Cyber Journals: Multidisciplinary Journals in Science and Technology, Journal of Selected Areas in Renewable Energy (JRSE), January Edition, 2012

Cost analysis of the material composition of the wind turbine blades for Wobben Windpower/ENERCON GmbH model E-82

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***Abstract*—Commercial wind turbines have developed incrementally in size over the past 30 years, so that the largest wind turbine by the end of 2005 had a nominal output of 5 MW and a rotor diameter of 124 m, and a single blade can weight 18 t. The question arises what is the maximum size of the turbine can be, considering the relationship between material/cost. In terms of the factors limiting the conceptual design of wind turbines include: static and fatigue strength; rotor mass in general (which has implications for the massive tower, the structure of the tower and foundations); stiffness of the blades (necessary to ensure clearance between the blade tip and the wind tower), transportability of the blade and tower.**

***Index Terms*—Material composition, Cost material analysis, Wind turbine blade, ENERCON.**

I. INTRODUCTION

Over the centuries, energy has been supplied by different sources like wood, coal, etc. At the same time there is an increasing concern about the pollution of the world/environment (generation of waste). This has led to a focus on a sustainable energy supply, which implies optimized use of energy, minimized pollution and, implicitly, reduction in energy consumption. These aspects have led to an increasing focus on short-time stored energy resources; among these the most developed types today are wind energy and biomass. For wind energy a converter is needed to turn the kinetic wind energy into operational energy, e.g., electricity. The converter is basically a rotor driven by the wind. The rotor needs some sort of a device, e.g., a wing or rotor blade to be able to rotate. The rotor is typically placed on a tower, and this converter is usually called a wind turbine (in the past, a wind mill) [1]. The blades of a wind turbine are subjected to laboratory testing and bent using a loop near the natural frequency of the same. The purpose of testing the rotor blades to verify that the paddle blades are secure and that the fibers do not break down with repetitive strain. After this test the blades are subjected to the static test are subjected to bending only one with a very high strength, to test the resistance that was after a long operation time.

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 I. In addition there are foundations and conventional ground-mounted systems, including transformers, switching and other power equipment.

TABLE I
TURBINE COMPONENT WEIGHT AND COST

Component	% of Machine Weight	% of Machine Cost
Rotor	10-14	20-30
Nacelle and machinery, less	25-40	25
Gearbox and drivetrain	5-15	10-15
Generator systems	2-6	5-15
Weight on Top of Tower	35-50	N/A
Tower	30-65	10-25

Source*: Rajadurai and Thanigaiyarasu [1]*

A material is that out of which anything is or may be made. Many factors affect the material selection. They are properties of materials, performance requirements, material's reliability, safety, physical attributes, environmental conditions, availability, disposability, recyclability, and finally economic factors. Among these properties, *(1)* one of the most important factors affecting selection of materials for engineering design is the properties of the materials. The important properties of the materials are mechanical, thermal, chemical properties,

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Manuscript received September 20, 2011. This work was supported in part by the State Government of Maranhão through Foundation for Research and Technological and Scientific Development of Maranhão (FAPEMA) – Brazil under PhD scholarship (BD-00007/08) and Economics Department of University of Aveiro.

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etc.; *(2)* the material of which a part is composed must be capable of performing a part's function (always it must be possible or not) without failure; *(3)* a material in a given application must be reliable; (4) a material must safely perform its function; (5) physical attributes such as configuration, size, weight, and appearance sometimes also serve functional requirements; *(6)* the environment in which a product operates strongly influences service performance; *(7)* a material must be readily available, and available in large enough quantity for the intended application; *(8)* the cost of the materials and the cost of processing the materials into the product or part [1-3].

Rotor blades have historically been made of wood, but because of its sensitivity to moisture and processing costs modern materials such as glass fiber reinforced plastic (GFRP), carbon fiber reinforced plastic (CFRP), steel and aluminum are replacing the traditional wooden units. Wood is a composite of cellulose and lignin. Wood finds many engineering applications and has long been a common construction material. Woods are potentially interesting because of their low density, but their rather low stiffness makes it difficult to limit the (elastic) deflections for very large rotor blades. Even wood materials with cellulosic fibers all aligned in the major load-bearing directions are close to the maximum performance possible for wood. Furthermore, wood is a natural material and thus environmentally attractive, but at the same time difficult to obtain in reproducible and high quality, which is a requirement for stable and economical manufacturing of rotor blades and thus economically attractive wind energy [4].

