new technologies • Explore materials that can be fabricated using conventional technologies • Enhance blade performance • Develop rapid, lower cost processing techniques – e.g., more rapid blade production • Investigate how to use existing materials in new ways • Build investor confidence • Develop reliable, robust on-site fabrication technologies	• Establish a collaborative Web site to facilitate information exchange • Test and verify new technologies • Develop integrated design teams • Perform a focused review of wind power system components • Cross-fertilize tower design information from telecommunications sector • Capitalize on beneficial opportunities offered by WindPACT and similar programs	• Facilitate power transmission with utilities • Support implementation of developed technologies – Showcases/demonstrations • Organize development path at sub-component level • Increase Congressional awareness of wind power benefits • Provide neutral forum for collaboration and technology planning • DOE—Market value of wind energy to other parts of federal government • Provide platform for the development of multi-industry manufacturing associations • Provide education outreach programs	• Use PNGV as model for strategic partnership between industry, government, and academia • Foster formal links between wind industry and manufacturing industry associations • Leverage resources to aid cross-fertilization and research • Examine opportunities for provision of power to rural industrial plants • Wind industry–collaborate with existing manufacturing associations in material and process industries • Prioritize R&D needs • Perform in-depth analysis and testing of materials and components • Familiarization with design criteria via central coordinating body • Roadmap future collaboration between wind and process industries • Investigate methods for industry to use green energy (esp. wind power) • Use existing data from other markets to assess/predict material performance – e.g., aviation industry, military • Get utilities involved • Encourage OEMs to facilitate collaborative R&D discussion • Investigate lower-risk testing/certification • Material and process industries—Inform wind organizations (e.g., AWEA) of capabilities and interest • Investigate cost-shared technology development/demonstration opportunities • Provide input to testing bodies and programs

Appendix A

List of Participants

List of Participants

Dan Ancona
PERI

Tom Ashwill
Sandia National Laboratory

Joseph Barrett
DOE-Philadelphia Regional Office

David J. Bennett
Eaton Metal Products

Chad E. Bennion
Utah House

Mitchell Bruce
PPG Industries, Inc.

John Ciovacco
Cyclics Corporation

Geoff Deane
Clipper Windpower Technology, Inc.

Sara Dillich
DOE-OIT

Phil J. Dougherty
DOE-OPT/WPA

Mark Elliott
Hexcel

Bill Ferrell
PPG Industries, Inc.

Vern Ferrin
Porter Coatings

Tim Flacco
Control Chief Corporation

Greg Garrett
Enron Wind

Brian Glenn
Enron Wind

Frank Golemba
Owens Corning

Dayton A. Griffin
Global Energy Concepts, LLC

Craig Hansen
Windward Engineering

David Jones
Southwest Windpower

Juan Juarez
Jeffco Products

Pat Kons
NUCOR Steel

Elliott Levine
DOE-OIT

John Miller
Trinity Industries

Kathi Montgomery
Montana Dept. of Environmental Quality

Pierre Mousset-Jones
MSM/UNR

R. Neelameggham
MagCorp

Mike Palmer
Saertex

Wayne Parcel
The Timken Corporation

Kirk Pierce
Enron Wind

Pete Pollak
Aluminum Association

Scott Richlen
DOE-OIT

Steve Robison
American Foundry Society

Michael Sandlin
Hexcel Composites

Michael Skillingberg
Aluminum Association

Justin Stover
C.C. Jensen, Inc.

Denise Swink
DOE-OIT

Tam Tran
Self

Jake Van der Meide
Legend Technologies

Gideon Varga
DOE-OIT

Jim Vemich
Mark Steel

Christine Watson
State of Utah Energy Office

David Williams
Alcoa

Harvey Wong
DOE-OIT

Jerry Zenger
University of Utah

Facilitators:

Jack Eisenhauer
Energetics, Inc.

Mark Ellis
Energetics, Inc.

