HiPRWind

High Power, high Reliability,Off-shore Wind Technology

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Summary of boundary conditions for scaling up turbine size

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Abstract

The wind industry is expected to grow fast in the near future. The turbine size optimization is a great issue but is difficult to define. In the present research, based on the available experience gained so far from the wind industry projects, the technological barriers and the limiting parameters for scaling up wind turbines are discussed. Furthermore, potential development areas and research topics that can enhance a reliable and more efficient growth are highlighted.

Keywords: Offshore Wind Energy, Upscaling; Cost of energy; Manufacturing; Installation; O&M; Materials; Gearbox, Grid, Substructures

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Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

Acronym	
€	Euro
ρ	Density
AC	Alternating Current
C_{Fuel}	Cost for fuel
C_I	Investment cost for the offshore wind farm
$C_{O\&M}$	Annual Operation and Maintenance cost of the offshore wind farm
CVT	Continuous Variable Transmission
DC	Direct Current
DD	Direct Drive
DLR	German Aerospace Centre
E	Annual energy production
E	Young´s Modulus
EU	European Union
EWEA	European Wind Energy Association
EWI	European Wind Initiative
GBX	Gearbox
GL	Germanischer Llyod
GWEC	Global Wind Energy Council
HSE	Health, safety and environment
HTS	High Temperature Superconducting
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IEC	International Electrotechnical Commission
Kg	Kilogramm
kNm	Kilonewtonmeter
kV	Kilovolts
kWhs	Kilowatt-hours
l	Liter
L_{Blade}	length of the turbine blade (m)
LCC	Line Commutated Converter
LCoE	Levelized Cost of Energy
LIDAR	
GBS	Gravity-based solutions
GFRP/GRP	Glass (-Fiber) Reinforced Plastic
GPa	Giga Pascal
GW	Gigawatt
m	Meter
m^3	Cubic meter
M_b	Merit Index
Mio	Million
Ml	Mega liter

MPa	Mega Pascal
MRI	Magnetic Resonance Imaging
Mt	Megatons
MV	Medium Voltage
MW	Megawatt
N	Cycle to failure
n	Life of the system
N.A.	Not available
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
OWA	Offshore Wind Accelerator
NDT	Non Destructive Techniques
O&M	Operation and Maintenance
P	Rated power of wind turbine (W/m^2)
PET	Polyethylene terephthalate
PM	Permanent Magnet
PVC	Polyvinyl chloride
r	Discount rate
RAVE	Research at Alpha Ventus
R	Turbine radius/blade length (m)
RCM	Reliability Centred Maintenance
S	Cyclic stress
SAN	styrene acrylonitrile
SC	Super Conducting
SCRIMP	Seeman Composite Resin Infusion Moulding Process
t	Tonne
TLP	Tension-leg-platform
UV	Ultraviolet
VRTM	Vacuum-Assisted Resin Transfer Moulding
VSC	Voltage Sourced Converter
yr	year
W	weight of the blade
W/m^2	Watt per square meter (rate of energy per unit area)

Part A: The technological barriers and the limiting parameters for scaling up wind turbines

Executive Summary: Part A

Over the past decade the global wind power market has undergone a noticeably big growth, there has been an annual increase by an average of 28% in terms of the total installed capacity[1]. The noticeable change in attitude towards wind power is driven by many different factors, which include the need of diversity in energy mix due to the costly fossil fuels, the need in securing power supply to match future demand and environmental factors such as air quality, public health and carbon reduction. Today wind energy accounts for 3% of the global electricity demand[2]. The European Wind Initiative (EWI) expects wind energy to supply 20% of Europe's electricity in 2020, 33% in 2030 and 50% in 2050[3]. Major wind power markets include Europe, North America (US) and Asia (China and India), where China has consolidated its position as global market leader with its total capacity of more than 62 GW in 2011[4] .

The high energy demand, requirements for higher power stability and the on shore land 'saturation', enhanced offshore wind park projects expecting higher annual energy harvest due to the increased mean wind speeds. The perspective for the annual installed power in 2050 is 50% onshore - 50% offshore. However, at the same time the 'wind' project has to be developed in a reliable, cost effective and environmentally friendly, accounting for the technological barriers that have to be overcome. This means that the wind turbine should be optimized in terms of material usage, survive under the applied loads, harvest the most out of the wind power and perform reliable for at least 20 years.

Despite the limited offshore experience, the wind turbines have been developed since 90's accumulating a great amount of know-how in design, manufacturing, installation and commissioning. Although it is not always possible to project the past into the future, the restrictive factors underlying the development up to know can enhance our understanding and help in answering questions like:

- 'What are the driving forces?'
- 'Should we go for larger turbines?'
- 'Can we upscale?'
- 'Which are the technical barriers and bottlenecks?'
- 'Which parameters have to be optimized?'

A basic financial approach is performed, focusing on the effect of the major structural parts on an offshore farm costs along with the operational and maintenance expenses. Technical barriers are discussed in terms of manufacturing, installation, design tools, available manpower, addressing for the future development challenges.

Cost of Energy-Upscaling

A driving parameter is the cost of energy, a term which is directly connected to installation, transportation, material usage optimization, energy output. Analysis of the available data concerning the cost shares of offshore farms designates that the turbine price itself including tower, substructure and the installation stands for around 45% of the final budget (€/MW) over a

[1] Global Wind Energy Council (GWEC), Greenpeace International: Global Wind Energy Outlook 2010, October 2010

[2] World Wind Energy Association (WWEA), World wind market recovers and sets a new record, February 2012

[3] European Wind Energy Association (EWEA), EU Energy policy to 2050, March 2011

[4] J. Matthew Roney, World Wind Power climbs to new record in 2011, March 2012

period of 20 years of life. Another 22% to 47% of the costs are assigned to the Operation and Maintenance (O&M). The high uncertainty is due to the implemented estimates and calculation models, since there is no experience for offshore projects that reached their life limit. Therefore, an optimized wind turbine in terms of mass will impact the initial invest while improved O&M could drastically reduce the total costs.

For future cost calculation, upscale concepts were implemented, resulting in the main conclusion that larger is not necessarily better for offshore wind turbines. The optimum size of offshore turbines is dependent on the technology used. Therefore, new technologies have to be used in future wind turbines to shift the optimum size of the wind turbine to higher rated power values. As today, it seems that the optimum size of the offshore wind turbines lies somewhere between 5 MW and 10 MW for the current technology used. Pure upscaling will not reduce the cost of energy for offshore wind farms.

Wind turbine blades

Manufacturing

Wind turbine blades are the direct interface between the wind and the generator. They integrate advanced technology in terms of design and material-structural performance. However, design for manufacturing and improved manufacturing processes are vital for the near future development towards lighter and more reliable structures. Automated manufacturing and further implementation of non-destructive techniques could enhance the final product reproducibility and improve quality control respectively. Improved material performance i.e. resins and adhesive materials with sufficiently reduced curing time could drastically decrease the blade mould life cycle about 40%.

Materials

State of the art blade designs are dimensioned, amongst the others, against first ply failure in static loading. Therefore, the optimization of the laminate basic building block i.e. the unidirectional layer, transverse to the fibre direction will be a major contribution towards lighter blades. New textiles resulting in higher specific compressive strength than E-Glass composites and being cheaper than Carbon could be implemented as alternatives. Consideration should be made on the epoxy resin and adhesives production that require a tremendous amount of water. New technologies, more friendly to the environment are needed. Furthermore, alternatives for balsa wood have to be found for core materials with competitive shear properties, since its natural production is limited. Since offshore wind turbines will operate in higher tip speeds and harsher environmental conditions than onshore, new materials will be required. Coatings with high erosion and UV light resistance as well as ‘self-cleaning’ properties against dust, salt and ice emerge as ‘hot’ topics.

Testing

Wind turbine blades are currently certified by material testing and full scale blade testing on a single test blade. The materials specimens and the test blade are often manufactured with special care. However during the service life of wind turbine blades several failure modes occur, which cannot be predicted with coupon testing or determined with full scale blade tests. These failures occur mainly due to manufacturing e.g. handling faults, material defects, or design faults due to lack of understanding in the structural and but the material performance.

The structural approval of wind turbine blades will become more and more challenging as the dimensions of the blades increases for technical and financial reasons with increasing blade dimensions. The costs for the design, for the blade manufacturing and for the blade test increase significantly, which leads to a drastically higher risk for the designers, manufactures and investors. Therefore, a reliability based certification methodology is required. The gap between the coupon scale and the full-scale testing can be bridged with a mixed approach of destructive testing component and structural i.e. component testing, numerical analysis and manufacturing quality control by non destructive testing methods. With such a reliability based certification methodology the effort of the manufactures to increase knowledge on the structural behaviour and the product quality will result in structural performance optimization.

Logistics/Installation

Large size blades can hardly be transported on roads any more. Dedicated fabrication facilities close to ports or shippable rivers are required and there will raise the need for special lifting devices that will allow handling these large blades without damaging them. Split blade designs and innovative material combinations could be a solution for the transportation to remote destinations with limited road network.

Pitch system

General/Manufacturing:

The stiffness challenge for the pitch bearings and the design limitations for the pitch speed are the restraining factors for the design of very large turbines. However, the bearing dimensions are not a critical issue for manufacturing.

