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Wind Power: the Material Requirements

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Tämän selvityksen tarkoituksena oli selvittää, mitä materiaaliteknisiä vaatimuksia tuulivoiman käytössä on. Lisäksi tutkittiin, miten ulkoiset vaikutukset (muun muassa sääolosuhteet) muuttavat näitä vaatimuksia. Työssä ei oteta kantaa tuulivoimayksiköiden sisäisiin mekanismeihin tai niiden materiaaliteknisiin vaatimuksiin. Ilmastollisia vaikutuksia on myös pyritty huomioimaan, esimerkiksi ilman epäpuhtauksia.

Pääpaino työssä oli selvittää tuulivoimayksiköiden kolmen pääosan (torni, kehiö ja siivet) materiaaleja. Lisäksi tutkittiin kolmen pääosan materiaalien vaatimuksien muuttumista sijainnin muuttuessa maalta vesistöön tai sellaisen läheisyyteen.

Tutkimuksessa keskityttiin yleisesti käytettäviin materiaaleihin, myös tulevaisuudessa käytettäviä materiaaleja on hieman tarkasteltu. Materiaali tähän selvitykseen etsittiin sekä kirjastoista että erilaisista tietokannoista Internetissä.

Selvityksen tuloksena voidaan todeta, että jo pitkään käytetyt materiaalit, kuten teräs, ovat yhä hyvin käytettyjä. Lisäksi erilaiset komposiittimateriaalit ovat yleisesti käytettyjä.

Asiasanat: tuulienergia, materiaalitekniikka, uusiutuvat energianlähteet, ekoenergia

SEINÄJOKI UNIVERSITY OF APPLIED SCIENCES

Thesis abstract

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The purpose of this thesis was to study what are the material requirements for wind power units. It was also studied how external influences, such as weather conditions, alter these requirements. In addition to ordinary weather conditions, it was studied what kind of particles and other impurities are in the air, and how these might affect a wind power unit.

The main focus of this thesis was to study the different materials used in the construction of wind power units and the requirements each main section (tower, nacelle and blades) have for the materials used. It was also studied how these requirements changed when the unit was constructed in or near a body of water.

In addition to the above, the materials commonly used at the time to writing were studied in this thesis. A small part of this thesis is given to the study of next generation materials. The material for this study was searched from libraries and from databases in the internet.

The study revealed that the use of old materials, such as steel, is very common. Also, different kinds of composite materials are commonly used.

Keywords: wind energy, material technology, renewable energy sources, eco energy

CONTENTS

USED TERMS AND ABBREVIATIONS

Wind Turbine Unit	*A single wind power plant*
Blade	*The blade of a wind power plant*
Wing	*The same as blade*
HSLA	*High-Strength, Low-Alloy steel or steels*
ASTM	*American Society for Testing and Materials*
AISI	*American Iron and Steel Association*
UNS	*Uniform Numbering System*
Concrete	*Composite material consisting of an aggregate of particles, bound together in a solid body by some type of binding substance, which is, cement*
Cement	*Substance that binds together the aggregate particles in a solid body*
THM	*Top Head Mass. The combined mass of all the elements found in the nacelle, nacelle itself and the rotors of a wind turbine*
PMEL	*Pacific Marine Environmental Laboratory. An American maritime research institute*

NOAA	*National Oceanic and Atmospheric Administration. An American research institute*

LIST OF GRAPHS AND TABLES

1 THE HISTORY OF WIND POWER

1.1 Non-electric usage

The first uses of wind power were to make trade, not all that much different than its use now. However, unlike today, the first wind power uses were in a sailing boat, some 5000 to 6000 BC (Carter 2006, 2).

This was around Persian Gulf, between the Ubaid communities in southern Mesopotamia and the groups of Arabian Neolithic located in the eastern Arabia (Carter 2006, 2).

So, wind power has long traditions, perhaps the most notable of them being both the treks of the Vikings as well as those of the Romans hundreds of years ago.

Wind power was very used in later periods, as well. In the Europe, they used to grind grain and pump water using wind power in the 18th and 19th century (Patel 2006, 11).

Between the early history of wind power and today, there isn’t all that much in common, as stated before. Using wind power to grind grain or pump water is much closer to the usage of wind power today, than powering our ships to do trade. Even though in both examples wind power is used to do the mechanical work, in the subject of pumping water for example, we have all the basics of a modern wind power plant, transforming wind energy into mechanical work. Nowadays, we use wind power to power our robots, our factories and our computers, which in turn, do the actual work.

1.2 The electric use

The electric use of wind power started in 1887, when a Scottish electrical engineer and teacher James Blyth built a wind power plant to power the garden lights in his holiday cottage, as well as the lighting in the cottage itself. That cottage was the first house ever to be powered by wind. (Price 2010.)

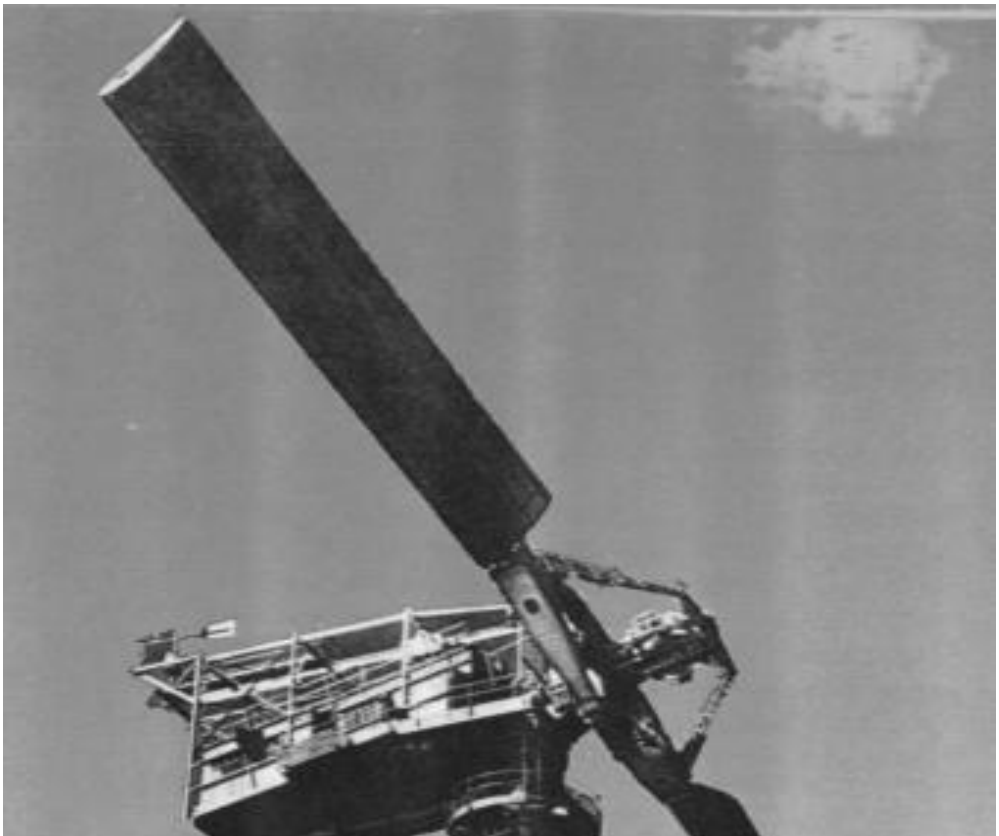
Although some experiments were made between the end of 1800s and the end of 1970, for example the basic design for rotor models used even today and the first wind turbine factory, wind power usage was low. Even with the production of the first megawatt grade wind power plant in Castleton, Vermont, USA. (Patel 2006, 9.)

The modern usage of wind power, started by James Blyth, is a fairly new idea, at least in the scale it is used today. Before the end of 1970, wind power was thought of being unreliable and, especially, ineffective way to produce energy (Patel 2006, 10). There were two bigger projects, however, that lead the way for modern wind power plants. In 1979, an experimental 2 megawatt wind power unit was built in Howard Knob Mountain, near the city of Boone in North Carolina, USA, and in 1988 when a 3-MW unit was installed Berger Hill, Orkney, Scotland. (Patel 2006, 11.)