Jennifer Cordero
Energetics, Inc.

Appendix B

Forum Agenda

Supplying Advanced Materials and Components for Wind Power Systems

Forum Agenda

August 29, 2001
Sheraton City Centre, Granary Room
Salt Lake City, Utah, USA

Time	Function
1:30 p.m.–1:45 p.m.	**Opening Remarks/Introduction** • ***Denise Swink****, Deputy Assistant Secretary – DOE Office of Industrial Technologies (OIT)* • ***Phil Dougherty****, National Coordinator – Wind Powering America, DOE Office of Power Technologies (OPT)* • ***Gideon Varga****, Project Lead – DOE-OIT*
1:45 p.m.–2:00 p.m.	**Overview of the Wind Power Industry** • Desirable technical and performance characteristics, current market trends, and future outlook - ***Dan Ancona****, International Program Manager – Princeton Energy Resources International*
2:00 p.m.–2:40 p.m.	**Wind Power Industry Presentations** • Critical barriers and technical needs of the wind power industry • Large turbine manufacturer perspective - ***Kirk Pierce****, Senior Engineer – Enron Wind Corporation* • Small turbine manufacturer perspective - ***David Jones****, Design Engineer – Southwest Windpower*
2:40 p.m.–3:25 p.m.	**Material and Process Industry Presentations** • Materials, manufacturing processes, and technologies available to wind power system and component manufacturers • Plastics perspective - ***John Ciovacco****, CEO – Cyclics Corporation* • Composite Materials perspective - ***Mike Sandlin****, Market Segment Manager, Wind Energy Americas – Hexcel Corporation* • Steel perspective - ***Wayne Parcel****, Global Manager-Energy Industry Sales, Steel – The Timken Corporation* • Aluminum perspective - ***David Williams****, Manager–Business Development, Alcoa, Inc.*
3:25 p.m.–3:35 p.m.	**Break**
3:35 p.m.–4:30 p.m.	**Facilitated Discussion** • Interactive discussion of opportunities and challenges • Next steps

Appendix C

Wind Turbines—Materials and Manufacturing Fact Sheet

Wind Turbine - Materials and Manufacturing Fact Sheet

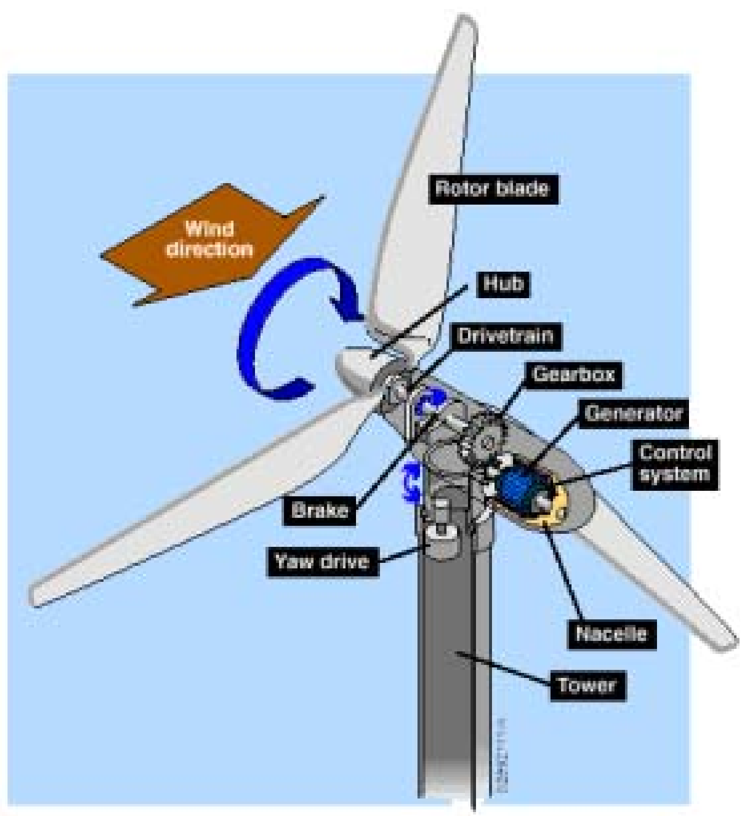
Prepared for the Office of Industrial Technologies, US Department of Energy
By Princeton Energy Resources International, LLC.
Dan Ancona and Jim McVeigh