Logistics/installation:

The logistics for the bearings can be compared with the logistics of the hub, since the connecting diameter will be the same, with the advantage that the bearings do not have a spherical shape, which allows an easier transportation.

Hub

Manufacturing:

There are only a limited number of suppliers that can provide very large foundry pieces. This is a restriction that even currently affects turbine manufacturers in their production. For very large hub diameters this issue would be even more important, since there are less manufacturing facilities that are able to produce very large foundry items. Different designs solutions with new materials (fibre reinforced materials) might circumvent the bottleneck.

Logistics/installation:

Large hubs are difficult to transport on the road, their spherical shape will reduce the transportability since the diameter will get in conflict with the bridges height restrictions. The limited number of foundries and their locations will require logistics solutions for those components or the construction of new foundries at suitable locations with easy access.

Drive train: Gearbox – Direct Drive, Generator

Manufacturing:

Large forged components are difficult to produce. There is a rather high market concentration since there are a very limited number of forgeries that are able to forge very large main shafts or axles. Additional capacities will have to be created or the design of the turbines has to be adapted to limit the use of forged components.

Traditional Gearbox design has certain size limitations. Therefore, many multipath drive trains designs and innovative gearbox designs are considered. As improved concepts against a 3 stage gearbox, often single-stage medium speed gearboxes, multi generator drive path concepts and direct drive (DD) turbines are considered for drive train improvements. Many failures could be tracked back to alignment errors that caused uneven load distribution and therefore excessive wear on bearing races. Modern Condition Monitoring systems will allow in combination with vibration sensors to observe the gearbox conditions.

Traditional Generators for Direct Drive turbines have limitations due to size, size of the air gaps between stator - rotor and costs of the magnet materials. For the very large generator diameters, manufacturing size limitations emerge especially for the bearings that maintain the optimal air gap between stator and rotor and thus sustaining the efficiency of the Direct Drive solution. New bearing solutions can overcome this issue.

Superconducting (SC) and Ceramic High Temperature Superconducting (HTS) Generators would allow significant weight advantage, but are not readily available on the market. There is the need for continued research and engineering efforts to enable the use of Superconducting technology in wind turbines.

Logistics/installation:

Dedicated manufacturing/assembly at offshore port sites is required to get the logistics for the manufacturing of the units handled. The weight and dimensions even of traditional gearbox designs would still be manageable for road transport and do not pose a logistic challenge.

The upscaling of the traditional Direct Drive turbine design results in high weight loads and thus logistic and installation issues are emerging. Lifting equipment and assembly locations would need to be adapted to suite the dimensions and weights requirements of larger wind turbines.

At present, generators are placed as unique module at the top of the turbine towers, which requires lifting a huge body mass up to 130 meters. With the development of bigger generators the weights and dimensions will increase considerably, requiring new transportation and installation technologies and equipments.

Yaw system

General/Manufacturing:

Yaw moments are caused by asymmetric loads and rotor torque in case the axis is tilted. By introducing appropriate systems on the hub to foresee to incoming wind loads a sudden increase in yaw moment can be avoided. Sufficient lubrication for the yaw gears and bearings will increase their operational performance and compensate the limited movements of the rollers and the movements due to deformations and tolerances in the bearing races. There are no manufacturing limitations due to the size for yaw drives.

Tower - Substructures

Manufacturing:

The current technology is sufficient for the manufacturing of large size thick wall towers while there are enough suppliers in the market available to produce them.

Dimensions of larger support structures can be in general a limiting factor for fabrication. Jacket support structures are mainly limited by the complex design, assembly and manufacturing process. However, this is no challenge specific for larger wind turbines, and can be mitigated by technological advances and a move towards mass production. Floating support structures are difficult to realize both financially and technologically. Moreover, current manufacturing, transportation and port infrastructure can all be limiting factors because of the size and draft requirements of these structures. Manufacturing processes are to be established for serial production.

Logistics/installation:

Substructures are very heavy components that cause difficulties for the handling. Ramming of piles implies environmental issues i.e. the noise created by ramming needs to be restricted with costly methods, there is room for improvements in the methods to achieve this. There are conflicts with other offshore uses predictable in respect to the suppliers, especially if larger quantities of substructures are required. Installation of larger wind turbines sets larger requirements on the lifting and seakeeping abilities of installation vessels. The towing of floating structures is sensitive to the weather. The cranes size is limited so far while the components are very heavy and difficult to handle. These factors imply the development of new wind turbine installation vessels. Environmental issues emerge e.g. for the ramming of piles. Suppliers conflicts especially for larger quantities.

Electrical infrastructure

Manufacturing:

There exists a high market concentration of manufacturers for electrical infrastructures. Only a very limited number of suppliers for sea cables or high voltage DC equipment, or other substation components as transformers are in the market.

Logistics/installation:

Wind farms need to be connected to electricity grids for transmission and distribution of the generated power, and the capacity in the connection point to the grid emerge as a limiting factor. Wind farm developers can be required to cover costs for necessary reinforcement of the grid, increasing the total project costs. For offshore wind farms, the distance to an existing (onshore) grid is generally long, leading to high grid connection costs. For some existing offshore wind projects the costs of grid connection have been found to range from 9 to 26 % of the total costs. However, the existing offshore wind farms are located relatively close to shore, and for future large wind farms located far offshore, these costs will be higher.

With increased wind power penetration level the impact on the system becomes significant, and the integration more challenging. Therefore, grid codes have been introduced, requiring wind power plants to behave more like conventional power plants with synchronous generators. Grid codes thus have been driving the development towards wind turbines with better controllability, but at the same time more expensive turbines.

Up to now, offshore wind farms have AC collection grids operating at MV level, typically 33 - 36 kV, depending on the power rating. The advantage of this solution is that conventional equipment (transformers, switchgear) can be used. The turbines are connected to radial feeders, which have lower cable costs than meshed grids. With increased wind turbine ratings, it can be necessary to split the collection grid into more radials due to thermal limits of conventional medium voltage switchgear. As the sites closest to shore have been developed first, existing offshore wind farms generally have AC transmission. DC transmission is preferred when the distance to shore is more than 80-120 km. BARD Offshore 1 wind farm, currently under development in the German North Sea, will have a HVDC connection to shore, via the BorWin1 converter platform located 125 km from shore. The power rating of the DC connection in 400 MW, and the voltage is +/-150 kV. Other similar projects are under development. Generally, these projects follow the concept of connecting a cluster of wind farms to shore via a common HVDC transmission link, reducing the overall grid connection cost. For offshore wind, VSC HVDC is used instead of the conventional LCC HVDC technology, as it is suitable in weak grids, and also has black-start capability.

In case DC transmission is used, it has been suggested to also have an internal DC collection grid, and with that saving the need for an offshore HVDC terminal. No such solution has been implemented yet, but research is going on. A main challenge is protection and fault handling in such grids.

Operation& Maintenance

The following main conclusions can be drawn regarding technical and logistical barriers of O&M, if upscaled wind turbines are applied in an offshore wind farm:

- The O&M contributes between 22-47% of the total cost for a wind farm along 20 year of operation.
- Highly educated and trained people are required to operate and maintain offshore wind farms.
- Higher failure rates per wind turbine are likely to be expected. However, more research is needed to quantify the increase in the failure rates, since the total number of failures in the wind farm can be lower or higher dependent on the increase in the failure rates.
- Technical restrictions are evident for hoisting large and/or heavy components. However, these challenges are already apparent in the installation phase and have to be addressed there.
- The restrictions for accessing and working on wind turbine are not dependent on the size of the wind turbine.

Offshore accommodation platforms or mother ships are probably needed for far offshore wind farms. These O&M concepts present rather a possibility to reduce cost of O&M than a technical barrier. However, the effect of upscaled wind turbines on the benefit of these concepts needs more research.

Logistics/installation:

The traditional vessels offer limited access to offshore wind turbines. Innovative designs have to be considered for the approach of floating wind platforms. Helicopter access should be considered. Mother ships will have to be implemented far offshore. High difficulties emerge with the recruitment of experienced/educated maintenance personnel.

Introduction: Part A

The possible limitations and future technological barriers for the turbines production and installation is directly associated with the forecasted in wind power targets. For 2020, 2030 and 2050 two different forecast scenarios, see Table 1, were chosen from a study conducted from the Global Wind Energy Council, Greenpeace International and the German Aerospace Centre (DLR)[5]. The scenarios were developed based on a mixture of historical figures, current policies and trends, new market development and discussions of future energy policy.

The more conservative i.e. the Reference scenario, takes into account only existing policies and measures. Based on the projections in the 2009 World Energy Outlook from the International Energy Agency (IEA), it assumes that the annual growth rate in wind power will decrease from 17% to 3% by 2015. After that the annual growth rate is predicted to remain almost constant until 2050. The growth of wind power up to 2050 has been extrapolated from the predicted figures from the DLR. The more optimistic scenario, the Advanced, predicts how the wind industry could grow in a best case, where there is a clear commitment to renewable energy in terms of political incentives and industry´s recommendations. It assumes the wind power growth rate will start off at 27% in 2010 (the actual rate was 23,6% according to WWEA Report 2010[6]), and then gradually decline to 9% by 2020 and drop to 4% by 2030. Both scenarios provide an estimation of possible development range for the future wind power market.