Most modern rotor has two or three blades. American designers have chosen two blades usually based on the argument that the cost of two blades is less than three. Others, especially the Danes, they argue that the extra cost of the third blade is offset by softer dynamic behavior of three rotor blades, and that the total cost of the turbine is virtually identical whether you use two or three blades. A three-blade rotor provides lower torque oscillations in the shaft, which simplifies the mechanical transmission [5]. If a two-bladed rotor is chosen - at least for large wind turbines - it is usual to have articulated the rotor, which is, allowing a few degrees of motion perpendicular to the axis of rotation. With an articulated hub, each blade, while passing through the top of the circle of rotation - where the wind speed is higher due to the vertical gradient - moves back a bit, while the other man, in the course of the circle of rotation - where the wind is less - they move forward. This move greatly relieves joint tension at the root of the blades, and the resulting cost / benefit more than offsets the extra cost of the joint hub. As the weight of the blades at the root introduces cyclic loading (in the plane of rotation), and also penalizes the structure of the tower, the blades must meet the criterion of minimum weight, fatigue resistance and structural rigidity [6].

For large commercial machines, the upwind, three-bladed rotor is the industry-accepted configuration. Virtually all large machines installed during the last several years are of this configuration. The three-bladed rotor offers the following advantages over the two-bladed configuration. Although the upwind choice is based largely on noise considerations, it also results in lower blade fatigue. Tower-shadow noise and impulsive blade loading for an upwind rotor are less than for a downwind rotor that passes through the tower wake. For an upwind rotor, the blade-number choice is then a balance among blade stiffness for tower clearance, aerodynamic efficiency, and tower-shadow impulsive noise. The three-bladed rotor configuration appears to provide the best balance [7]. Modern rotors with more than three blades are used only when you need a large starting torque, which is basically the case of mechanical pumping of water. By the look streamlined, however, a large number of blades and high starting torque imply lower efficiency. The rotor must be made with very sturdy, accurate airfoils, good surface finishing, which are required to maximize aerodynamic efficiency [8].

Most modern rotor blades of large wind turbines are made of plastic reinforced with fiberglass or polyester or epoxy fiberglass. Another possibility is to use carbon fiber as reinforcement material. This possibility is uneconomic for large wind turbines. Materials such as wood, wood-fiber-epoxy are under development. The steel and aluminum have weight problems and fatigue. Currently it is used in small wind turbines.

II. PRINCIPLES FOR DEVELOPMENT OF BLADES

The basic principles for the construction of blades for wind turbines are summarized [9] as follows: *(1)* maximize the annual energy yield for a given set of wind conditions, e.g. as specified by IEC Standard 61400-1 [10]; *(2)* limit the maximum loss of energy (usually by controlling pitch and / or stall - aerodynamics); *(3)* surviving extreme static loads and fatigue during the nominal lifetime (usually 15-20 years); *(4)* limit deflection of the tip, to avoid the impact of the tower (from the wind turbines); *(5)* avoid the potential resonance conditions; *(6)* minimize weight and cost relation.

The higher the wind turbine, it becomes more critical the issue of weight and blade fatigue load, because the total weight of the rotor is characterized effectively in the rest of the structure and foundations of the tower to avoid the effect of weight and load throughout the structure. The blades of large wind turbines are typically manufactured with thin covers of composite materials. Fiberglass/epoxy laminate and wood/epoxy materials are frequently used, but carbon fiber has been enhanced at critical sections. The blades are usually built from multiple parts to be superimposed on different templates and then being stuck - part of the compression part of traction, shearing and blankets [11].

The external geometry is fairly complex surfaces made of three-dimensional (3D) resulting from the wing sections together with varying torsion angles, lengths of wire, and the local pitch axis. For the internal structure, manufacturing methods often result in thick adhesive joints in key structural locations.

The blades must be able to survive a static peak load usually calculated based on a 50-year period for gusts of wind. The fatigue strength of a 20 year cycle implies cycles in the order of 4 x 10^8 [7]. The load to be supported by the blades is a complex issue, consisting of aerodynamic forces, rotational forces, and gravity loads. The aerodynamic loads include the effects of variation of average wind speed (spatial and temporal) - including the wind shear from the top to the bottom of the turbine, the tower shadow effect, and shaft misalignment - turbulence and effect belt upstream turbines.