Recognition of the value of wind energy as a low cost, clean source for electricity is creating major new business opportunities for manufacturing and materials innovation. Worldwide growth in wind generation since 1994 has been 30% or higher annually. The cost of energy from large wind power plants has declined to less than $0.05/kWh at good wind sites. By the end of 2000, the global capacity had passed 17,600 megawatts (MW) [See reference 1], and in the United States alone, more than 1,800 MW of new installations should be completed this year [2, 3].

The combined sales of large wind power plants and small turbines for distributed generation is now $4-5 billion annually worldwide and growing. Small turbines (less than 100 kW each) are being produced for the growing distributed generation and off-grid markets. Grid-connected wind power plants typically employ hundreds of 1 to 2 MW turbines today and larger, 3 to 5 MW machines, with 100-meter (m) (110 yards - longer than a football field) or greater rotors are being developed. The wind turbine manufacturing business has grown from a "cottage industry," with hand-built subsystems, to sales warranting large-scale production operations.

Parts of a Wind Turbine

Wind turbines come in many sizes and configurations and are built from wide range of materials. In simple terms, a wind turbine consists of a **rotor** that has wing shaped **blades** attached to a **hub**; a **nacelle** that houses a drivetrain consisting of a **gearbox,** connecting shafts, support bearings, the **generator**, plus other machinery; a **tower**; and ground-mounted electrical equipment.



Wind Turbine Nomenclature

The wing shaped blades on the rotor actually harvest the energy in the wind stream. The rotor converts the kinetic energy in the wind to rotational energy transmitted through the drivetrain to the generator. Generated electricity can be connected directly to the load or feed to the utility grid [4].

The weight and cost of the turbine is the key to making wind energy competitive with other power sources, because research programs have significantly improved the efficiency of the rotor and maximized the energy capture of the machine. The real opportunity today is through better, low cost materials and though high volume production, while ensuring the reliability is maintained. The typical weight and cost of the primary turbine components today are shown in Table 1. In addition there are foundations and conventional ground-mounted systems, including transformers, switching and other power equipment.

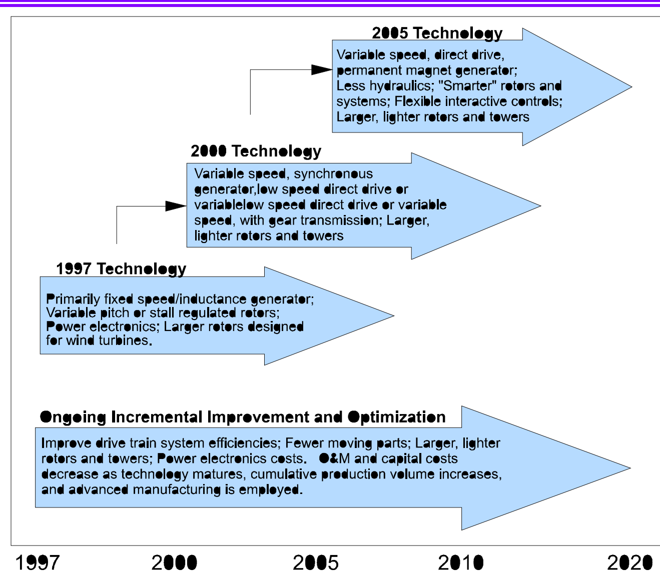
Table 1. Turbine Component Weight and Cost