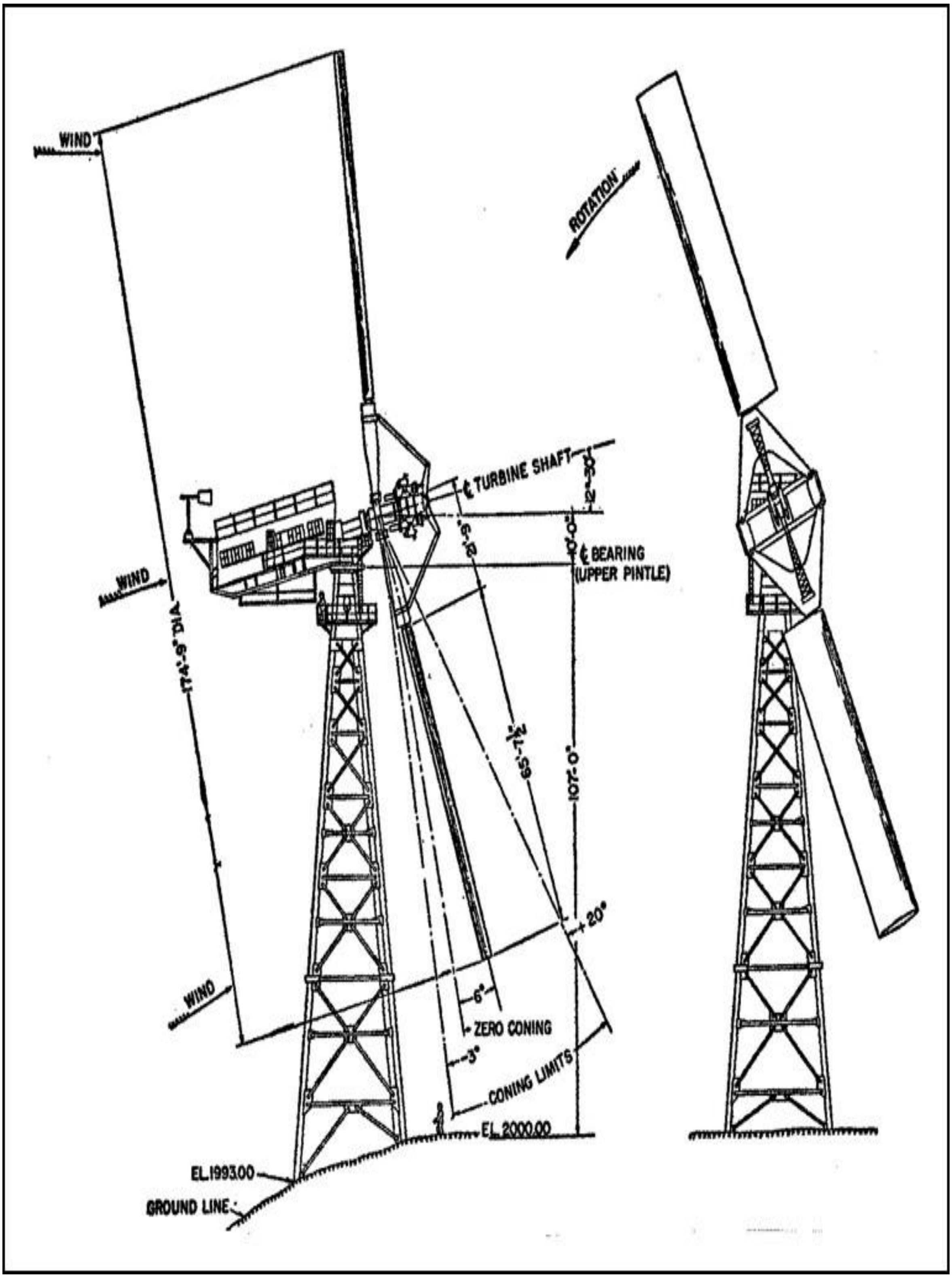
1.3 The historical design

The design of a wind power plant, or a unit, has been pretty much the same throughout the years. On the top, there is a turning top piece that holds all the “internal” parts, such as sensory equipment, brakes and transmissions, and the tower (Patel 2006, 26.)

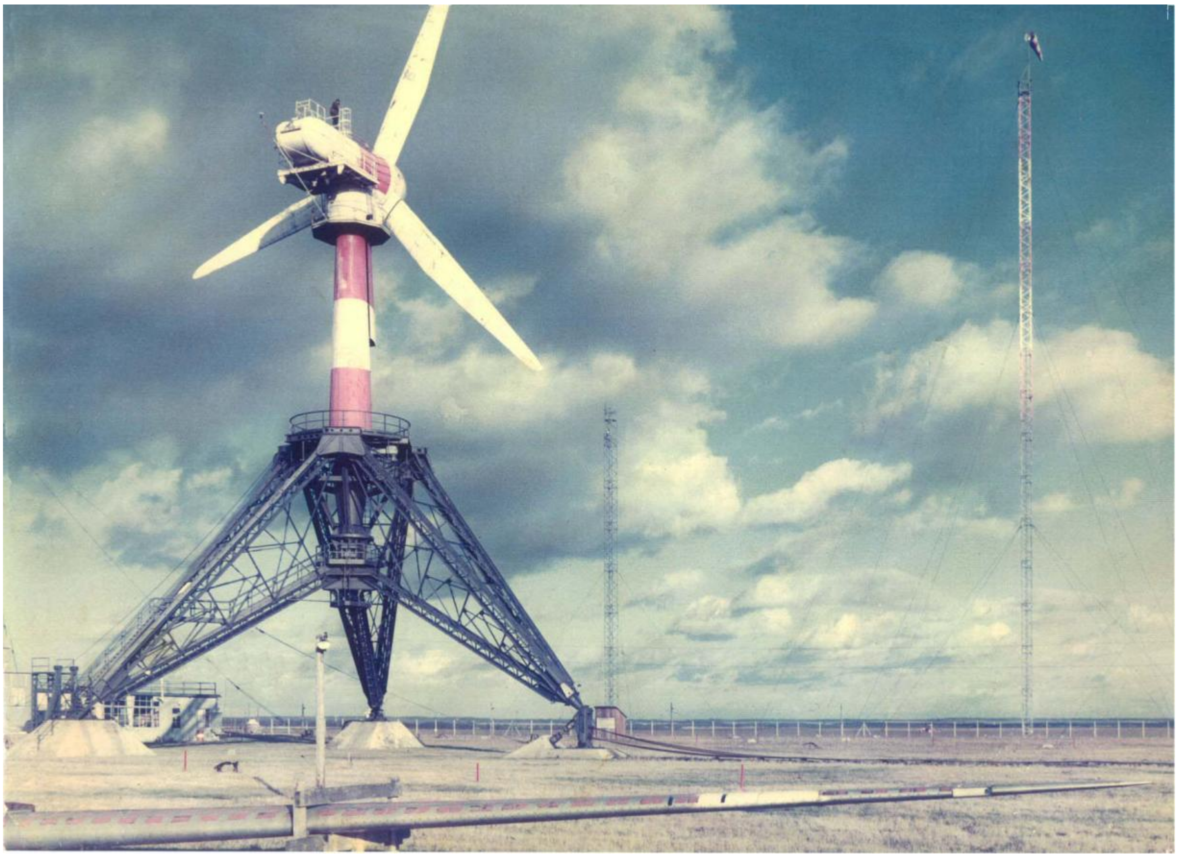
Because a picture says more than a thousand words, I have gathered some pictures below that show the reader exactly what I am talking about.



Picture 1: Smith-Putnam wind turbine. (Integener.com, 2010.)



Picture 2: Sketch or a drawing for the Smith-Putnam wind turbine. (Putnam 1982, 112.)



Picture 3: Nogent-Le-Roi wind turbine, France. (Eolienne.cavey.org, 1958.)

Bundesarchiv, Bild 183-1989-0525-004
Foto: Sindermann, Jürgen | Mai 1989

Picture 4: Rostock, East Germany. (Bild, 1989.)

Picture 5: Mod-2, Washington, USA, 1981. (grcimagenet.grc.nasa.gov, 2006.)

Picture 6: Modern wind turbines. (www.wind-energy-the-facts.org 2010.)

As you can see from the aforementioned pictures, the basic design has roughly been the same throughout the years, with the modern units seen with both two and three rotor blades.

2 THE MODERN DESIGN

Even though there are a number of designs nowadays, there are a few common factors as well. One could say that the basic design is the same in all modern wind power units.

These common parts are as follow:

- Tower structure
- Rotor with two or three blades attached to the hub
- Shaft with mechanical gear
- Electrical generator
- Yaw mechanism, for example a tail vane
- Sensors and control. (Patel 2006, 61.)