Table 1: Global and EU wind power capacity prediction[5]

			2010	2015	2020	2030	2040	2050
Global	**Reference**	**Scenario**						
Global	Cumulat.	[GW]	185	295	415	572	732	880
Global	Annual growth	[GW]	26,7 (17%)	20,9 (3%)	25,7 (4%)	41,2 (3%)	46,3 (2%)	55,5 (2%)
Global	**Advanced**	**Scenario**						
Global	Cumulat.	[GW]	202	533	1.071	2.342	3.305	4.028
Global	Annual growth	[GW]	43,3 (27%)	87,6 (20%)	120,1(9%)	185,4(4%)	185,4(2%)	185,4(2%)
EU	**Reference**	**Scenario**						
EU	Cumulat.	[GW]	86	138	184	234	n.a.	n.a.
EU	Annual growth	[GW]	9,3	10,4	9,2	5	n.a.	n.a.
EU	**Advanced**	**Scenario**						
EU	Cumulat.	[GW]	87	163	294	515	n.a.	n.a.
EU	Annual growth	[GW]	9,3	15,2	26,2	22,1	n.a.	n.a.

[5] Global Wind Energy Council (GWEC), Greenpeace International: Global Wind Energy Outlook 2010, October 2010

[6] World Wind Energy Association WWEA 2011, World Wind Energy Report 2010, April 2011

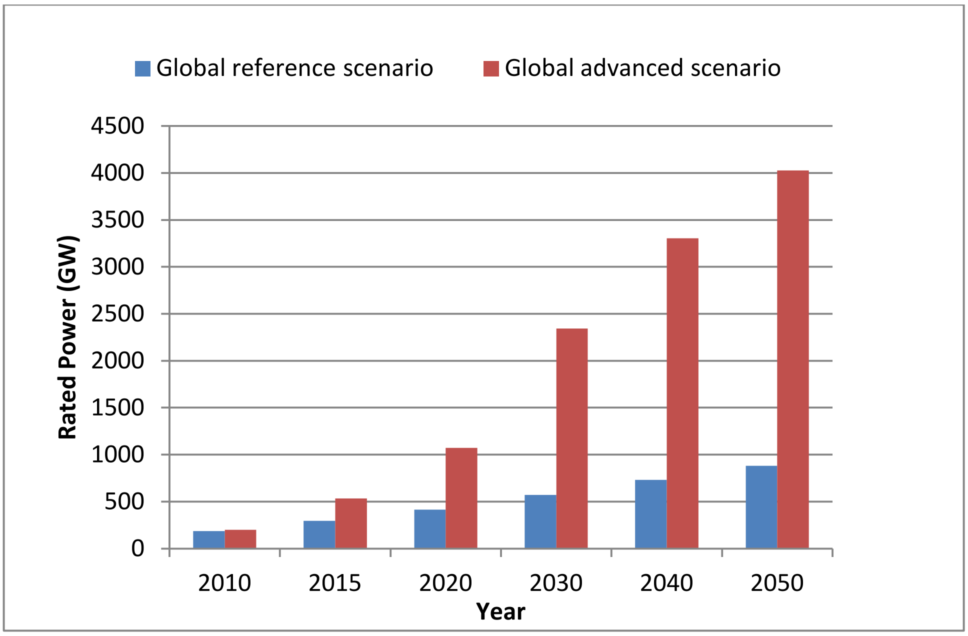

Figure 1: Global wind power forecast until 2050

The forecasted annual growth in wind power capacity only refers to capacity provided by new installations and does not account for repowering. The two scenarios differ significantly with respect to prediction of accumulated wind power and annual growth. For example, the advanced version forecasts 2.300 GW of globally installed wind power in 2030 (vs. 570 GW in the Reference scenario) and an average of 185 GW of annual growth (vs. 41 GW in the Reference scenario). The advanced scenario predicts an almost exponential growth in global wind power up to 2050 reaching a total installed power capacity of over 4000GW and an annual growth of 185GW, which is more than four times higher than forecasted by the reference scenario. The current situation is best represented by the advanced scenario. At the end of 2011 a total wind power capacity of 238 GW (2010: 195 GW) was installed worldwide, including about 4 GW in offshore wind parks. The global annual growth in wind power was 42 GW in 2011 (2010: 35,8 GW).

According to the European Wind Association (EWEA) the total installed wind power capacity until the end of 2011 was 94 GW in the EU, which was enough to supply 6.3 % of EU´s electricity demand[7].

Onshore/Offshore

Beside the forecasted wind power capacity, variations in type and size of turbines to be installed may also impact the amount of material required for blade production. Hence, in order to take into account the future trend in onshore and offshore installations, a forecast in variations of onshore and offshore wind power installations with respect to the total annual installation capacity are listed in Table 2.

Currently most of the onshore wind turbines lie within the 1.6 - 3.5MW power segment, whereas the offshore trend is moving from 5MW to 6-7MW wind turbines[8]. The forecast in onshore and offshore wind farm demand depends on many factors such as the maturity of the

[7] Global Wind Energy Council (GWEC), Release of global wind statistics: Wind Energy Powers ahead despite economic turmoil, February 2012

[8] MAKE Consulting, Wind turbine trends, balancing technology & cost to secure profitable growth

existing wind power market, availability of wind resources and area for installation, as well as grid and energy policies, which varies from country to country.

Today, Europe is the world´s most mature wind market. During 2010 the annual installed wind power in the EU was 9,3GW from which 8,3GW were installed onshore and 883MW offshore[9]. Due to the strict grid codes, limited land availability and weak winds, the EU will increase its focus on installation of large scale offshore wind farms within the upcoming years to meet its policy goals. The global wind market is currently still dominated by onshore wind farms. In 2010 the offshore wind power installation capacity only accounted for 0,5% of its total annual installation capacity. Worldwide 985MW offshore wind power were installed in 2010[9].

Table 2: EU onshore and offshore installation forecast[9]

EU	Scenario	Total wind power	Onshore			Offshore		
		Annual Inst Capacity [GW]	Capacity [GW]	Capacity [%]	Rated power [MW]	Capacity [GW]	Capacity [%]	Rated power [MW]
2010		9,3	8,4	90,5	2,5	0,9[10]	9,5	3
2020	Reference	9,2	6,6	72	3[a]	2,6	28	6[a]
	Advanced	26,2	18,9	72	3[a]	7,3	28	6[a]
2030	Reference	5	2,1	42	3[a]	2,9	58	10[a]
	Advanced	22,1	9,3	42	3[a]	12,8	58	10[a]
2050	Reference	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Advanced	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

[a]: arbitrary assumption

Table 3: Global onshore and offshore installation forecast

Global	Scenario	Total wind power	Onshore			Offshore		
		Annual Inst. Capacity [GW]	Capacity [GW]	Capacity [%]	Rated power [MW]	Annual Inst Capacity [GW]	Capacity [%]	Rated power [MW]
2010		192	191	99,5	1,5	1,0	0,5	3
2020	Ref.	25,7	23,1	90	1,75[a]	2,6	10	6[a]
	Adv.	120,1	108,1	90	1,75[a]	12,0	10	6[a]
2030	Ref.	41,2	30,9	75	2[a]	10,3	25	10[a]
	Adv.	185,4	139,1	75	2[a]	46,4	25	10[a]
2050	Ref.	55,5	27,8	50	3[a]	27,8	50	10[a]
	Adv.	185,4	92,7	50	3[a]	92,7	50	10[a]

[a]: arbitrary assumption

Within the current study a general increase in offshore wind power installations is considered for both the EU and globally. For the EU, the annual wind power installation is forecasted to be dominated by offshore wind turbines by 2050 (25% onshore and 75% offshore). Worldwide about half of the annual wind power installed in 2050 is estimated to come from offshore

[9] European Wind Energy Association (EWEA), Pure Power-Wind Energy target for 2020 and 2030, 2011

installations. Furthermore, the tables also show the development trend in the average rated power of the new installed wind turbines. Within the offshore sector, the average rated power for the EU and global wind market is estimated to undergo a more drastic increase reaching 10MW in 2030 and onwards. Worldwide the onshore wind turbines the average rated power is estimated to slowly increase from 1.5MW to 3MW by 2050, whereas within the EU the average onshore wind turbine size is expected to reach 3MW within the upcoming decade.

In this context some major questions are posed and therefore,

- 'Why larger machines?'
- 'What are the potential advantages of increasing the size of wind turbines?'
- 'Upscaling wind turbines– or advancing the technology?'

Before addressing this question, a qualification is necessary: The use of "size" in this context can be misleading. In the present research will be also considered increases in the rating of a wind turbine, i.e., in the nominal power produced under design wind conditions. This notion of "size" does not necessarily imply larger wind turbines, since higher rotational speeds, higher rotor solidity or better blade design and control can lead to increases in nominal power production without significant increases in rotor diameter. In practice, however, increasing the rating of a wind turbine is most easily achieved by increasing rotor diameter.