Component	% of Machine Weight	% of Machine Cost [5]
Rotor	37177	20-30
Nacelle and machinery, less	25-40	25
Gearbox and drivetrain	37025	37178
Generator systems	36927	37025
Weight on Top of Tower	35-50	N/A
Tower	30-65	37188

There appear to be several areas where technological progress and cost reduction are needed. Turbine subsystem costs are generally evenly split between rotor, nacelle, drivetrain power systems, and the tower. There is no single component that dominates turbine cost. The rotor is the highest cost item on most machines and must be the most reliable. Towers are normally the heaviest component and could benefit from weight reduction, but lightening the rotor or tower-top weight has a multiplier effect throughout the system including the foundation.

Expected Technology Evolution

The components of turbines are changing as the technology improves and evolves. There is a trend toward lighter weight systems. Light weight, low cost materials are especially important in blades and towers for several reasons. First the weight of the blades and rotor is multiplied through out the machine.



Source: Renewable Energy Technology Charecterizations, Electric Power Research Institute, EPRI TR-109496, December 1997

Wind Turbine Technology Evolution

The tower weight is key because it is typically 60% of the weight of the turbine above the foundation, due to the fact that sophisticated light-weight, high-strength materials are often too costly to justify their use.

Another technology shift is occurring in the drive train. In some cases the gearbox is being eliminated by employing variable speed generators and solid state electronic converters that produce utility quality alternating current (AC) power. This trend began in small machines and is now being incorporated in turbine sizes from 100 kW to 3 MW. Other trends in wind turbine technology are discussed in detail in the Renewable Energy Technology Characterizations published by the Electric Power Research Institute (EPRI) [5] with DOE support.

Market and Turbine Component Materials Data

To estimate the quantities and types of materials used in wind turbines, a database was compiled from a variety of industrial, DOE laboratory and existing PERI sources. Much of the wind turbine and component characteristics and weight data came from the DOE, Wind Partnerships for Advanced Technologies (WindPACT) program database through NREL and their subcontractors, as well as directly from turbine manufacturers, their web sites and marketing materials. Twenty-eight types and models of turbines were analyzed in this report, ranging from small models for direct current (DC) battery charging (e.g. the 0.4 kW Southwest Windpower turbine), to large grid connected alternating current (AC) machines currently commercially available (e.g. the Enron 1.5 MW) and being employed in 100-200 MW wind power plants. Very large multi-megawatt machines being designed for future wind farm applications, both on- and off-shore (e.g. the 5 MW NREL concept turbine), were also included in expected future markets after 2005. The specific models, type and size, that were assumed for each manufacturer as the basis for estimating current and future market share in our model is shown in Table 2. The actual unit production and sales data incorporated in the market share database is considered proprietary by the manufacturers. This data was used in estimating weights of materials shown in Table 3.

Table 2. Turbine Models Used in Current and Future Materials Usage Estimates

Turbine Make	Rated Power (kW)
Southwest Windpower	0.4, 1.0
Bergey	1.5, 10
Atlantic Orient Corp.	50
Northern Power Systems	100
Enercon	500, 850
Micon	600, 900
Bonus	600, 1000
Vestas	660, 850, 1650, 2000
Nordex	1000
Mitsubishi	600, 1000

Future Market Projections

The surge in growth in wind turbine installations in the United States and around the world is expected to continue and actually accelerate. In a study conducted by the World Energy Council (WEC) projected worldwide wind capacity of 13 gigawatts (GW) by 2000 (actual installed capacity was 13.6 GW by the end of 1999), increasing to 72 GW by 2010 and 180 GW by 2020. WEC also considered an "environmentally driven scenario" that has much faster growth if national policies were adjusted. That scenario projected 470 GW of wind power by 2020.

In the United States, the American Wind Energy Association (AWEA) supports the DOE projections for wind power.