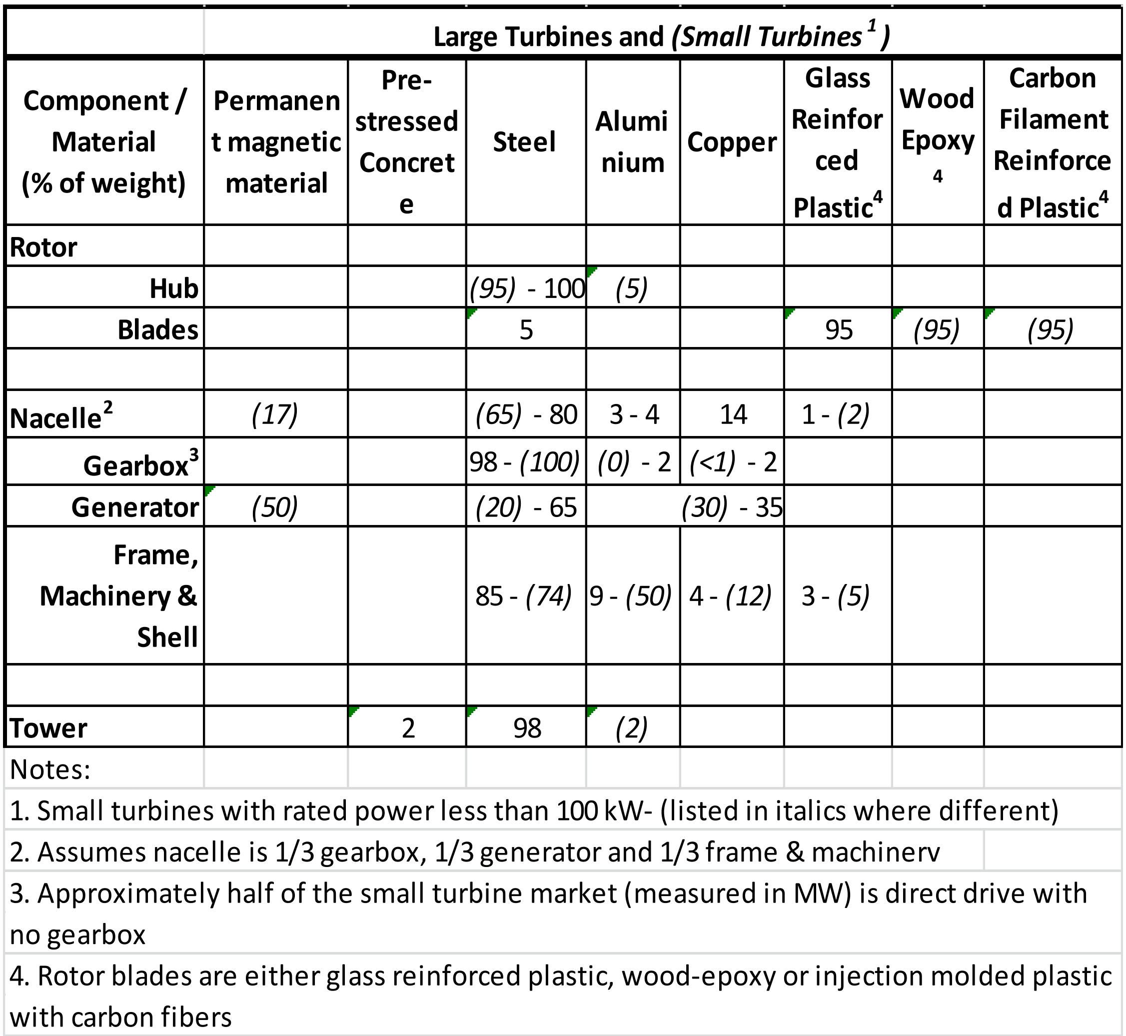
In addition, or including, in those previously stated, each unit also has great many auxiliary systems, such as brakes, start and stop control and speed-control for production purposes. (Patel 2006, 61.)

To truly appreciate the engineering of wind turbine systems, one must first understand the requirements of said units.

For example, the expected life of a wind power unit is 30 years. Because of that time, and well as the nature of the construction, many parts in a unit must withstand tremendous amounts of stress cycles, 4×10^8 fatigue stress cycles to be more exact. Not even aircraft or automobile engines or even bridges have this high stress rates, making the wind turbine units one of the most challenging constructions made by man. (Ancona & McVeigh, 2001, 5.)

All this, combined with the fact that weather has a great impact on the functionality, productivity, maintenance requirements, cost and, indeed, the very lifespan of any given wind turbine unit makes the material selection for them extremely important. Below is a chart (1), which has the percentages of small and large, but not medium sized, wind turbine units.

Chart 1. Material usage and distribution of large and small wind turbines.



	Large Turbines and *(Small Turbines[1])*							
Component / Material (% of weight)	**Permanent magnetic material**	**Pre-stressed Concrete**	**Steel**	**Aluminium**	**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 & machinerv

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 & McVeight 2001, 5.

The difficulty in material selection for wind power units does not lie in the small- and medium-sized turbines. The new units, going up to 6 MW, are so large that and require so high-performance materials that more traditional materials cannot be used. Therefore new materials must be introduced. Traditionally, the blades are made from glass reinforced composite. Glass reinforced composite is an excellent material in many ways, but for the biggest units being built today, glass is no longer a viable material. Since the requirements for blades rise, so must the materials used in making them be of higher quality. Insert the carbon reinforced composites. Much more expensive but have many qualities that glass reinforced composites lack, weight being one of the most important ones. (Marsh 2003, 2.)

Material requirements for modern wind power units. As stated before, wind power units face tremendous stress factors, but they are not the only things which must be taken into account when designing a modern wind power unit. Modern wind power units must be able to handle extreme winds and gusts, even as much 100 mph or more. The stiffness in them must be tailored so, that there is no chance for bending that damages the unit, resonance frequencies must be avoided, they must resist erosion from rain, grit, dust and salt (in the coastal and offshore systems). Not to mention a very potent environmental enemy any plastic has, the UV radiation in sunlight. (Mash 2003, 3.)

This being said, one must remember where the best location for wind power turbines is, and that is in the ocean. Offshore wind farms are in the most hostile environment for wind power units, being exposed to waves, sunlight, ice, currents and storms, as well as those dangers listed in the previous paragraph. From these examples, the wave force is the greatest threat. The general structure of the wind turbine tower must be able to absorb, deflect and dissipate all the energy from continuous wave forces for 20 to as long as 50 years. (Patel 2006, 133 – 134.)

In order to make this issue, or issues, more easily comprehended and easier to solve, the unit is broken into three parts: the blades, the nacelle and the tower.

Blades. The blades have been originally made from the natural composite, wood (hemicellulose fibers in a lignin matrix). Wood is easy to machine or laminate into the required forms. In the 1980s wood was the natural choice, but in the last 30 years composite materials have taken huge leaps and nowadays there are materials far superior to wood available, holding more consistent properties, higher specific strengths and easier molding to optimal aerodynamic shapes, these being only part of the reasons why synthetic composite materials have surpassed wood as the prime blade material. Although some manufacturers, such as NEG Micon Rotors, remain faithful to wood, its use in modern wind power units is more in combination with modern, synthetic composites. (Mash 2003, 1.)

Glass reinforced composites have been very widely used in blades for a long time, because of the many good properties glass-fiber composites have, they are not high-performance enough for the ultra-large blades made today. New materials had to be sought; the answer was carbon-fiber based composites. LM Glassfiber, a company in Denmark which claims roughly 40% of the worlds blade production, keep using glass-fiber as long as they can, as said in a comment from LM group manager of marketing Steen Broust Nielsen, “*We know it’s possible to produce ultra-large blades by using a lot of carbon. The trick is to do it without. We’re applying smart engineering rather than expensive materials. We believe in extending the envelope of lower-grade materials into higher-performance areas so that wind power costs can continue to be driven down*”. (Mash 2003, 2.)

All in all, the blade materials used in modern medium- to ultra-large wind power units are made from a variety of different composites, including carbon- and glass-fiber based composites. These materials have the necessary strengths, lightweight and many other vital properties needed for a wind power unit rotor blade.

The most commonly used composite material is glass-fiber based composites, because of their ease in shaping and the price. Although carbon-fiber based composites can be used as well, the price and some technological reasons prevent their wide-spread use in a modern wind power unit rotor blade. (Kenche 2006, 11.)