Three main answers have been given traditionally to the aforementioned questions respectively:

- Better access to wind resources: Larger rotors extend the swept area to higher elevations where higher wind speeds occur.
- Economies of scale: Existing infrastructure can be more efficiently used, and necessary investments for parts of the equipment are reduced. In particular with regard to siting and the installation, it is typically more cost-efficient to install a single large turbine than a number of smaller machines. A very large turbine can also justify the cost of additional expensive equipment (e.g., LIDAR wind measurement devices) which can lead to improved control and load mitigation, thereby reducing the support structure and overall relative cost.
  Additional reasons can be given: Wind turbine size is regarded to be a metric of progress and such social aspects can work favourably in obtaining public acceptance. Also the electrical infrastructure seems to be better adapted for multi-megawatt sources, which can be an issue for individual and small wind projects[11].Nevertheless, there are likely physical limits to the size of wind turbines. Recent experiences have shown that larger machines could be more costly than smaller machines – with our present limited knowledge and experience with larger machines. Therefore, it is expected that an optimal size of a wind turbine exists. This might already reflected in empirical data, which shows an exponential growth in the size of machines for the past 25 years that recently seems to have stopped[11].
- Given that a wind turbine is a mechano-physical system for power generation, it is relatively straightforward to increase the size of a wind turbine geometrically. This is only of academic interest as long as upscaling does not also lead to a reduction in cost. There are good reasons why larger machines should be more economical, on the long-term, but the key point to note is that upscaling and technological advances are two distinct processes by which the cost of wind energy can be reduced. Ideally, both go

[11] Jamieson P: *Innovation in wind turbine design.* Wiley-Blackwell, 2011

hand in hand, and a probable scenario is that research and interest in larger wind turbines will also lead to more efficient technological solutions for smaller machines.

The present report is aiming to summarize the technological barriers in upscaling wind turbines and also investigate the potential markets for the installation of 10MW wind turbines. Therefore it is consisted of two distinct parts.

In Part A, a technical description of the costs of energy for state of the art offshore projects is followed from a more specific analysis for each of the turbine parts. The goal is to investigating the future development limiting factors and bottlenecks, associated with materials, manufacturing, supply chain, logistics, and installation. In that framework of the future wind turbine development is attempted based on the upscaling concept, stressing out the considerations and the challenges towards larger turbines and reduced cost of energy. Potential technical progresses are also discussed.

In Part B a global research of the potential markets for 10 MW offshore wind turbine installation is described. Driving parameters were the natural resources and the availability of natural terrains i.e. coastal areas, along with available infrastructure. Political issues e.g. stability, corruption, public acceptance and policies for renewable incentives were also considered base on international standards.

1 Cost of energy

1.1 Description

Within the energy sector one of the most important drivers for the business is the Levelized Cost of Energy (LCoE)[12] i.e. the normalized cost for a specific source to produce kWhs over the lifetime of e.g. an offshore wind farm over 20 years.

For the offshore wind projects a simple formula (Eq.A1) for the LCoE is:

$$\boldsymbol{LCOE} = \frac{\sum_{t=1}^{n} \frac{C_I + C_{O\&M} + C_{Fuel}}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E}{(1+r)^t}} \qquad \text{(Eq. A1)}^{13}$$

where

C_I: Investment cost for the offshore wind farm [€]

$C_{O\&M}$: Annual Operation and Maintenance cost of the offshore wind farm [€/yr]

C_{Fuel}: Cost for fuel (this cost is zero since the wind resource is for free) [€/yr]

E: Annual energy production (kWh)

r: Discount rate

n: Life of the system

The LCOE is a parameter that can be compared to other energy sources and can be optimized either with minimizing the nominator or maximizing the denominator. All the details for the estimation of the LCOE are presented in the following paragraphs.

It should be noted that no special financial issues are included in the aforementioned formula i.e. discount issues, future replacement, degradation costs, etc which will be required for a complete analysis.

1.2 Cost of components and values for a typical offshore wind farm

The costs of an offshore wind farm can be divided into main components as the wind turbine, sub-structure, installation of the wind turbine / sub-structure, electrical infrastructure (inter array cable, offshore substation, export cable to shore), project management and assessments, operation and maintenance, and decommissioning. Cost values for these categories are presented in Table 4 based on different sources. All values are transferred to €/MW by using the exchange rate of the respective year.

[12] T.K. Jacobson, Materials technology for large wind turbine rotor blades - limits and challenges

[13] http://en.wikipedia.org/wiki/Cost_of_electricity_by_source (accessed 21st June 2012)

Table 4. Cost numbers for offshore wind farms

All values in €/MW	**Fingersh et al. 2006**[14]	**ODE 2007**[15]	**Douglas Westwood 2010**[16]	**EWEA 2009**[17]	**Kaiser et al. 2010**[18]
	Modell based calculation, 3 MW turbine shallow water	Information collected from industry, wind farm 90 * 3,6 MW	Own calculations, wind farm near shore 600 MW	Horns Rev and Nysted, turbine split based on 5 MW turbine	Market research and models
Turbine incl. tower	729 000	776 000	1 368 000	815 000[a]	
Blades	98 000		274 000	181 000	
Hub	25 000		68 000	22 000	
Pitch	25 000			32 000	
Main shaft	28 000			15 000	
Gear box	125 000		205 000	105 000	
Generator	65 000		57 000	28 000	
Electronics	128 000		194 000	70 000	
Yaw drive	14 000			11 000	
Main frame, nacel. cover	63 000		23 000	34 000	
Tower	127 000		342 000	214 000	
Other	31 000		205 000	16 000	
Sub-structure	297 000	141 000	490 000	350 000	
Installation	265 000	235 000	399 000	b	448k – 739k
Electr. Infrastr.	247 000	541 000	524 000	355 000	
Project manag., others	32 000	235 000	308 000	160 000	
O&M	1 440 000	541 000	1 596 000	1 120 000	
Decommissioning	47 000				104k – 125 k

a – inclusive installation, b – included in turbine cost

14 Fingersh, L.; Hand, M.; Laxson, A. (2006): Wind Turbine Design Cost and Scaling Model. National Renewable Energy Laboratory (NREL) (NREL/TP-500-40566)
15 ODE (2007): Study of the costs of offshore wind generation. DTI (Department of Trade and Industry). United Kingdom (URN--07/779)
16 Douglas Westwood (2010): Offshore Wind Assessment for Norway. The Research Council of Norway.
17 EWEA (2009): The economics of wind energy. With assistance of Søren Krohn, Poul-Erik Morthorst, Shimon Awerbuch, María Isabel Blanco, Frans van Hulle, Christian Kjaer
18 Kaiser, Mark J.; Snyder, Brian (2010): Offshore Wind Energy Installation and Decommissioning Cost Estimation in the U.S. Outer Continental Shelf. Energy Research Group. Baton Rouge (Louisiana)

The cost values are dependent on the underlying assumptions for cost calculations and large differences can be observed for several cost categories. The total cost are in a range of around 2.5 million €/MW to 4.7 million €/MW. The total cost value of Douglas Westwood is more than 50 % higher than the other values and the wind turbine costs are more than 70 % higher. No good explanation for that deviation could be found. These cost information can always be of indicative character since cost are dependent on several external factors as for example the market development, steel prices, day rates for vessels etc. The share of the different cost categories compared to the total cost is presented in Table 5. These values can indicate where a reduction of cost may have a significant impact on the total cost.

Table 5. Shares of the different cost categories

Turbine components in % of turbine cost	**Fingersh et al. 2006**Error! Bookmark not defined.	**ODE 2007**Error! Bookmark not defined.	**Douglas Westwood 2010**Error! Bookmark not defined.	**EWEA 2009**Error! Bookmark not defined.
Turbine incl. tower	24%	31%	29%	29% [a]
Blades	13%		20%	22%
Hub	3%		5%	3%
Pitch	3%			4%
Main shaft	4%			2%
Gear box	17%		15%	13%
Generator	9%		4%	3%
Electronics	18%		14%	9%
Yaw drive	2%			1%
Main frame, nacelle cover	9%		2%	4%
Tower	17%		25%	26%
Other	4%		15%	2%
Sub-structure	10%	6%	10%	13%
Installation	9%	10%	9%	b
Electrical infrastructure	8%	22%	11%	13%
Project management, others	1%	10%	7%	6%
O&M	47%	22%	34%	40%
Decommissioning	2%			
Total	100%	100%	100%	100%

a – inclusive installation, b – included in turbine cost

The cost shares show that turbine cost stand for around 25 – 30 % of the total cost, and with the sub-structure and the installation cost, these components are responsible for around 45 % of the costs.

Cost shares for electrical infrastructure have a share between 8% and 22 % depending on the source. Expenses for O&M in the life time of the offshore wind farm stand for 22 – 47% of the total cost. These numbers shows that a high uncertainty is connected to the O&M costs. In addition, the O&M costs for the whole life time for an offshore wind farm have to rely on estimates and models due the fact that no offshore wind farm has reached the end of the life time up to date.

The cost structure of an offshore wind farm gives an indication where cost improvements can have a high impact on the total cost. Even though the cost numbers show that the costs per component can vary quite significantly and are depending on underlying factors. In addition, these numbers cannot be used to give cost estimate for a future offshore wind farm with upscaled wind turbines. We will look more into this aspect in the next chapter.