Projecting the blades involves the application of material data used in tests of wind turbines Smaller and extrapolating them to design a large, complex, where the experiences of multi-material load conditions. A key area of concern is the adhesive bond between distinct substructures within the shovels, and appropriate characterization and modeling of these areas or sections of the blades of modern wind turbines.

The blade manufacturing standards prohibit current material and structural safety factors to accommodate the uncertainty inherent in the design process. In addition, the complete battery of tests of the blades is used to certify the designs for static and fatigue generally (though with a charge distribution rather artificial and accelerated life testing). The modeling of the blades is a useful tool for understanding the complexity of the charge distribution, the mapping of regions of high voltage and to identify regions of critical flaws (Fig. 1). It can also be applied to evaluate the potential of new materials and innovative design concepts.

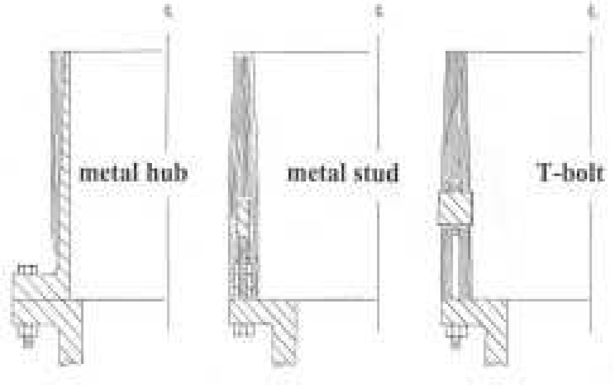


Fig.1. Regions of critical flaws in blades [7]

According to Tangler [7] a critical design region of any blade is the hub attachment. Blade-root joint designs used over the years have been strongly driven by cost, which typically represents 20% of the blade cost. Of the various hub types used in the 1980s, the tapered metal root cylinder hub has survived in various forms. Vestas, the largest manufacturer of wind turbines, fabricates their blades with an aluminum root cylinder. An example of this root design and other current design approaches are seen in Fig. 1. Over the last several years, the embedded-metal-stud and T-bolt designs have become more popular in new blade designs. The metal stud root, which originated with the wood composite blade, is now used with fiberglass blades. The metal-hub and metal-stud root joint result in the fiberglass being mainly in tension. For the T-bolt root joint, fiberglass inboard of the circular bolt is in compression while that outboard is in tension. Both the metal-stud and T-bolt designs have the advantage of using a larger blade-root diameter for a given hub flange diameter, which results in a more structurally efficient blade-root joint.

A. Current trends in blade manufacturing

A large number of turbine system manufacturers are currently moving toward in-house production of their own blades, and in doing so are using diverse materials and manufacturing methods. Nordex and GE Wind have both built blades in the 40-50 m length range using hand lay-up of primarily fiberglass structure in open-mold, wet processes. NEG Micon is building 40 m blades with carbon augmented wood-epoxy. Vestas has a long history of manufacturing with prepreg fiberglass. TPI Composites is manufacturing 30 m blades using their SCRIMPTM vacuum-assisted resin transfer molding (VARTM) process. Among the more novel approaches in current use for large blades is by Bonus, where blades 30 m and greater are being produced from a dry preform with a single-shot infusion, eliminating the need for secondary bonding [3].

B. Manufacturing Alternatives

Although several manufacturers are still using open mold, wet lay-up processes and increasingly stringent environmental restrictions will likely result in a move toward processes with lower emissions. In current production, two methods are emerging as the most common replacement for traditional methods. These are the use of preimpregnated materials and resin infusion, with VARTM being the most common infusion method. Both VARTM and prepreg materials have particular design challenges for manufacturing the relatively thick laminate typical of large wind turbine blades. For VARTM processes, the permeability of the dry preform determines the rate of resin penetration through the material thickness. For prepreg material, sufficient bleeding is required to avoid resin-rich areas and eliminate voids from trapped gasses. Another promising alternative is partially preimpregnated fabric, marketed by SP Systems under the name SPRINT and by Hexcel Composites as HexFIT. When layed-up, the dry fabric regions provide paths for air to flow, and vacuum can be used to evacuate the part prior to heating. Under heat and pressure, the resin flows into the dry fabric regions to complete the impregnation [3].