Nacelle. The nacelle, which contains most of the mechanics in a wind power unit such as gearbox and brakes, is usually made of steel but sometimes from copper. In rare cases, the nacelle is made from aluminum. For the nacelle, there are a lot of possibilities for innovation because of the limited options for nacelle material now used. (Ancona & McVeigh 2001, 6.) Some of these innovations are coming in the form of composite materials, as will be shown later.

Tower. The tower is a very crucial element in a wind power unit, giving the top-section the height it needs to be effective. Because of the simple facts of physics (leverage and momentum), the tower needs to be made from a very strong material that is cheap. That material is steel and steel reinforced concrete. Cost is a big issue here, because the tower can represent over 60% of the total materials needed for a wind power unit, although according to Danish wind energy association, the tower is usually around 20 % of the total cost of a wind turbine (Danish Wind Energy Association, referred 29.07.2010). There are two options at the moment for the tower. The other is that the tower is made more or less purely of steel, and the other is concrete towers, but they require almost as much steel as reinforcing material as a steel tower would need. (Ancona & McVeigh 2001, 6.)

3 WIND POWER MATERIALS AND EXTREME WEATHERS

Because roughly 70 % of Earth surface is covered by water and at sea it is always windy one must look to the oceans for a vast amount of wind energy. This also produces a lot of problems. Anchoring the wind power unit is one, corrosion due to salt, for example, is another, not to mention the difficulties in regular maintenance and emergency maintenance and repairs. (Patel 2006, 119 - 139.)

Because of these issues, in this thesis the material requirements are separated for wind power units under extreme weather on land and in sea / water areas.

3.1 Onshore units

The requirements in materials for land based wind power units produces less difficulties than compared to those for offshore units. The reason for this is the eroding nature of the elements that affect the offshore units. The combination of sea water, high solar radiation and constant, usually high, winds, makes the material selection more difficult compared to land units. (Patel 2006, 119 - 135.)

Wind power units located on land can have less rigid anti-corrosion options and they do not need to withstand such winds as offshore units. Land based units, on the other hand, might be exposed to other kinds of both natural and human produced hazards. These hazards include, but does not limit to, earthquakes, vandalism and accidents. (Patel 2006, 119 - 135.)

Because of these less demanding requirements, the tower can be made from the materials listed in Table 1.

Also, the eroding effect of air pollution must be taken into account because of the designed life-cycle of a wind power unit. Unfortunately, there is little scientific data on this matter, but since air pollution accelerates erosion it is only reasonable to consider that air pollution increases the erosion rate of wind power units. This generates the need to implement materials that are resistant to pollution and / or acidic environments to wind power units, thus creating more expensive units. Usually, this is not necessary because of the location of wind power units, since they need to be placed in open areas and, thus, are usually located away from sources of pollution. With the implementation of dispersed energy production this might change in the future. (Qiu & Kumosa 1996, 10.)

Materials that are particularly well suited for land based wind power units are steel, concrete (as well as steel reinforced concrete) and various composite materials, such as glass reinforced composites. These materials are also well suited for offshore units, but for small units, which are always based on land, material selection also includes wood and wood composites. The most challenging of all the material selection for a land based unit is the material for the rotor blade, because this determines how efficiently the energy from the wind can be harvested. (Dalili et al. 2009, 429.)

Due to the increasing need in renewable energy, wind power units are being pushed into climatic zones, that are distinct and each have their own, unique challenge that must be overcome. (Dalili et al. 2009, 429.)

In the following three of these zones are divided into titles of their own.

3.1.1 Northern areas and icing

The effects of icing can vary, but the most severe case of icing is the full stop of the unit. This case is the easiest to define, but since the unit is shut down, practically all operators are willing to go to extreme measures to avoid this occurrence. There are cases which help to understand the severity of this type of icing. For example, in Sweden, the Äppelbo wind turbine was stopped for seven weeks in the winter 2002 - 2003. Between 1998 and 2003, the Swedish statistical incident database reported a total of 1337 ‘stop’ incidents similar to that in Äppelbo. The total downtime that resulted was a massive 161,523 hours.

There are less severe cases, cases where the unit is not shut down, but rather work at a reduced efficiency. As studied, even small amount of icing can result in rotor blade imbalance and loss of aerodynamic properties. These result directly in the loss of efficiency. In very harsh environments the annual power loss can be as much as 20 to 50 %.

Even though on occasions, stall regulated units may experience an increase in power production due to accretion of ice on the rotor blades (which, some believe to be due to the shape of the icing which resembles a leading edge flap), this has undesirable effects on a long-term period. These are the harmful effects on generator and on the blade mechanical health.

Because the icing makes the blades go off balance, the decrease in fatigue life is a serious problem, since it shortens the life-span of the blade and the time between maintenance, which is a serious financial problem especially for remote and hard to get to locations.

On top of all, there are the human risks involved with blades covered in ice. Because of the rotational movement and the size of the blades used in megawatt class units, the distance of dangerous zone from the unit is quite long. For calculating a rough estimate of the danger zone, one can use the following equation:

$$d = 1.5\,(D + H) \tag{1}$$

where d is the rough estimate of the ice that is thrown
D is the rotor diameter
H is the height of the nacelle

This equation does not provide an exact figure, but gives a rough estimate. (Dalili et al. 2009, 430.)

According to studies, there are three main types of icing that occur at different sites. Two of these, in-cloud icing and precipitation, have effect on wind power units. The third main type, frost, doesn’t seem to have effect on wind power units. (Dalili et al. 2009, 431.)

3.1.2 In-cloud icing

When super-cooled droplets, forming at clouds with ambient temperature of -20 to -35 °C, hit a surface, is when the in-cloud icing occurs. The in-cloud icing can be further divided into rime and glaze ice.

The droplets size and temperature determine whether if the ice will be considered as hard or soft rime, or glaze.

When super-cooled droplets impact a surface and, if the thermal energy is released quickly enough by wind and radiation so, that on the surface, no liquid water is present, then rime is formed. Rime ice, which is white, breaks off more easily than glaze. When the droplets are small and the water density of the air is low, soft rime is formed. Soft rime has a lower density than hard rime due to larger air gaps between the frozen particles.

When the super-cooled droplets, after impacting on a surface, do not lose their thermal energy quickly and some parts of the droplet still remain as liquid, glaze is formed. Being significantly harder to remove than rime, due to high density which is the result of very low amount air trapped inside, glaze is a solid cover of clear ice. (Dalili et al. 2009, 431.)

3.1.3 Precipitation icing

When rain or snow, for example, freezes after being hitting a surface, precipitation icing occurs. A temperature of 0 to 3 °C ensures that snow, being wet at this temperature, will have some water in it and can stick to a surface. This, in turn, allows the snow crystals to bind together when they come into contact with a surface.

Usually the strength of binding of wet snow is low as it first forms, but if the temperature after this falls under 0 °C, it has the possibility to become very hard. (Dalili et al. 2009, 431.)

3.2 Offshore units

The material requirements for offshore units must be able to withstand constant winds that can reach tens of meters per second; they must be able to withstand high amount of UV radiation (both from direct sunlight as well as the radiation reflected from the water surface) and the eroding effect of the salt in sea water. Also, the energy and the resonance amplitude of the waves must be taken into account. The temperature of the water as well as objects, such as chunks of ice that the water might be carrying and that might collide with the tower and / or the foundation must be taken into account in the designing process. Areas, where tide is heavy, it must also be taken into account. (Patel 2006, 129 - 139.)

The items to consider mention above make sure that the materials used in offshore units cannot be identical to those used in land based units. At the very least they must be made to withstand more corrosive forces and UV radiation. In offshore and near-shore units the tower can be made from prestressed concrete, but they will require high amount of steel used for reinforcement. (Ancona & McVeigh 2001, 8.)

3.2.1 Current icing solutions in wind power units

A lot of effort is made to identify and prevent icing in modern wind turbine units. Most of the icing solutions used are taken from aviation industry, and are divided into two main categories: active and passive. (Dalili et al. 2009, 431 - 432.)

Active methods have external system applied to the blade, and passive methods rely on the blade to prevent accumulation of ice. (Dalili et al. 2009, 431 - 432.)

In addition to these two main types, there are two types of systems that can be introduced to a blade: de-icing and anti-icing. De-icing removes ice from the surface of a blade once it has already formed, and anti-icing aims to prevent the forming of ice in the first place. Both of these can be used as active or passive method. The following sections describe these. (Dalili et al. 2009, 432.)