1.3 Cost development under consideration of upscaled wind turbines

The use of upscaled wind turbines with higher rated power in an offshore wind farm will have direct consequences for the cost per MW installed capacity. We assume that the total capacity of the wind farm is given. Therefore, the use of upscaled wind turbines will lead to a reduced number of wind turbines needed. We will look into how this affects the individual cost components of an offshore wind farm:

- Turbine cost
- Foundation cost
- Installation cost
- Electrical infrastructure cost
- Project management, others
- O&M costs
- Decommissioning cost

Turbine Cost
The price of a wind turbine measured in €/MW are quite stable according to real price data derived from producers. Figure 2 shows the price developments of wind turbines with rated power between 2 MW and 5 MW.

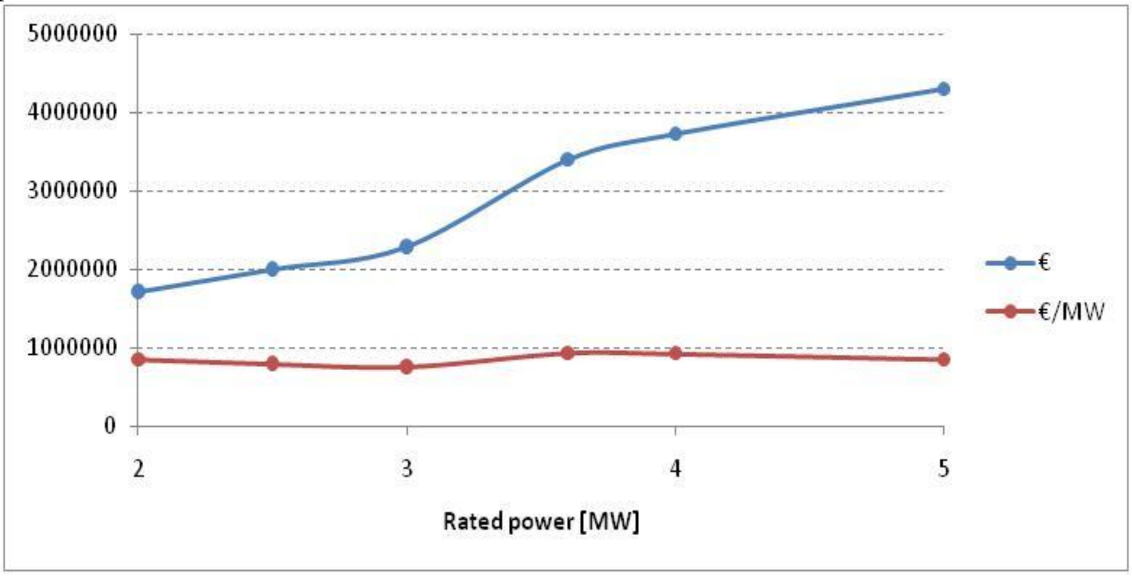

Figure 2. Price trends of wind turbines with size (based on data from ODE 2007)

The price trend implies constant cost per MW, but relies also on several uncertainties. First of all price cannot directly translated into cost since several other factors have an influence on the price as for example the supply and demand for wind turbines. Secondly, it is difficult to give a prognosis for the price development for wind turbines larger than 5 MW based on these data. Thirdly, different turbine technologies may be used for the different rated power.

In addition, the Upwind project[19] came to the conclusion that the levelized cost for upscaled wind turbines will increase. This is due to the fact that the weight of the turbine increases faster than the power for pure geometrical upscaling and weight can be simplified seen as costs. The cost increase differently for the individual turbine components and Fingersh et al.[14] developed simplified cost formulas for all components as presented in

Table 6.

Table 6 . Simplified cost formula for wind turbine components

Component	Simplified cost formula
Blade	const * rotor radius ^ 3 + const * rotor radius ^ 2.5 + const
Hub	const * rotor radius ^ 2.5 + const
Pitch	const * rotor radius ^ 2.7
Low speed shaft	const * rotor radius ^ 2.9
Main bearings	rotor radius * const + rotor radius ^ 2.5 * const
Gearbox	Machine rating ^ (1…1.25) * const
Generator	Machine rating * const
Electronics	Machine rating * const
Yaw drive	const * rotor diameter ^ 2.96
Mainframe	const * rotor diameter ^ (0.85…1.953)
Tower	const + const *swept area * hub height
Component	Simplified cost formula

Based on these cost formula, it can be expected that the cost per MW of the wind turbine will increase. However, the cost increase is only valid when pure upscaling without a change of technology is applied. It is possible that the cost will increase less or even stay stable when new technologies are applied as indicated in Figure 2.

Sub-structure
The cost of the sub-structure increases linear with the rated power of the wind turbine according to Fingersh et al. (2006). Therefore it can be expected that the cost per MW will not increase and be stable when scaling up the size of the wind turbine.

Installation cost
The installation cost are dependent mainly dependent on the number of wind turbines and sub-structures that have to be installed. Since less wind turbines are needed to reach the total capacity, it is assumed that the installation cost per MW will decrease.

Electrical infrastructure cost
Fewer turbines mean also fewer inner array cables to connect the turbines to the substation. All the other electrical cost as for the substation and the export cable are only dependent on the total capacity of the wind farm and not on the rated power of the single wind turbines. Therefore a small decrease of the cost per MW can be expected.

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[19] Sieros, G.; Chaviaropoulos, P.; Sørensen, John Dalsgaard; Bulder, B. H.; Jamieson, P. (2012): Upscaling wind turbines: theoretical and practical aspects and their impact on the cost of energy. Wind Energy 15 (1), 3–17

If the total capacity of the wind farm is not fixed, but the wind farm area, the use of upscaled wind turbines would lead to higher total capacity even though the spacing between the turbines has to be increased due to larger wake effects. In this case, the cost per MW would decrease more significantly since the installation cost for the electrical infrastructure is a fixed part of the costs.

Project management, others
The cost for site assessment and project management cost are only to a small part dependent on the number of turbines. Cost can be saved due to less soil investigations and the complexity of the project is slightly reduced so that some minor savings in the project management will occur. Besides this the cost are independent from the number of turbines. Therefore a minor decrease of the cost per MW can be expected. Moreover, as for the electrical infrastructure cost, the cost per MW will decrease more significant if the wind farm area is the fixed value and not the capacity of the wind farm due to a large part of fixed cost in this cost category.

O&M costs
Fewer turbines should lead to a lower total failure number and less total planned maintenance activities. Even though, the single maintenance activities will be more costly due to the larger wind turbine components, a significant decrease in maintenance costs can be expected. On the other hand, operational costs are more or less independent of the wind turbine size and will be equal. As a result, the O&M costs per MW will decrease with when using wind turbines with higher rated power.

Decommissioning
As for the installation cost, the decommissioning cost are mainly dependent on the number of wind turbines and sub-structures. Since the number of wind turbines is reduced, a decrease of the cost per MW can be expected.

In summary, it can be concluded that the cost per MW are reduced for almost all cost components of an offshore wind farm if the turbines are scaled up. The turbines themselves are the only exception, since a significant increase of the cost per MW can be expected. In total this increase of wind turbine costs exceeds the savings of the other cost components as indicated by the Upwind-project (Sieros et al. 2012)[19]. Their results showed an increase of cost of energy in the range of 5 % when upscaling from 5 MW to 10 MW and 15 % when upscaling from 5 MW to 20 MW. But it has to be kept in mind that this only applies for pure upscaling without changes in technologies.

The construction cost of offshore wind farms, measured per MW, indicates an upward trend with increasing size of wind turbines, see Figure 3. The size of the bubbles represents the number of the turbines in the wind farm.

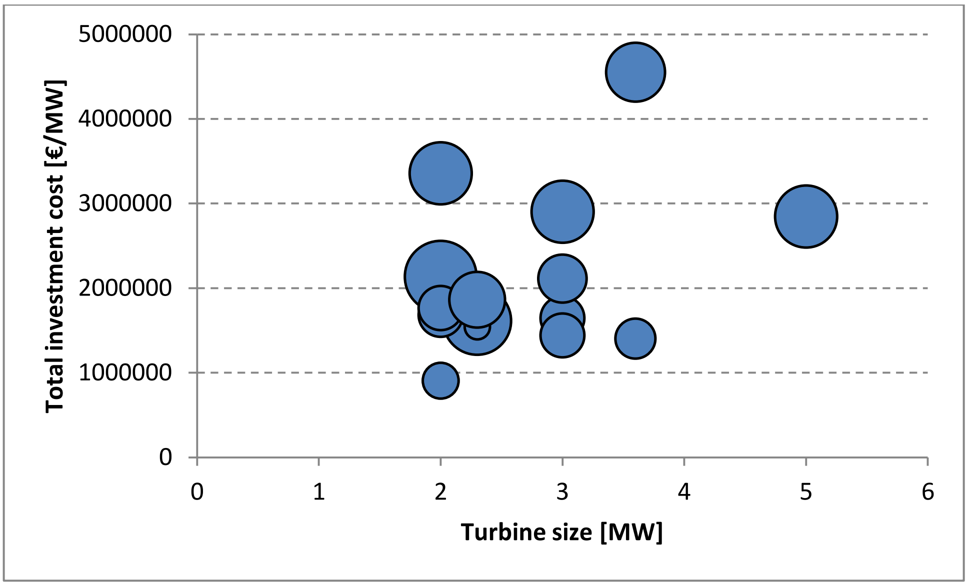

Figure 3. Construction cost of offshore wind farms in relation the wind turbine size (based on data from Snyder and Kaiser 2009)[20]

Even though the upward trend is only shown for the total construction cost, the cost increase can be related to the cost of the wind turbines, since it can be expected that the other cost components as installation, electrical infrastructure, etc. have stable cost per MW or even a decrease in cost with larger turbine size as explained earlier. In addition, the turbine costs are responsible for a major part of the construction cost as shown in Table 5. However, this trend can be only an indication and not a proof since cost components can change significantly from year to year as for example installation cost that are highly dependent on day rates for renting installation vessels.