- Provide at least 5% of the nation's electricity by 2020 with 10 GW online by 2010 and 80 GW by 2020.
- Double the number of states with more than 20 MW installed to 16 by 2005 and to 24 by 2010.
- Provide 5% of the electricity used by the federal government (the largest single consumer of electricity) by 2010 with 1,000 MW online.

The members of the European Wind Energy Association (EWEA) have increased their estimates for wind installations in that region. Since 1993, the market for new turbines has grown at over 40 % per year. During 1999 was a record year with over 3000 MW installed in that year, resulting in a total installed capacity of 9,500 MW. This is well above the EWEA's old target for 2000 of 8000 MW. With support from the European Commission, studies show and the wind industry believes that the target of 40 GW will also be passed sooner, so the target for 2010 has been raised to 50 GW, of which 5 GW are expected to be offshore capacity. Similarly, a new target of 150 GW was agreed to by EWEA for 2020, of which 50 GW will be offshore.

The future markets for wind turbines in the United States and Europe are large but the biggest potential is expected to be in Asia, Latin America, the Former Soviet Union and Africa. These are the markets where demand for electricity is growing the fastest and the need for sustainable development with reliance on domestic energy resources are the greatest [6]. Growth in these markets could surpass both Europe and the U.S. by 2020.

Materials Usage in Current Wind Turbines

A wide range of materials are used in wind turbines. There are substantial differences between small and large machines and there are projected changes in designs that will accommodate the introduction of new material technologies and manufacturing methods. The estimated materials use in small and large turbines is shown in Table 3. To arrive at a total, the material usage is weighted by the estimated market share of the various manufacturers and machines types.

Table 3. Percentage of Materials Used in Current Wind Turbine Component

Large Turbines and *(Small Turbines*[1]*)*

Component/ Material (% by weight)	Permanent Magnetic Materials	Pre-stressed Concrete	Steel	Aluminum	Copper	Glass Reinforced Plastic [4]	Wood Epoxy [4]	Carbon Filament Reinforced Plastic [4]
Rotor								
Hub			*(95)* - 100	*(5)*				
Blades			5			95	*(95)*	*(95)*
Nacelle [2]	*(17)*		*(65)* - 80	3 - 4	14	1 - *(2)*		
Gearbox [3]			98 -*(100)*	*(0)* - 2	*(<1)* - 2			
Generator	*(50)*		*(20)* - 65		*(30)* - 35			
Frame, Machinery & Shell			85 - *(74)*	9 - *(50)*	4 - *(12)*	3 - *(5)*		
Tower		2	98	*(2)*				

Notes:
1. Small turbines with rated power less than 100 kW- (listed in italics where different)
2. Assumes nacelle is 1/3 gearbox, 1/3 generator and 1/3 frame & machinery
3. Approximately half of the small turbine market (measured in MW) is direct drive with no gearbox
4. Rotor blades are either glass reinforced plastic, wood-epoxy or injection molded plastic with carbon fibers

The trends in design and manufacturing differ between small and large turbines. Small machines tend to use lighter weight castings in an effort to reduce costs. Many parts are die cast aluminum in small turbines, while in large machines steel castings or forgings are needed to meet strength and structural fatigue requirements. The size of steel castings for large turbines, especially the blade hub units, is one of the manufacturing challenges.

Material fatigue properties are an important consideration in wind turbine design and materials selection. During the expected 30 year life of a wind turbine, many of the components will need to be able to endure 4×10^8 fatigue stress cycles. This high cycle fatigue resistance is even more severe than aircraft, automotive engines, bridges and most other man-made structures.

Future Component Development Trends

There are new component developments underway now that will significantly change the materials usage patterns. Generally there are trends toward lighter weight materials, as long as the life-cycle cost is low. Specific development trends in turbine components are discussed below:

Rotors Most rotor blades in use today are built from glassfiber-reinforced-plastic (GRP). Other materials that have been tried include steel, various composites and carbon-filament-reinforced-plastic (CFRP). As the rotor size increases on larger machines, the trend will be toward high strength, fatigue resistant materials. As the turbine designs continually evolve, composites involving steel, GRP, CFRP and possibly other materials will likely come into use.