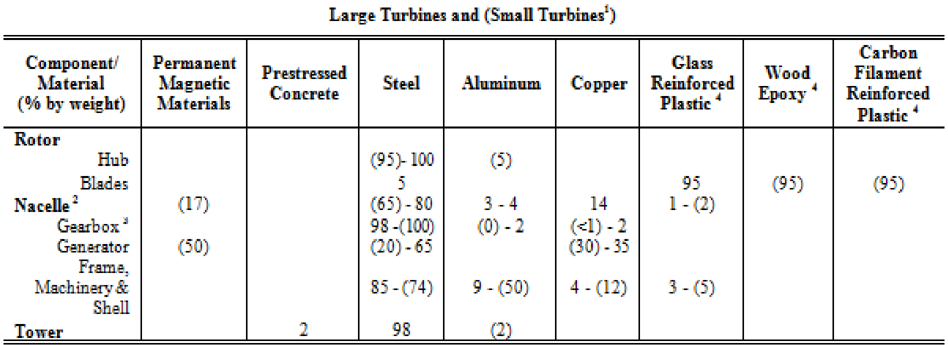
An elevated temperature post-cure is desirable for both prepreg and VARTM processes. Current commercial prepreg materials generally require higher cure temperatures (90°-110°C) than epoxies used in VARTM processes (60°-65°C). Heating and temperature control/monitoring becomes increasingly difficult as laminate thickness is increased. Mold and tooling costs are also strongly affected by the heat requirements of the cure cycle. In all cases, achieving the desired laminate quality requires a trade-off between the extent of fiber compaction, fabric/preform architecture, resin viscosity, and the time/temperature profile of the infusion and cure cycles. The use of automated preforming and automated lay-up technologies are also potential alternatives to hand layup in the blade molds. Benefits could include improved quality control in fiber/fabric placement and a decrease in both hand labor and production cycle times [4].

Further economies may be realized if the carbon fibers can be processed into a form that favors both structural performance and manufacturing efficiency. Much of the composites industry literature and advertising concerning "affordable" or "low-cost" processes are based on an aerospace perspective. The price point established by the current commercial manufacturing of wind turbine blades is very low compared with other composite structures, particularly for composites with relatively demanding aerodynamic and structural design considerations [13]. These price points have been realized within the wind industry through substantial fine-tuning of the current manufacturing methods, and are based on well-established properties and performance for the baseline materials and structural design [2, 14].

III. PRODUCT CHARACTERIZATION

Specially designed for medium wind speeds, the turbine Enercon E-82 - with the new design of the blade and tower versions up to 108 meter tall, has excellent performance with a power of 2 MW. The technical specifications of the turbine are summarized in Table II.

TABLE III
WEIGHT AS A PERCENTAGE OF MATERIALS USED



Large Turbines and (Small Turbines[1])

Component/ Material (% by weight)	Permanent Magnetic Materials	Prestressed 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 .
Source: Ancona & McVeigh [12].

For a better characterization of the constituent materials of the blades of the turbine in analysis according to Ancona & McVeigh [12], were considered the same percentage of materials used in the existing components of a typical wind turbine (Table III).

As reported in Table II, the manufacturer Wobben Windpower/ENERCON E-82 model is made of GRP and has an approximate weight of 6.9 t, which results in a weight of 2.3 t for each turbine blade in question. It may be noted that all three blades uses 0.345 t of steel (345 kg) and 6.555 t of GRP. The predominant type of fiber used is the Fiber-E, which has good mechanical properties, but less stiffness and strength of the Fiber-S, which is about ten times the price (Fiber-E of approximately € 2.10 kg; Fiber-S around € 12-20 kg [18]). Generally, the properties inherent to fatigue about Fiber-E are consistent from source to source.

TABLE II
TECHNICAL SPECIFICATIONS OF E-82 WIND TURBINE

Manufacturer	Wobben Windpower/ENERCON GmbH
Model	E-82
Rated power	2.000 kW
Rotor diameter	82 m
Rotor shaft height	78-138 m (tower tubular steel or concrete foundations and different)
Rotor with active control of blade pitch angle	
Type	*Upwind*
Direction of rotation	Clockwise
Number of blades	3 (40 m each)
Swept area	5.281 m^2
Material of blades	GRP (epoxy resin)
Weight of the blades (approx)	6.9 t
Rotor speed	Variable, (6 – 19.5 rpm)
Cut-in	2 $m.s^{-1}$
Cut-off	28-34 $m.s^{-1}$

Source: ENERCON GmbH [17].