1.4 Comparison of the Levelized Cost of Energy

Based on (Eq. A1) and the available data in **Error! Reference source not found.**, the levelized cost of energy for the offshore wind parks were calculated assuming a discount rate of 2%. Note that the formula does not include financing issues, future replacement or degradation costs, etc. which would be required for a more accurate calculation. The levelized cost of energy per kWh for the offshore wind is presented in
Table 7.

Table 7. Levelized cost of energy

Farm		Fingersh et al. 2006	ODE 2007	Douglas Westwood 2010	EWEA 2009	Kaiser et al. 2010
Capacity factor	(%)	38,13	-	27	35,5	-
Levelized cost of energy	(€/MWh)	506	-	603	504	

[20] Snyder, Brian; Kaiser, Mark J. (2009): Ecological and economic cost-benefit analysis of offshore wind energy. In Renewable Energy 34 (6), pp. 1567–1578. Available online at http://dx.doi.org/10.1016/j.renene.2008.11.015 (accessed 21st June 2012)

This simplistic approach should be treated with caution. It cannot be directly compared to the literature [21] since the calculation formulas and the considered assumptions might be different. A first comparison shows a 10-30% difference to the maximum predictions of the Levelized Cost of Energy of the offshore wind. This at least indicates that there are a lot of challenges to overcome in order to be competitive with onshore but also other energy sources like natural gas[21].

[21] Bloomberg New Energy Finance (BNEF) LCOE model as of Q4 2011

2 Blades

2.1 General

Over the past decades there has been a significant increase in turbine size. Up to 2010 over 80% of wind turbines had a rated power of 1.5MW to 2.5MW, about 8,4% of the wind turbines had a rated power of greater than 2.5MW and the rest are of the size up to 1MW. The future wind market foresees the trend to go towards bigger turbines with larger turbine blades. By 2014 is expected more than 43% of the operating wind turbines to have a rated power greater than 2.5MW[8]. At the same time the percentage of large scale wind turbines with blades greater than 45m will increase from 13% to 76% of the overall wind market[8]. The increased mean wind velocity with height drives the development towards larger wind turbines having larger power output per unit rotor area. This means that the offshore wind turbines will be exposed to more demanding environmental conditions. Hence, challenges are posed in terms of achieving adequate turbine design and operating strength, blades manufacture process and blade transportation, which are explained later in the manufacturing chapter.

2.2 Up-scaling calculations of wind turbines with glass fiber blades

Currently the largest wind turbines under operation have a rated power of over 7.5MW and a rotor diameter of 126m. As for the next 10 to 15 years the wind industry anticipates wind turbines with a rated power of 8 to 10MW and a rotor diameter of 180 to 200m. Blade size up-scaling, implemented as a tool for projecting the current know-how to the future, is facing many challenges. Limits faced within material technology development and during wind turbine blade manufacture are explained later in the following paragraphs.

In order to take into account the wind turbine development trend of increasing blade length and greater power capacity, a simple up-scaling calculation of turbine blade lengths was carried out within the current study. (Eq. A2) was used for the estimation of rated power for a given blade radius, which also takes into account the additional swept area due to the hub. The hub radius was defined as a function relative to the blade length based on a series of figures from commercial blades, see Table 8[22]. Furthermore, an average wind power density of 350W/m² (Table 9) was derived from a series of wind power density values of commercial wind turbines at 12m/s. In general the wind power density, also known as the specific power installation, may vary for different turbine designs and operating site conditions[23].

$$\boldsymbol{P = \pi\left(R + (0,5729e^{0,0144R})\right)^2 \times 390W/m^2} \qquad \text{(Eq. A2)}$$

where

P: rated power of wind turbine (W/m^2)

R: Turbine radius/blade length (m)

[22] http://www.repower.de/de/wind-power-solutions/windenergieanlagen/ (accessed 21st June 2012)

[23] J.P.Molly, Rated Power of Wind Turbines: What is Best?, DEWI GmbH, Wilhelmshaven

Table 8. Hub radius of commercial blades

Wind turbine	Blade length	Hub radius
	m	m
N.A.	25	0,852
Repower-3.2M82	40	1
Repower-3.2M92	45,2	1,05
Repower-3.2M104	50,8	1,2
Repower-3.2M114	55,8	1,2
Repower M6	61,5	1,5

Table 9. Wind power density of commercial turbines

	Blade radius	Rated power	Swept area	Wind power density
	m	MW	m²	W/m²
Repower	61,5	5	12425	402
Mervento	57	3,6	10679	337
Enercon	50	3	8228	365
Enercon	61	7,5	12224	614
Enercon	41	2,3	5551	414
N.A.	48	1,5	7587	198
Average				388 ≈ 390

The blade weight for the different blade lengths was calculated based on a blade mass development curve for glass fiber turbine blades, which was developed by a study done by the Fraunhofer Institute for Wind Energy and Energy System Technology (Figure 4)[24]. Within the Fraunhofer study a series simplified blade scaling calculations were carried out based on the design of the NREL 5MW 61.5m baseline turbine. The calculated results for blades having a length of 11.6m (DEBRA blade lentgh), 30m, 40m, 90m and the 61,5m NREL blade are indicated as results in Figure 4. Overall the calculated blades have shown a very similar trend line compared with some typical commercial blades of the blade manufacturer EUROS and LM. The blade mass is given by the equation:

$$\boldsymbol{W = 0,00017166 \times L_{Blade}{}^{2,83357828}} \quad \text{(Eq. A3)}$$ [24]

where

W: weight of the blade (t)

L_{Blade}: length of the turbine blade (m)

[24] F. Sayer, Internal Study, Bremerhaven: Fraunhofer Institut für Windenergie und Energiesystemtechnik, 2010

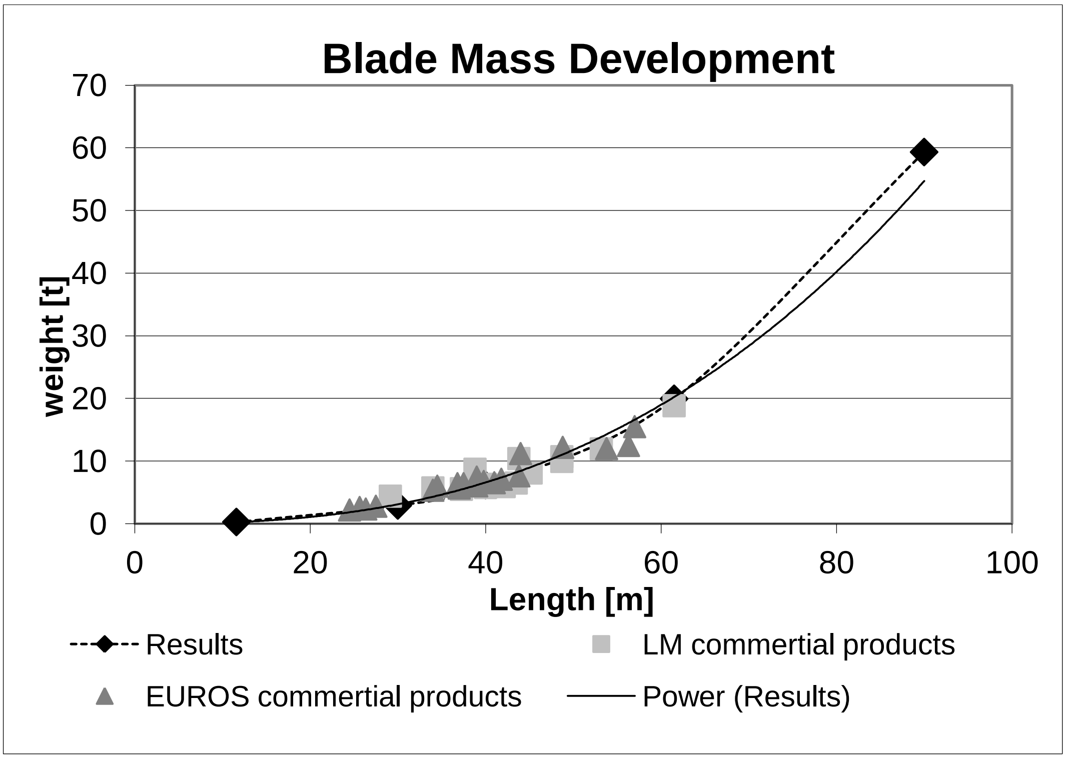

Figure 4: Blade mass development curve for glass fiber blades[24]

Figure 5 shows a decreasing trend in turbine´s power per unit mass with respect to the blade length for the glass fiber blades from the calculation model above. This indicates that by just upscaling the overall blade efficiency is reduced by increasing the length of the turbine blade. It should be noted that for the up-scaling calculations the same blade design was assumed for all blade lengths. For comparison purposes the graph also displays the specific power of up-scaled turbine blade models from the Sandia National Laboratories (SNL) Wind Energy Department[25]. Within their study for an 100m all glass baseline wind turbine blade, potential up-scaled wind turbine blade models were developed and analysed based on the 61,5m blade of NREL´s offshore 5MW baseline wind turbine. The specific power in both cases decreases significantly with larger blade lengths.