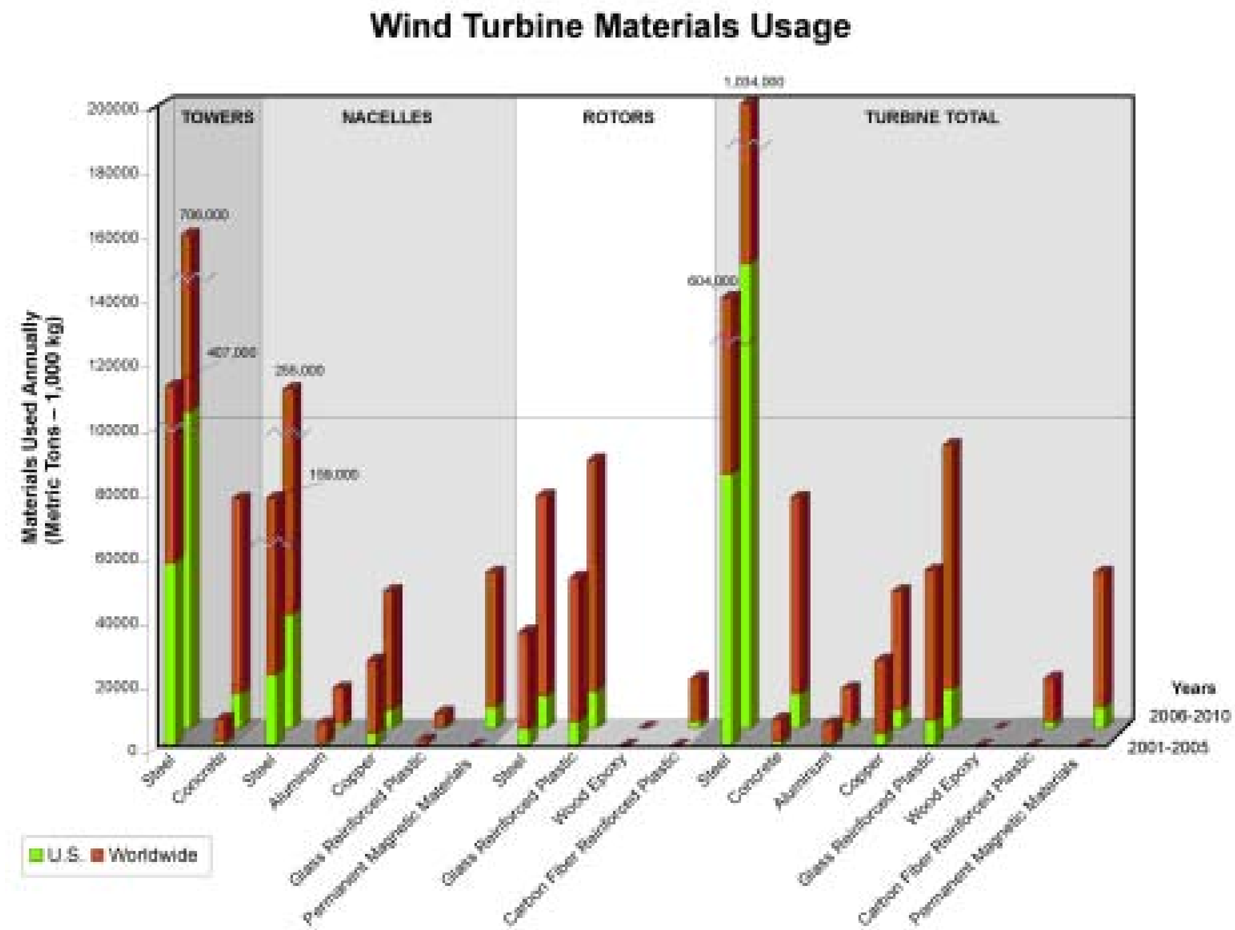
Gearboxes — The step-up gearbox used on large turbines today is expected to be replaced in many future machines. Most small turbine designed for battery charging use a variable speed, permanent magnet, variable frequency generator connected to a rectifier. As high power solid state electronics are improved, larger and larger machines are likely to use AC-DC-AC cycloconverters. This is the case on turbines being developed by Northern Power Systems (100 kW), the ABB (3 MW), and in some commercial machines. This trend will increase the use of magnetic materials in future turbines. Large epicyclic gear boxes used in large ships, may continue to be the drive system for some large turbines.