3.2.2 Active methods

Active methods that are used to protect wind power units blades require an external power source to function and include thermal, pneumatic and chemical techniques. All of these can function as anti-icing or de-icing system. (Dalili et al. 2009, 432.)

Active de-icing systems

While small airplanes use a rubber boot on the leading edge of the wing, that expands and contracts on the ice-areas in the wing. This technique is fine for an airplane, but since this kind of technique modifies the aerodynamics of the wing, in the case of wind power unit it modifies the surface of the blade. This, in turn, increases the aerodynamic interference of the blade. Also, an inflated boot would increase the noise the wind power unit makes. This has the possibility of being a serious problem when close to households. (Dalili et al. 2009, 432.)

Moreover, the mechanical complexity of an inflatable rubber boot system would greatly increase the need for maintenance during the expected 20-year lifespan of a wind power unit. While this might be bearable in land based units, the maintenance costs, which already are high, in off-shore units would be unbearable. (Dalili et al. 2009, 432.)

Active anti-icing systems

Most anti-icing systems, that are active, and have been developed to at least the stage of a prototype, have been based on thermal energy to melt any ice that might cover the blade. Heating of the blade can be done by several means:

- *Electrical resistance heating*. Being simple in design, the heating element is laminated into the blade, near the surface, they are time and place tested since they have been used in aerospace industry for many years, but they have also been developed for wind power units in the mid-1990s. (Dalili et al. 2009, 432.)

- *Indirect heating of the surface*. Used in Enercon turbine in Switzerland, in this method there is a heating element, a radiator or warm air, inside the blade and it’s then transferred to the surface of the blade by some mean, for example conduction. (Dalili et al. 2009, 432.)

- *Microwave heating.* Even though this system might be usable at some point, so far there are no units using this method. (Dalili et al. 2009, 432.)

- There are many ideas and patents that use clean air as a mean of anti-icing and / or de-icing, such as the invention of Lorenzo Battisti, who has a patent in US for his invention for anti-icing system for wind power units (US2005/0242233 A1.)

3.2.3 Passive methods

The definition of a passive method is to take advantage of the physical properties of the blade and its surface to prevent the forming of ice, or to eliminate the ice that has already accumulated on it. Passive methods are similar to active methods so that they can act in anti-icing or de-icing role. (Dalili et al. 2009, 433.)

Passive de-icing systems

- Even though there is little published information on wind power unit blades flexing, it is known to be an effective way to de-ice the blades. This is based on the system being designed so, that the blades are flexible enough to crack the ice accumulated on the blade. Unfortunately, there are some draw backs in this method. First, there is the possibility that some ice stick to the blade so strongly, that the flexing is unable to crack it with vibration. Secondly, the flexing of the blade affects the aerodynamics of the blade, which in turn affects the power output. (Dalili et al. 2009, 433.)

- A new electro-expulsive system designed for Raytheon’s Premiere I business jet has proven itself on aerospace application, but the validity of this method is yet to be proven on wind power applications. (Dalili et al. 2009, 433.)

- Other passive means, such as facing the blades to the sun or start stop cycles, can be used. These methods may work in light icing conditions but unfortunately, few studies have been published to prove their efficiency. What must be considered here as well is the fact that these methods can cause damage to the unit itself, and / or reduce the power output. (Dalili et al. 2009, 433.)

Passive anti-icing systems

Passive anti-icing methods are all basically the same. The blades are coated with a substance that reduces the shear forces between the blade and the ice are not new; they have been used in aerospace industry for a long time. One of these substances is the StaClean®, which the manufacturer states to be non-wetting, slicker than Teflon®, highly impact and abrasion resistant. These qualities would make it ideal for wind power unit blade coating material. It has already been used by the Yukon Energy in 1996, and it was reported to be an effective way of reducing icing issues. (Dalili et al. 2009, 433.)

Being as it may, coating of wings, let it be in aeroplane or wind power industry, is the only way of effectively method at this time to prevent adhesion of insects and the corrosion of leading edge. (Dalili et al. 2009, 433.)

3.3 Effects of insect contamination

While insects might seem irrelevant to a structure the size of a megawatt class wind power unit, according to studies they are relevant. (Dalili et al. 2009, 433 - 434.)

Insects that fly and hit at the leading edge, which is the most important part of the blade in terms of power output, they can decrease the power output by as much as 55 %. (Dalili et al. 2009, 433 - 434.)

This is due to the insects that smash the blade and stick there, interfering with the aerodynamics of the leading edge of the blade. (Dalili et al. 2009, 433 - 434.)

Since the drop of power output is several percent even when the amount of insects is low, in the long run it is expensive. Therefore, there are ways to get rid of the dead insects from the blades. The simplest and cheapest way to get rid of the dead insects is to wait for rain to wash the blades clean. This also cleans the blades from possible air pollutants, at least to a certain degree. A non-stick coating of the blades, such as the StaClean® mentioned before, helps in this. Also, there are blade cleaning devices similar to a car wash that can be used to clean the blades. The drawback of this cleaning method is that the unit must be stopped for the process. A third option is to pump water up the tower and through the blades and clean them that way. This option can be used while the unit is active. (Dalili et al. 2009, 433 – 434.) The drawback of this is that a lot of energy must be used to pump the water. Also, if the unit is in a remote area, the cost of transporting the water to the site might be expensive. In addition to these, this cleaning option must be implemented in the design, which could add a considerable cost in total to the units price and therefore increase the time is takes for the unit to pay itself back.

3.4 Effects of erosion

Wind turbine units that are exposed to high amounts of sand and / or water droplets can erode. This erosion affects the aerodynamics of a blade and thus deteriorates the power output of the unit. The erosion potential depends on the force at which the matter in question hits the blade. While relative velocities of the airfoil and the object that hits it, as well as the geometric shapes determine the force of impact, the rotational speed and wind speed determine the impact velocity. (Dalili et al. 2009, 434.)

Today, erosion is usually dealt with by applying an elastomeric material on the leading edge of the blade, usually in the form of tape. While these tapes must be replaced frequently, they fail to absorb the impact of the particles; they remain a viable solution for small turbines even if they increase the drag on the blades surface. (Dalili et al. 2009, 434 – 435.)

4 MATERIALS USED IN MODERN WIND POWER UNITS AND THEIR PROPERTIES

The modern wind power units are divided into main parts (tower, nacelle and blades) and each main part is given a subsection. In each subsection materials commonly used today for that main part are listed and their properties are being explained. When possible, diagrams, charts and the like are being used to clarify the matter.

4.1 Tower

As stated earlier in this thesis, modern wind power units' towers are usually made from steel or steel reinforced concrete.

Because the inability to find the specific alloy, or alloys, commonly used in wind turbine towers, it was decided to add in the following some commonly used steels and steel alloys which might be used for tower material.

Steels and steel alloys are indentified by their AISI/SAE or ASTM number. This number, with the UNS number, tells how much in weight per cent there is of any element in the alloy. In AISI/SAE numbering the first two or three numbers give the average carbon content in hundredths of a weight percent. (Shackelford 2000, 402.)

For example, plain carbon steel that has 0.40 wt % of carbon is designated as 1040 steel. (Shackelford 2000, 405.)

Low-carbon steels are typically used in structural shapes (I-beams, for example), sheets that are used in pipelines (most wind turbine towers are pipes that have greater diameter the closer they are to the ground), buildings and bridges, and automobile body components. (Callister 2000, 358 – 359.)

The high-strength low-alloy steels, on the other hand, are more resistant to corrosion (which, in turn, lowers the requirements for the coating of the tower). Also, usually having greater tensile, as well as yield, strength have made sure that HSLA steels have replaced low-carbon steel in applications, where structural strength is critical. (Callister 2000, 358 – 359.)

Low-carbon steels and High-strength, Low-Alloys (HSLA) steels:

Chart 2: HSLA steels that could be used in towers, with general information about their properties

Designation[a]		Composition (wt%)[b]		
AISI/SAE or ASTM number	UNS number	C	Mn	Other
		Plain Low-Carbon Steels		
A36	K02600	0.29	1.00	0.20 Cu (min)
		High-Strength, Low-Alloy Steels		
A440	K12810	0.28	1.35	0.30 Si (max), 0.20 Cu (min)
A633 Grade E	K12002	0.22	1.35	0.30 Si, 0.08 V, 0.02 N, 0.03 Nb

[a] The codes used by the American Iron and Steel Institute (AISI), the Society of Automotive Engineers (SAE), and the American Society for Testing and Materials (ASTM), and in the Uniform Numbering System (UNS) codes are explained in the text.