[25] D. Todd Griffith and Thomas D. Ashwill Sandia Report, The Sandia 100m all-glass baseline wind turbine blade: SNL 100-00

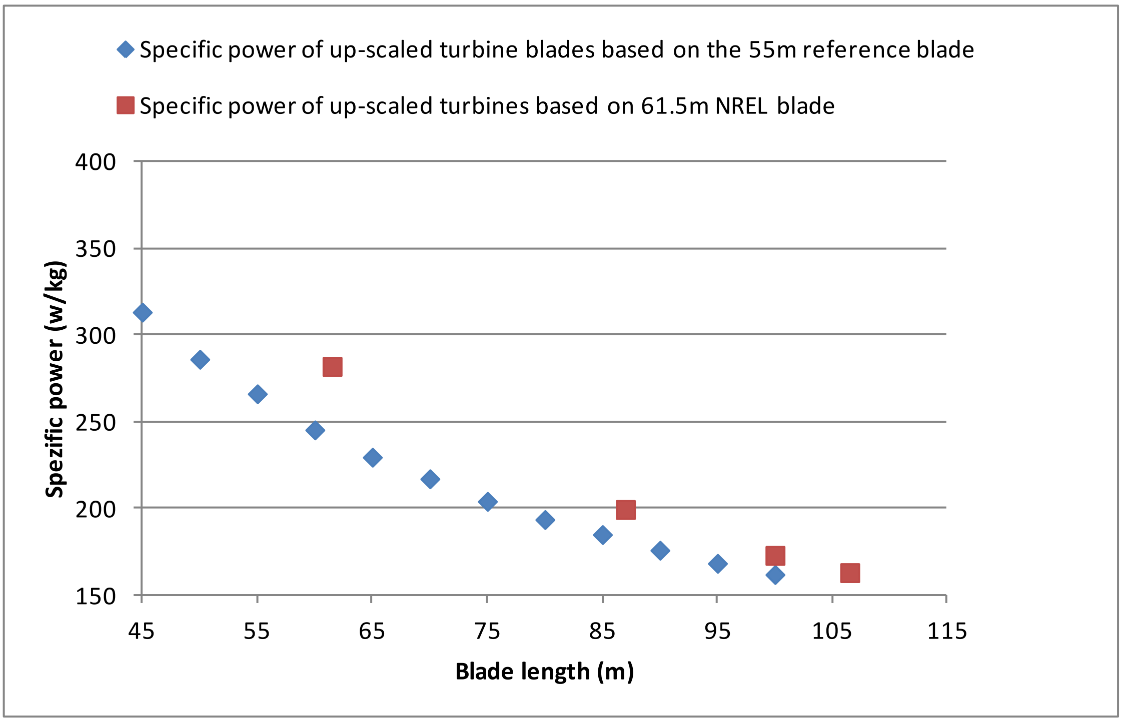

Figure 5: Specific power in W/kg vs blade length

Even though larger wind turbines can generate greater amount of total wind power, the efficiency of larger wind turbines has still to be optimised in the future. The significant decrease in specific power displayed by the up scaling results indicates that improvements in current blade designs or alternative new blade designs and technology are required, to achieve similar or better efficiency than the smaller blades.

A potential approach to increase the specific blade power output can be achieved by load mitigation through smart blade designs. Load reduction is foreseen by incorporating structural bend-twist coupling within the blades. This innovative technique allows passively reduced loads by twisting to feather. As rotor blades increase in length the blade loading is subjected to increases by a larger proportion than the amount of power; therefore, load reduction will enhance 10, 15 or 20 MW blade designs. Karaolis, N. (1989)[26] was one of the first to examine the feasibility of bend-twist coupling in wind turbine rotor blades, and showed the initial potential to couple the bending and twist response for load reduction. Of note since his original work was that conducted by Sandia National Laboratories, USA in designing a 9 m rotor blade that incorporates bend-twist coupling. This rotor blade was designed, manufactured, and laboratory tested to prove its feasibility and usefulness with generating positive results in the laboratory and test field. Bottasso[27], et. al. from Politecnico di Milano, Italy conducted some of the most recent work (2011) in designing a rotor blade with utilizes bend-twist coupling and analyzing its performance in cooperation with an active rotor pitch system. Through intelligent incorporation of bend-twist coupling in a rotor blade design this work showed the ability to

[26] Nicos M. Karaolis, The Deisgn of fiber reinforced blades for passive and active wind turbine rotor aerodynamic control, University of Reading, 1989

[27] C.L. Bottasso, Optimisation-based study of bend-twist coupled rotor blades for passive and integrated passive/active load alleviation, Politecnico di Milano, Milano, Italy, December 2011

reduce blade mass while also reducing the loading on the rotor blade and further on to the rest of the system.

2.3 Typical materials on wind turbine blades

Depending on the wind turbine blade design, there is also a variation in the amount of materials used within the blade. At present the dominating materials used within turbine blades are fibre-reinforced plastics, core materials and adhesives. In general glass fibres are more common for the manufacture of turbine blades.

In order to have an estimation of the material deployment for the turbine blades, the material weight distribution of a 55m reference glass fibre blade model developed by the Fraunhofer Institute was taken as a baseline, see Figure 4[24]. Within the current study it was assumed that the proportion of turbine materials within the up-scaled turbine blades remains the same as in the reference turbine blade. This approach may be conservative for the wind turbines with large blade size, as it assumes the same blade design and hence the same material and weight distributions for all blade lengths. Hence, the approach doesn't account for possible design and material limitations during blade up-scaling, such as limitation in structural strength for longer blades, which in turn will affect the type and amount of material used within the blades.

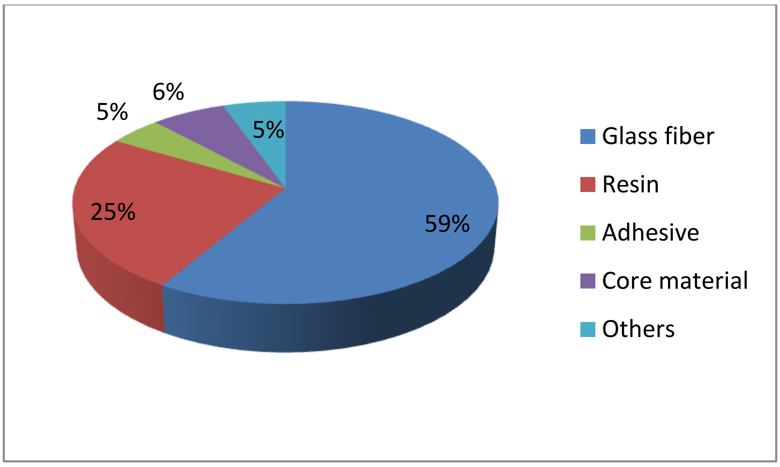

Figure 6: Material weight distribution for the 55m reference turbine blade

2.3.1 Use of carbon fiber within wind turbine blades

A big challenge of larger turbine blades is the increased blade weight and the need for higher material stiffness. The heavier the blades are, the higher is the wind speed needed to turn the rotor, which in turn affects the turbine efficiency. Hence, in place of the predominantly used fiberglass, carbon fibre reinforced polymer is increasingly used as an alternative material for blade reinforcement, to achieve lighter and stiffer blades, which will increase the specific power output per unit blade mass. Within the wind industry carbon fibre reinforcements are introduced into the blades to increase their global stiffness, as well as for the reinforcement of the blade root.

2.3.2 Turbine material forecast

The availability of material resources is crucial for large- scale manufacturing of wind turbines. The current study focuses on the most important materials used for turbine blade manufacture. Based on the figures forecasted, estimation of annual material demand for turbine blade manufacture was carried out, see Table 9. The main factor influencing the material demand is given by the difference in energy forecast from the two scenarios. Overall due the increase in energy demand, the amount material required for production is also increased. In order to evaluate whether these production rate would be realistic, the current production status of these materials is reviewed within the next chapter.

Table 9: Predicted annual demand of main materials required for future production of wind turbine blades

Global	Scenario	Total			
		Glass fiber	Resin	Adhesive	Core
		(t)	(t)	(t)	(t)
2020	Reference	138.984	58.891	11.778	16.490
	Advanced	649.491	275.208	55.042	77.058
2030	Reference	270.495	114.617	22.923	32.093
	Advanced	1.217.229	515.775	103.155	144.417
2050	Reference	473.885	200.799	40.160	56.224
	Advanced	1.583.031	670.776	134.155	187.817

2.4 Material properties, production and availability

The selection of suitable materials for the turbine blades depends on various factors, where the main criteria are high material stiffness, low density and long-fatigue life. From the operating point of view high material stiffness is required to minimize blade deflection, hence maintain optimal aerodynamic performance. Gravitational forces can be reduced by employing low density materials such as composites. In order to reduce material degradation long-fatigue life is also required.