TABLE IV
MECHANICAL PROPERTIES OF MATERIALS

Material Type	Tensile Str (Mpa)	Tensile Modelus (GPa)	Typical Density (g/cc)	Specific Modulus
Carbon HS	3500	160-270	1.8	90-150
Carbon IM	5300	270-325	1.8	150-180
Carbon HM	3500	325-440	1.8	180-240
Carbon UHM	2000	440+	2.0	200+
Aramid LM	3600	60	1.45	40
Aramid HM	3100	120	1.45	80
Aramid UHM	3400	180	1.47	120
Glass – E glass	2400	69	2.5	27
Glass – S2 glass	3450	89	2.5	34
Glass – quartz	3700	69	2.2	31
Aluminum Alloy (7020)	400	69	2.7	26
Titanium	950	110	4.5	24
Mild Steel (55 Grade)	450	205	7.8	26
Stainless Steel (A5-80)	800	196	7.8	25
HS Steel (17/4 H900)	1241	197	7.8	25

Source*: DOE and EWEA [15, 16].*

Laminated carbon fiber reinforced blades for wind turbines are more limited by the compressive strength and ultimate pressure. Moreover, the presence of even smaller amounts of misalignment of the fibers has been shown to reduce static and fatigue properties significantly. Property of maximum compression is achieved with laminates that have the straight track fiber, usually unidirectional pre-impregnated [19].

Additional criteria are not always recognized within the industry, such as reliability, noise, and aesthetic considerations. Based on these criteria, the configuration of choice by wind industry in recent years has been in three-blade rotor, due to its moderate size, lightweight, two-bladed rotors with swing.

As reported in Table II, according to the manufacturer Wobben Windpower/ENERCON E-82 model is made of GRP and has a weight of 6.555 tons of GRP. In analyzing the approximate cost to the Fiber-E, would have been € 6.555 was used and the Fiber-S (S2) the amount would be around € 78.660. The terms of the indicators of the mechanical properties, Young's Modulus (GPa) and tensile strength (MPa), one can conclude that the substitution of Fiber-E for fiber-S would increase the tensile strength of 43.8%, but for Young's Modulus would be only 24.6%, (see Table IV).

When considering the gains in mechanical properties compared to two types of material analyzed (Fiber-E and Fiber-S) and the increase in costs in the order of 1.100%, is justified that the equation to be solved for the blades of wind turbines is the ratio weight-resistance-cost. This situation can be confirm by Rajadurai & Thanigaiyarasu [1] whereby in an increasing cost order E-glass is the cheapest, Aramid fiber is of moderate cost and the carbon fiber is the most expensive of all. It is a simple matter to devise materials performance indices for the various modes of loading where either mass or cost are to be minimized.

IV. DISCUSSION AND CONCLUSIONS

These are a crucial component, requiring sophisticated production techniques. Global supply used to be dominated by an independent blade maker, although many major turbine manufacturers produce their own blades. There is no shortage of supply at present, but the availability and price of carbon fiber – a major sub-component for large blades – remains a problem. Several carbon companies have entered the wind energy market to address this problem [20]. There is a strong quest to develop new components in the days that will significantly alter current patterns of media use. Usually there are trends of lighter materials, while the cost of the life cycle is low.

The blades are exposed to the wind that through the lift on the aerodynamic profile causes loads at right angle to the blades, which therefore react by bending flap-wise. These loads are both static, causing a permanent bending of the blades, and dynamic, causing a fatigue flap-wise bending because of the natural variations in wind speed. In addition, these static and fatigue load spectra vary during rotation, as seen by a given blade, when the blade points upward and downward, respectively; this is caused by the natural wind shear, which is the increase of average wind speed with increasing height over the terrain [21]. Most rotor blades in working today are built from plastic reinforced with fiberglass (GRP - Glass-Reinforced Plastic). Other materials that have been tested including steel, plastic and various composites reinforced with carbon fiber (CFRP - Carbon Fiber Reinforced Plastic) (Fig. 2). As you increase the size of the rotor in larger machines, the tendency is to increase the fatigue resistance of materials. As the turbines are continually evolving, compounds involving steel, GRP, CFRP and possibly other materials will be in use.