[b] Also a maximum of 0.04 wt% P, 0.05 wt% S, and 0.30 wt% Si (unless otherwise mentioned).

Source: Callister 2000, 359.

Mechanical characteristics of selected hot-rolled materials as well as their typical applications:

Chart 3: The mechanical characteristics of previously mentioned steels

AISI/SAE or ASTM number	**Tensile Strength [MPa (ksi)]**	**Yield Strength [MPa (ksi)]**	**Ductility [%EL in 50 mm (2 in.)]**	**Typical Applications**
		Plain Low-Carbon Steels		
A36	400 (58)	220 (32)	23	Structural (bridges and buildings)
		High-Strength, Low-Alloy Steels		
A440	435 (63)	290 (42)	21	Structures that are bolted or riveted
A633 Grade E	520 (75)	380 (55)	23	Structures used in low ambient temperatures

Source: Callister 2000, 359.

Stainless steel is also used in wind power unit towers because of the endurance it has against corrosion, which reduces the requirements of coating for the tower. While stainless steel is divided into three main categories (austenitic, martensitic and ferritic), when observing the typical applications where these three are used, the austenitic stainless steel is most likely used in tower applications.

Chart 4: Characteristics of an austenic stainless steel that could be used as a tower material

				Mechanical Properties			
AISI number	**UNS number**	**Composition (wt%)**[a]	**Condition**[b]	**Tensile Strength [MPa (ksi)]**	**Yield Strength [MPa (ksi)]**	**Ductility [%EL in 50 mm (2 in.)]**	**Typical Applications**
				Austenitic			
316L	S31603	0.03 C, 17 Cr, 12 Ni, 2.5 Mo, 2.0 Mn	Annealed	485 (70)	170 (25)	40	Welding construction

[a] The balance of the composition is iron.

[b] Q & T denotes quenched and tempered

Source: Callister 2000, 362 – 363.

All in all, due to lack of standardization in tower materials which are allowed to be used, and with the development of new and improved coating materials, either the plain low-carbon steel A440 or HSLA A633 Grade E steel are very likely the steels which are used in the construction of towers for megawatt -class wind power units.

In addition to steel and steel alloys, concrete is sometimes used to make towers. More so with the increasingly large units which are constructed today. This is due to the height and size of the unit. The forces that affect the tower are so great, that a steel tower would have to be so enormous that the cost, in addition to other problems such as transporting, would be too great. Also, concrete is more resilient material against climatic forces, such as erosion and virtually immune to corrosion.

The concrete used in wind turbine towers is steel reinforced and therefore while concrete is cheaper than steel, the amount of steel used to reinforce the concrete makes it quite expensive, narrowing the margin of cost between pure steel tower and steel reinforced concrete tower. (Ancona & McVeigh 2001, 5 - 8.)

The concrete in wind power unit towers is usually prestressed, which has been used in, for example, bridges. Most likely the type of cement used in wind turbine towers is ASTM type I cement, which is general purpose cement. For more hazardous environment, such as deserts or northern areas, different kind of cement is required. Also, especially for areas where fine particles move with the wind, the concrete might need to be coated with a substance that protects the concrete from being grinded down little by little.

With the previous in mind, the University of Dayton Research Institute in Ohio has studied the use of composite materials in wind turbine towers of up to 100 meters height. With the trend of larger and larger turbines new, cheaper and lighter materials for towers must be found. (ReinforcedPlastics.com, referred 12.08.2010)

4.2 Nacelle

Since nacelle holds the gearbox, brakes, cooling systems and all the other secondary systems required for the operation of a wind power unit, the nacelle must be made of strong enough material to withstand the environment, yet light enough not to affect the tower. While bigger units are large enough for maintenance crew to perform their tasks in the nacelle without it being removed, smaller units might require the complete removal of the nacelle cover for maintenance routines. (Roger et al. 2002, 10.)

Since top head mass, THM, is a very important factor in wind power units, the nacelle material is usually glass reinforced fiber composite, or more commonly, fiberglass, which are made into laminated shells, which insulate the gearbox and other parts located inside the nacelle against temperature. They also work well in insulating the noise from gearbox. (Patel 2006, 64; Windturbines.net, referred 02.08.2010.)

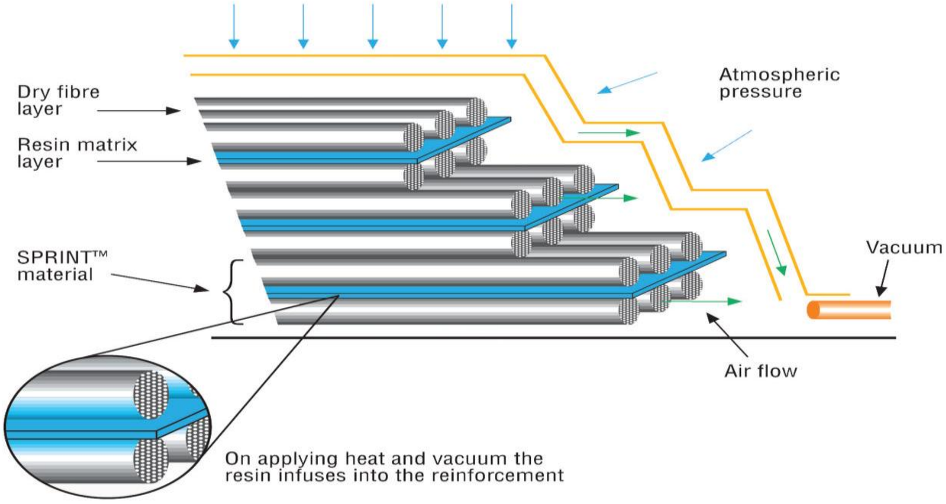
4.3 Blades

Since composite materials are the only ones that fulfill all the requirements for wind turbine blades (price, weight, strength, et cetera), there are many types of composites used and tried over the years, everything from wood and wood-based composites to metal blades. (Ancona & McVeight 2001, 5.)

Before, fiberglass was the best choice for megawatt -class wind turbine blades, but since the trend in wind turbines is to go bigger and bigger, according to Nordex Rotor, a German wind turbine blade manufacturer, fiberglass has outlived its usefulness in large wind turbine blades. Nordex Rotor has instead started to develop carbon fiber for their blades. Some enterprises, for example LM Glasfiber from Denmark which is the world’s largest wind turbine blade manufacturer with some 40 % market share, consider glass reinforced fiber composites still being a viable solution for wind turbine blades, and believe that the price difference between carbon fiber and fiberglass is enough to keep fiberglass in business. (Mash 2003, 1.)

There are many things that speak for the use of glass reinforced composites in wind turbine blades, two very important factors being price and weight, in that order. Since the cost of wind energy in kW / € is extremely important factor in its development and implementation, the cost of parts, such as blades, has to be as low as possible. When using blades that are, for example, 56 meters in length (such as the Nordex Rotor 5 MW turbines blades), fiberglass simply might be too cumbersome. With the development of techniques and production lines, the price of carbon fiber used in blade manufacture should go down and open more options for manufacturers. Despite the price of using carbon fiber as blade material, according to studies, many manufacturers are, at the very least, looking into the possibility of using carbon fiber. (Mash 2003, 2.)

While the trend might be towards carbon fiber, the development of glass reinforced composite is still strong, as we can see from the picture below:



Picture 7: Sprint™, which is developed by SP Systems, is part of a new class of 'semi-preg' materials (source: Materials - Key to harnessing the power of the wind)

The SP Systems Sprint™ has interlaid layers of hybrid fabric, glass or carbon with resin film that's pre-cured to its Beta state. Other companies, such as Hexcel Composites or Advanced Composites Group have similar products as the Sprint™. (Mash 2003, 1.)

As studied by Mandall et al., the most problems that wind turbine blades have in terms of fatigue strength is due to poor choice of materials (environmentally sensitive-resins and heterogeneous, stranded glass fabrics, for example). Many of these problems would be eliminated or, at the very least, they would be greatly reduced by the use of straight fibers that are well dispersed which are used in an environmentally resistant and tough resin. (Mandall et al. 2002, 263.)

Also, the sandwich construction type of wind turbine blades could be improved by modifying the 30° edge termination (to a thin laminate) that is used, to 5° would all but completely eliminate the declination of strength. While the it would be more challenging to use the 5° termination, it would be much more efficient in many ways. (Mandall et al. 2002, 263.)

5 CORROSION ON WIND TURBINE MATERIALS

Since corrosion can be a major issue for wind turbines, especially with offshore units, a section of this thesis is dedicated to corrosion and how to negate its effects.