Nacelles — The nacelle contains an array of complex machinery including, yaw drives, blade pitch change mechanisms, drive brakes, shafts, bearings, oil pumps and coolers, controllers and more. These are areas where simplification and innovation can pay off.

Towers — Low cost materials are especially important in towers, since towers can represent as much as 65% of the weight of the turbine. Prestressed concrete is a material that is starting to be used in greater amounts in European turbines, especially in off-shore or near-shore applications. Concrete in towers has the potential to lower cost, but may involve nearly as much steel in the reinforcing bars as a conventional steel tower.

Material Usage Trends Through 2010

The component development trends described above are reflected in the following material use projections. The overall annual material usage trends are shown in the following figure for two periods, from now though 2005 and for 2006 though 2010. Introduction of much of the new technology discussed above is expected to be incorporated in commercial machines during the later period. Materials used in machines installed in the U.S. are included as part of the global totals.



The following observations are based on the results of the material usage analysis:

- Turbine material usage is and will continue to be dominated by steel, but opportunities exist for introducing aluminum or other light weight composites, provided strength and fatigue requirements can be met.
- Small turbine production volume is increasing rapidly which can be accommodated by manufacturing mechanization and innovation that will lower costs.
- Elimination of the gearbox by using variable speed generators will increase through use of permanent magnetic generators on larger turbines increasing the need for magnetic materials.
- New high power electronics will help reduce the need for gearboxes and also decrease losses occurred during transmission of wind power to distant load centers.
- Simplification of the nacelle machinery may not only reduce costs, but also increase reliability.
- Blades are primarily made of GRP, which is expected to continue. While use of CFRP may help to reduce weight and cost some, low cost and reliability are the primary drivers.
- Increasing the use of offshore applications may partially offset this trend in favor of the use of composites.
- Prestressed concrete towers are likely to be used more, but will need a substantial amount of steel for reinforcement.

- Wood epoxy, used in early blade production, is not expected to be a material of choice despite excellent fatigue properties.
- Wind turbine component and materials manufacturing are major and expanding business opportunities for at least the next 10 years.
- The largest market for wind turbine systems and materials in the future will be outside North America and Europe, but this market will be slower in development.

References:

1) International Energy Agency, Implementing Agreement for Co-operation in the Research and Development of Wind Turbine Systems, *Annual Report 2000*, May 2001.

2) American Wind Energy Association, *Global Wind Energy Market Report: Wind Energy Growth Was Steady in 2000, Outlook for 2001 Is Bright.* AWEA web site: http://www.awea.org/faq/Global05-2001.PDF.

3) American Wind Energy Association. 2001. Wind Project Database: Wind Energy Projects Throughout the United States. AWEA web site: http://www.awea.org/projects/index.html.

4) Department of Energy, *Wind Power Today*, DOE/GO-102001-1325, May 2001.

5) Electric Power Research Institute and DOE, *Renewable Energy Technology Characterizations*, EPRI TR-109496, December 1997.

6) Legerton M L, Adamantiades A G, Ancona DF, *Wind Power Plants*, World Energy Council Conference, Houston, TX, Working Group Paper 3.3, 15 September 1998.