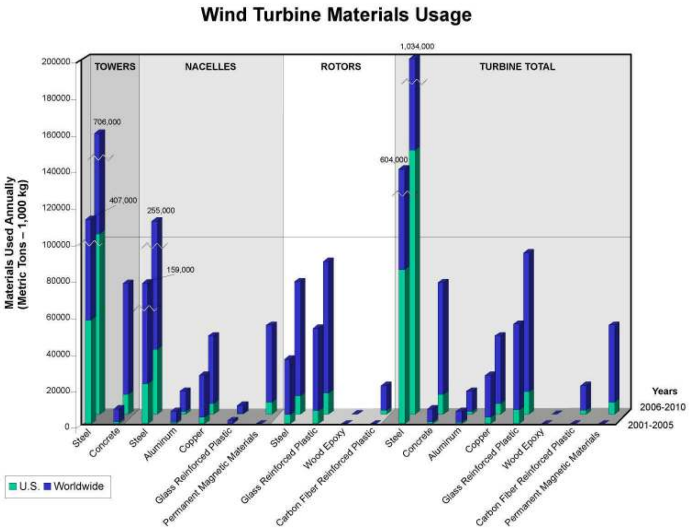


Fig .2. Wind turbine material usage [7]

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

1. Use of materials of turbine is and will continue to be dominated by steel, but there are opportunities for the introduction of aluminum or other compounds of low weight, long and fatigue strength requirements can be met.
2. Small volume production of the turbine is increasing rapidly which can be accommodated by mechanized production and innovation that will reduce costs.
3. Elimination of the gearbox using variable speed generators will increase through the use of permanent magnetic generators in larger turbines increasing the need for magnetic materials.
4. The blades were primarily made of GRP, and it is expected to continue. Although the use of CFRP can help reduce weight and cost, low cost and reliability are the main drivers.
5. Increase the use of offshore applications may partially offset this trend toward the use of composite materials.
6. Epoxy wood, used at the beginning of the production of blades, is not expected to be the material of choice

despite the excellent fatigue properties.

7. Manufacture of components for wind turbines and represent major business opportunities and tend to expand at least the next 10 years.
8. The largest market for wind turbine systems and materials in the future will be outside North America and Europe, but this market is developing slower.

Most turbine blade designs use E-glass. Its stronger cousin is S-glass. This specialty glass fiber, originally designed for marine applications, has significantly better properties than E-glass, but its higher cost has limited its use in turbine blades. However, as rotor size increases, the enhanced properties of S-glass offer an alternative to carbon fibers. It provides most of the benefit of carbon without the very high cost. Moreover, with the mass production of the fibers required by the turbine blade industry, the cost of S-glass will come down significantly [22].

To keep blade weight growth below the cubic power of radius, designers have reduced margins, incorporated new materials, used more efficient manufacturing processes and explored innovative design concepts. Meanwhile, blades have maintained a design fatigue life of 20–30 years within the constraints of certification load and material safety factors. Ongoing research topics include the optimal use of commercial carbon fibers, load mitigation through aeroelastic tailoring, development of improved blade design criteria, and innovative blade geometry. New trends include the use of carbon and carbon hybrid materials and longer blades, more slender in the chord direction, with higher-thickness aerofoils for increased structural efficiency [23]. If low-cost commercial-grade advanced materials, such as carbon fiber, become available in reliable quantities with guaranteed long-term pricing, blade design will change from heavy blades using low-cost glass to lightweight blades using higher-cost carbon.

The trends for rotor blades are for increasing size and, most critical, reduced weight. This couples with the ever-increasing size of turbines, which are supposed to deliver reduced costs for wind energy (cost/kWh). The materials and, in particular, composites are important elements in this development because they deliver low density, good stiffness, and potentially long lifetimes. New trends in the materials occur with respect to properties, design, and monitoring, as well as manufacturing technology. Today's markets are worldwide, with suppliers of wind turbines mainly located in Europe (72%), with activities in United States (18%) and Asia (10%). The wind turbines are generally being placed off-shore in parks or farms, both to exploit the more free and generally stronger winds and also to reduce the environmental effects on land [24].

In order to meet the challenge as wind turbine blades grow longer and to allow for the next generation of larger wind turbines with intelligent blades, higher demands are placed on materials and structures. This requires more thorough knowledge of materials and safety factors, as well as further investigation into new materials. Furthermore, a change in the whole concept of structural safety of the blade is required. Kensche [25] reviewed the trends in the fatigue investigations of materials for wind turbines. He points out that many topics remain to be explored. In particular, there should be a focus on the basic understanding of damage and failure mechanism, effects and interpretation of the stochastic loadings, multiple stress states, environmental effects, size effects, and thickness effects. New initiatives are in progress in the field of condition monitoring (structural health monitoring), and several manufacturers of wind turbine blades are already fitting the blades with sensors. The challenge is to be better able to interpret the signals and to know the actions to take. This requires an even better basic understanding of the life cycle behavior and the degradation mechanisms.

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