Since there are many types of corrosion as well as the ways to combat it, only the general types of corrosion and only the most common ways to combat the corrosion are marked.

Since onshore units will most likely endure the 20 - 30 year lifespan the current wind turbine has without excessive and / or otherwise significant corrosion protection unless the units are located in areas, where the air pollutions are highly sulfurous such as is the case of China. Therefore, the following subsections will be dealing with offshore units, for the significantly increased need for corrosion protection needed.

5.1 General information

In standard SFS 4596, the environmental circumstances in Finland have been divided into five (5) sections, M0 to M4, according to their affect on corrosion of metals. (Korroosiokäsikirja 1988, 222.)

An important factor in environmental corrosion is the time when a surface is wet covered on visible or invisible layer of water. Also, the sulfur dioxide and chloride content in the air are of importance. When determining the stress level of the environment, the factors that will effect corrosion in the immediate vicinity of object are also of importance. The effect from immediate surroundings to corrosion usually has more weight than the environment in the local area. (Korroosiokäsikirja 1988, 222.)

Stress level M0 accordant corrosion stress is dominant in indoors, where the relative humidity is kept above critical levels most of the time using heating and air conditioning. (Korroosiokäsikirja 1988, 222.)

Stress level M1 accordant corrosion stress is in unheated indoors, where both temperature and humidity fluctuate. (Korroosiokäsikirja 1988, 222.)

Stress level M2 accordant corrosion stress is in clean country climate. (Korroosiokäsikirja 1988, 222.)

Stress level M3 accordant corrosion stress is in outdoors, where the air has impurities. The quality and quantity of impurities divide the stress level to **city-**, **ocean-** and **industrial climate**. (Korroosiokäsikirja 1988, 222.)

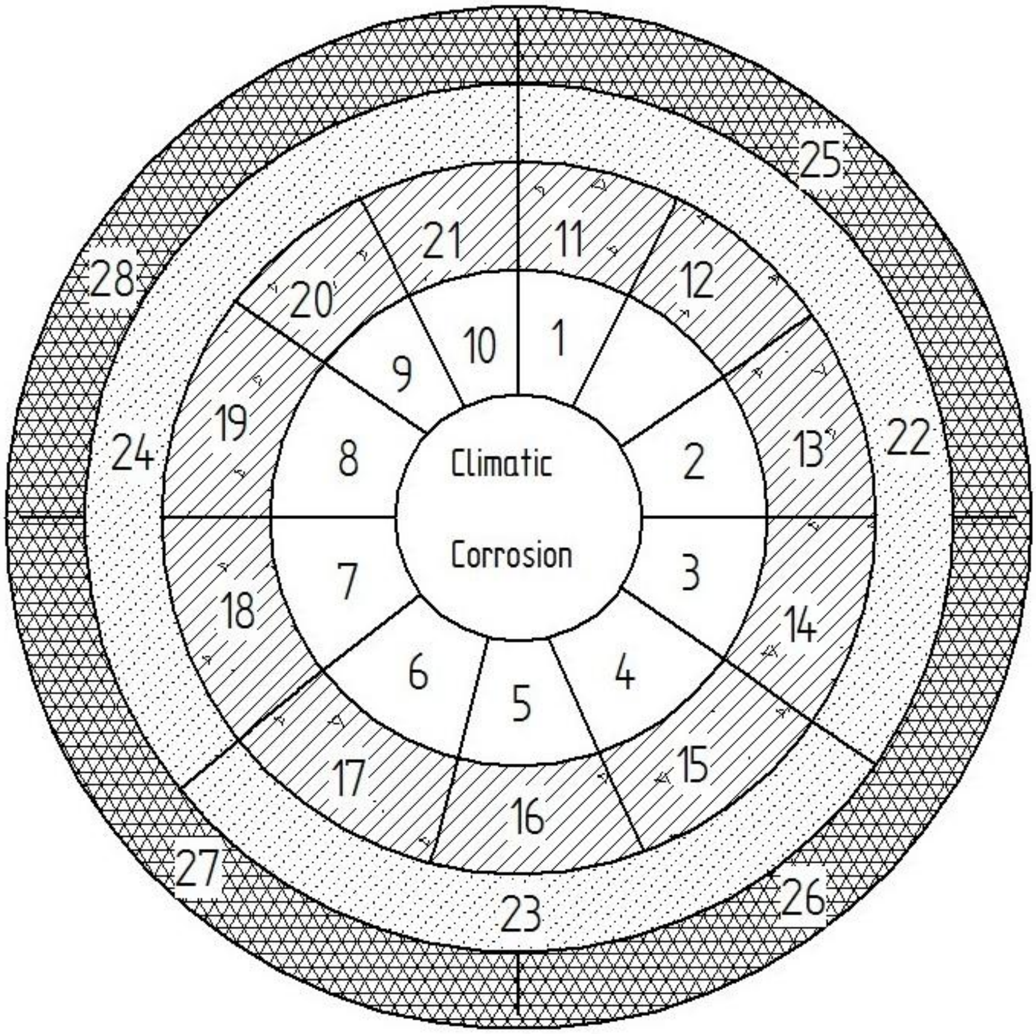
Stress level M4 accordant corrosion stress cut across special circumstances, where the near vicinity of the object affects decidedly the corrosion speed and -prevention methods. Typical agents that cause corrosion stress in special circumstances are:

- corrosive gasses
- moisture chemical dust
- splatter
- submersion in liquid
- submersion in earth
- touching some other substance
- biological stress
- mechanical stress
- thermal stress (Korroosiokäsikirja 1988, 222.)

In addition to standard SFS 4596 /1/, the standard ISO 9223 divides climates according to wet time as well as sulfur dioxide and chloride contents. There are five (5) wet time classes τ_1…τ_5, four (4) sulfur dioxide classes P_0…P_3 and four (4) chloride classes S_0…S_3. Based on these factors that affect metal corrosion the climates are divided into five (5) corrosion classes 1…5. For steel, zinc, copper and aluminum the carrion speed for the first 10 years is given in standard ISO 9224. (Korroosiokäsikirja 1988, 222.)

Below is a pie chart that shows the effects of gaseous, liquid and solid material in climate corrosion.

Chart 5: Chart of the effect of gaseous, liquid and solid matter in climatic corrosion, with the explanations of different sectors below



Source: Korroosiokäsikirja 1988, 223.

1. Flying dust
2. For example, KCl (Potassium Chloride), NaCl (Sodium Chloride)
3. Ice
4. NH_3 (ammonia)
5. Oxygen, moisture in the air, Carbon Dioxide
6. For example, SO_2 (Sulfur Dioxide), Cl_2 (Chlorine), NO_2 (Nitrogen Oxide), CO_2 (Carbon Dioxide), H_2S (Hydrogen Sulfide)
7. Aerosols, fog, rain
8. For example, H_2SO_4 (Sulfuric Acid), H_2SO_4 (Sulfurous Acid), $H_2O + CO_2$ (Carbonic Acid), HCl (Hydrogen Chloride)
9. For example, $NH_3 + H_2O$ (Ammonium Hydrogxide)
10. For example, chlorinated hydrocarbons
11. Dust
12. Rust
13. Salts
14. Snow
15. Caustic
16. Neutral
17. Acidic
18. Water
19. Acids
20. Alkaline

21. Organic compounds
22. The chemical and mechanical effect of solid stimulators
23. Gaseous stimulators
24. The chemical and mechanical effect of liquid stimulators
25. Total radiation (visible light and UV -radiation)
26. Electric reserve
27. Organic substances (micro organisms)
28. Temperature (thermal radiation)

5.2 Air as corrosion environment

The corrosion of metals in climatic environments happens as electrolyte via water based solution, as so called wet or electrochemical corrosion. Therefore, the most important factor in corrosion speed is the surface wet time. (Korroosiokäsikirja 1988, 225.)

Moisture. Surface gets wet due to rain or fog, or when the moisture in the air condensates onto a (metal) surface. The film needed for corrosion is so thin, that surfaces are considered to be wet without visible moisture when the relative air humidity is 80 - 90 %. For most metals there is a so called critical relative moisture value, above which corrosion is significantly faster. Even though this value shifts according to many factors, for steel the corrosion is significantly faster in a sulfur dioxide atmosphere when the relative humidity is above 60 - 65 %. Once corrosion is started, the air humidity needed to keep it going could even lower. For example, steel can corrode when the relative air humidity is just 40 %, if there is chloride content rust on the surface of the steel. (Korroosiokäsikirja 1988, 225.)

Temperature. When temperature raises corrosion usually accelerates, but warmth also evaporates moisture from surfaces. Corrosion does not appear in clean atmosphere when temperature is lower than 0 °C, however on an unclean surface corrosion is possible even when temperature is a few degrees below zero because many salts lower the freezing point of electrolytes. (Korroosiokäsikirja 1988, 225.)

Microclimate. In same environment different structures can corrode in highly differing ways. The angle of the surface and its direction affect how much moisture and impurities get to a surface. Vertical surfaces corrode less than horizontal surfaces where moisture gathers more easily. (Korroosiokäsikirja 1988, 225.)

Impurities in the air. Even though it is necessary for atmospheric corrosion to have a moisture surface, even in wet conditions corrosion is not very strong, if there are no impurities in the air. Impurities in the air originate partly from natural activity, such as biological decay processes (sulfur hydrogen) and sea salts (chlorides, sulfates), and partly due to human activity, for example, fossil fuels (sulfur dioxide, nitrogen oxides). The sulfur compounds and chlorides in the air are the substances that most shorten the life span of metallic components. (Korroosiokäsikirja 1988, 225.)

Impurities can enter a surface with rain or fog, or they can be absorbed on a surface directly from the air. Rain “waters down” the effects of impurities, and it can even wash away some of the impurities on a surface. Usually, the condensation phenomenon, when moisture condensate on surface to form a electrolyte layer, is usually more corroding than that caused by rain. (Korroosiokäsikirja 1988, 225.)

Chlorides originate from sea and their affect withers down quickly when travelled inland. Because of chlorides the relative humidity of air necessary for wetting surfaces is lowered down. (Korroosiokäsikirja 1988, 225.)

Sulfur dioxide (SO_2) oxidizes in the air into sulfur tri-oxide, which reacts with the moisture in the air forming sulfur acid (H_2SO_4). Once on a metallic surface, it transforms into sulfate. Most of the important non-metallic sulfates are water-soluble so the rain can wash them away. This way the forming of a new corrosion layer eats more metal. (Korroosiokäsikirja 1988, 225.)

The effect of nitrogen oxides (NO_x) on metallic climate corrosion has been studied, but the only solid information is that there is still much to be studied, as well as more precise techniques are needed. (Arroyave & Morcillo 1995, 10.)

Atmosphere types. To fully assess the strength of climate corrosion the climate conditions can be classified into country-, city-, industrial- and ocean-climates. Below is a table that clarifies and condenses these climate types.

Chart 6: Climates and their characteristics

Climate	**Typical characteristics**
Country climate	The amount of impurities is small
City climate	Gaseous (SO_x, NO_x) and solid (smut, dust) impurities in the air
Industrial climate	As city climate, but with more impurities
Ocean climate	Relative humidity and amount of chlorides is high

Source: Korroosiokäsikirja 1988, 226.

Structural durability demands can also be described with the strain-classes of standard SFS 4596 (“Corrosion of metals. Environmental conditions classification.”), where the structural microclimate is taken into account. (Korroosiokäsikirja 1988, 226.)

5.3 Climatic corrosion of metals

Steel. In a moist environment a layer of ferro hydro-oxide which oxidizes further into red-brown rust (FeOOH). While the rust layer does not prevent corrosion, it does slows it down a bit. In an ocean climate the chlorides accelerate the corrosion process by creating water-soluble alkali salts. Also, the sulfur dioxide in the air accelerates the corrosion of steel. Ordinary carbon- or construction grade steel is not used outdoors unprotected, but rather they are either painted or hot galvanized. (Korroosiokäsikirja 1988, 226.)

While the so called weatherproof steels contain small amounts of additives, such as chrome and copper, which turn the rust layer into a protective layer. While these weatherproof steels withstand sulfur compounds fairly well, chlorides prohibit the protective layer from forming. Other substances can be used to protect steel, such as zinc. Zinc has brilliant properties as a coating material, such as corrosion speed of 1/10 from that of steel. Also, zinc gives a cathode protection to steel. (Korroosiokäsikirja 1988, 226.)

Stainless steel. The oxide layer on stainless steel is very protective. Austenite stainless steels can withstand effects of impurities well, however on martensitic stainless steels surface impurities can cause pitting and even spots of rust. The depth of pitting is usually under 0.1 millimeter, and climatic corrosion causes mainly just esthetic problems. (Korroosiokäsikirja 1988, 226.)

5.4 Prevention of corrosion

Because of the length of the life span as well as the great forces affecting the wind power units, the prevention of corrosion is critical. There are many different types of corrosion and each wind power unit or farm must be studied before starting the designing process. Also, the designers should look into the possibility of preventing corrosion where possible, where this course of action is action is economical. (Dalili et al. 2009, 437.)

A general type of corrosion prevention is coating the surfaces that are in contact with surrounding environment, such as the tower, the nacelle and the blades. Tower, if made from steel, could be made from steel that is resistant to the types of corrosions that will take place. For example, painting the tower is a good way to defend against corrosion. Also, some sections of the unit is made from a corrosion resistant material, such as fiberglass that is used to make the nacelle. Blades are made from composite material as well, such as fiberglass or carbon fiber. Blades are also usually coated with something, such as the StaClean™ which was mentioned earlier. Coating the blades is also necessary for other than anti-corrosion, which was treated earlier in this thesis. (Dalili et al. 2009, 437.)

6 RESULTS AND DISCUSSION

The materials used and implemented in wind energy were studied in this thesis, keeping the focus on external materials. Another focus of this thesis was to concentrate on medium and, especially, large wind turbines. The reason for this kind of selection comes from the trend of creating bigger and larger units and farms to provide more and more renewable energy to compensate the growing needs of industry and private citizens. It was found out that traditional materials are used to create the foundation and building the tower; however research is done to eliminate some of the traditional materials from the making of wind turbines. The reason for this is quite obvious: the price and weight of steel, for example, are high and with the growing demand of steel suitable for off-shore units, the price can only grow.

With the growing demand of clean energy, energy that does not produce greenhouse gasses, the wind farms are moving further and further into more and more hostile areas. Deserts, barren areas in the most northern sections of the world, such as in northern Siberia and even mountains are becoming homes to wind farms. With these exceptionally challenging areas designers must understand the specific requirements of these areas. In this thesis some these are introduced and listed are some of the challenges and solutions in each.

The author believes that the future of renewable energy is primarily in wind energy, and therefore more studies should be made to determine the materials and specific requirements for wind turbines in extreme areas.

7 CONCLUSIONS

While there is already a variety of materials that can be used and utilized in place of more traditional materials the key to effective and as-cheap-as-possible wind energy remains in the materials used to build the wind turbines. This leads to the usage of more traditional materials. Also, the fatigue and strength factors are issues that must be given a serious thought. Wood, for example, simply cannot withstand the forces that are in megawatt -class wind turbines, whereas HSLA steels are wasted in small, merely few hundred kilowatt, turbines.

The study of composite materials has opened the way to a much more efficient way of harnessing the energy of wind. While traditional materials, such as steel and concrete, hold their own at certain places, composite materials are, in many ways, superior to them. For example, while the nacelle could be made from aluminum or steel and then be insulated, to keep the moisture out and noise in, enterprises use fiberglass because it is lightweight, strong and generally suits as the nacelle material much better than aluminum or steel. Wind turbine blades are an even clearer example. They could not be made from any other material than composites within the reference frames given (price, weight and strength), or perhaps from specialty materials, such as magnesium-aluminum alloys. While small turbine blades can be made from for example wood, the blades of a large, multi-megawatt class turbine, would be all but impossible to make from any other material than composite, since cost is always an issue in large wind turbine units.

With the need to build more and more renewable energy, wind turbine units are moved into more and more hostile environments. This presents many challenges in the prevention of corrosion in wind turbines. Luckily, there is a vast amount of information available on almost any problem that rises, starting from insect-based corrosion to oceanic corrosion. However, since the size of wind turbines increase so does the cost of anti-corrosion per unit, which can become a problem. Corrosion of composite materials used in wind turbines in highly acidic environments is also a question unanswered, but in time this also will be answered. Since the advancement of materials used in wind turbines goes forward all the time and more and more interdisciplinary materials become available, the challenges involving corrosion and weather in general might diminish but never fully go away.

By combining knowledge from a variety of fields the designers today, and in the future, can rise up to the challenges produced by the changing world and the need for clean energy everywhere.

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