The mechanical design of a rotor blade corresponds nominally to a beam. To enhance the selection of materials the merit index is introduced to compare the performance of different materials in terms of stiffness and weight. The merit index[28] is defined in Equation A4, where E is the material stiffness and ρ is the material density. The general design aim is to achieve a specified bending stiffness at minimum structural weight, which can done by having the highest merit index value. For example the two superimposed arbitrary merit index lines with M_b =0.003 and 0.006 in Figure 5 represent a range of material, which fulfill the material selection criterion. Materials along the merit index lines are equally good in stiffness to density ratio while lighter and stiffer materials lie above and to the left of the merit index lines.

As a second selection criteria the absolute material stiffness is chosen, which is represented as a horizontal line on the graph. A stiffer material will cause less deflection in beam, which is an important design criterion for the dimensioning of the rotor blades. Depending on the turbine design a particular stiffness level in blade is required for maintaining the tip to tower clearance. For the actual example, a material stiffness range between 10 to 20GPa will give a sensible deflection in beam design. On the graph an arbitrary line at E=15GPa is shown for demonstration purpose. As result most of woods, some composite and porous ceramics are excluded from the selection.

$$\boldsymbol{M_b = E^{1/2}/\rho} \qquad \text{(Eq. A1)}$$

[28] M.F. Ashby, Material selection in mechanical design, 1993

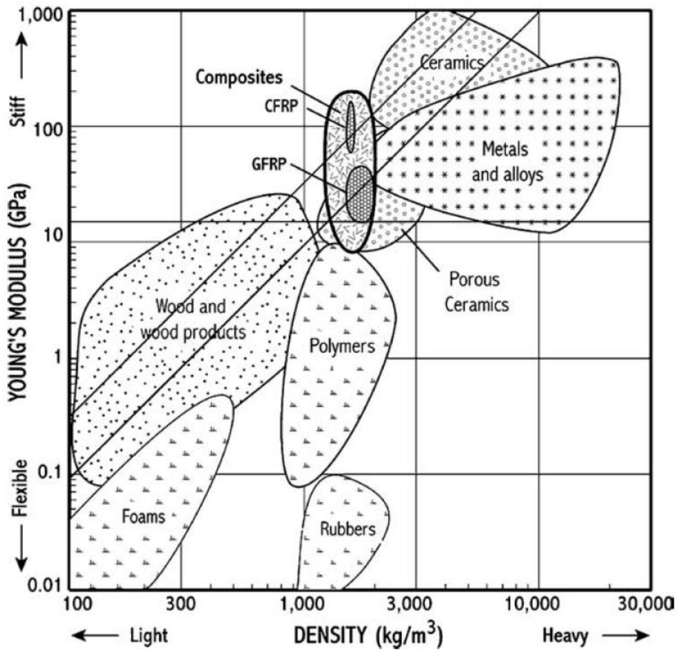

Figure 7: Stiffness versus density diagram for all material[29](Copy right by Annual Reviews)

Despite the material strength it is also required to include the fracture toughness of the material within the selection procedure. High material toughness for blade materials is required to increase the blade ability to resist fracture caused by high fatigue loading. A similar diagram displaying the material toughness in relation to density can be found in the study by Ashby, 1993[28]. Potential materials, which fulfil these requirements, are in this case wood, composites and ceramics. Ceramics can be eliminated due to their low fracture toughness per unit area for good fatigue resistance[29].

Due to the good material properties of composite materials such as high specific density, good fatigue performance and relative low price, they have been mostly used for turbine blades construction. Table 10 displays some of the main fibre types used for turbine blades. Although Aramid fibres provide an overall moderate mechanical performance, it is not used for the manufacture of turbine blades due to its high material cost and low compressive strength. As previously described the two main fibre types used today are E-glass, carbon or hybrid combination of the two.

Table 10: Material properties of main fiber types [30]

Fibres					
Type	Stiffness E GPa	Tensile strength GPa	Density Kg/m^3	Specific stiffness GPa/ Kg/m^3	Cost Euro/kg
E-Glass	72	3500	2540	0,028	2-3
Carbon	350	4000	1770	0,198	15-20
Aramid	120	3600	1450	0,083	19-31

[29] Povl Bronsted et al. , Composite Materials for Wind Turbine Blades, April 2005

[30] Professor Mike Kessler, Blade Materials

A large gab is noticed between E-Glass and Carbon raw material costs i.e. a factor of 7-10, as long as in the specific stiffness. Innovative materials in between these ranges could be considered as alternatives for wind turbine blade manufacturing.

2.4.1 E-glass

Fiber glass, also known as glass-fiber reinforced plastic (GFRP), is a fiber reinforced polymer made of a plastic matrix reinforced by fibers of glass. The plastic matrix may be a thermosetting plastic e.g. epoxy or thermoplastic. The basic raw materials for fiberglass products are a variety of natural minerals and manufactured chemicals. The major ingredients are silica sand, limestone, and soda ash.

The extrapolated IEA data showed that in 2010 the global glass fiber production was at 140 Mt/y[31]. Until 2050 the future global production volume of glass fibers are said to be uncertain due to different influencing factors. For example, the production and costs of the composites are mainly influenced by the cost and demand of the plastic matrix used to impregnate the fiber glass. The availability and costs for resins are expected to fluctuate, as they are made from petroleum-based chemicals. Overall, the global glass fiber production volume in 2050 can be assumed (in analogy with other materials) to increase by two to three times than the current production, i.e. producing 280 to 420 Mt of glass fibers per year.

2.4.2 Carbon fiber

Carbon fibers deliver a far better strength to weight ratio compared to glass, with 2457kNm/kg and 1307 kNm/kg respectively. However, the deployment of carbon fibers is still limited due to its high material costs. Currently the cost of carbon fibers is about 15-20 Euro/kg, where the typical price of E-glass ranges from 2-3 Euro/kg (1-2 pounds/kg)[32]. Hence, it is often most economical to use a mixture of glass and carbon for the design of turbine blades[33]. Exceeding a certain size the use of carbon fibres will become viable in spite of their 15-20 times prices increase over glass fibres, due to the fact that their weight required for the stiffness of a very large blade will be far lower than that of a glass fiber blade and therefore the cost advantage will be compensated.

Worldwide the global demand in carbon fiber has been increased from 24.000t in 2009 up to about 36.000t in 2011. Further increase in market capacity is expected within the up-coming years. The majority of the carbon fiber produced is used for the manufacturing of different composite materials.

2.4.3 Resin

Resins are widely used within different industry sectors such as packaging, building and construction, automotive ect. For the manufacture of wind turbine blades different types of resins are used to impregnate the fibers or for the production of adhesives. The two most popular systems used are polyester and epoxy. Resins, adhesives and cores are expected to

[31] J.P. Birat et al, Technology offer for production goods and services, Qualitative description of the links between social services and technologies in a post- carbon society and data for energy and CO_2 intensity of materials, June 2011

[32] http://www.netcomposites.com/composite-guide-glass-fibre-fiber.html (Gurit) (accessed 21st June 2012)

[33] Gasch R., Twele T., Wind Power Plants. Fundamentals, design, construction & operation, Springer

fluctuate, as they are made from petroleum-based chemicals. The resin is crucial for the laminate performance as it connects the fibers into a load-sharing system.

Epoxy resin

In 2008 the worldwide production of epoxy was at 1,6 Mio tonnes [34]. The primary raw material resources for the production of epoxy are petrol and natural gas, in some case coal is also used. The primary raw material required for the production of 1 kg epoxy is shown in Table 11, where for examples the use of additives is not taken into account.

Table 11: Raw materials required for the production of 1 kg epoxy resin[34]

Fossil fuels (kg)	3
Mineral raw materials (kg)	2,6
Water usage (excl. cooling fluid) (l)	19

For 2020, the Advanced scenario predicts 649.491t of resin are required for blade production, meaning that about 1948Mt of petrol and 12340Ml of water would be needed. This huge amount of petrol and water required could be a limiting factor for the epoxy resin production.

Currently it is estimated that 22% of global water use is industrial, with high-income countries using 59%, and low-income countries using 8% only[35]. The current industry is reliant on water for all levels of production, as it can be seen from tremendous amount of water required for the resin production, where water used for cooling has not been accounted yet. The high growth in global population, global industrialization and urbanization, will lead to an overall increase in demand for water. Water crisis are already present within different part of the globe. With the increased water use by humans, a reduction in water available for industrial purposes is caused. Hence, new manufacturing processes requiring less water need to be developed.

Polyester

During the early stages of wind turbine blade mass production, Polyester was used as the main resin material, a technological transfusion from the boat building industry. The major change from hand lay-up to resin transfer moulding technology enhanced though the epoxies implementation. Still, polyesters remain easier to process after the infusion process i.e. they require no post curing and they are at least three times less expensive[36]. Epoxies are currently preferred instead of polyesters mainly because of health/environment issues i.e. absence of toxic styrene vapours during production and because of smaller slope of the S-N curve in the GL recommendations[37].

[34] Bundesministerium für Verkehr, Bau und Stadtentwicklung, Grundstoffe, Epoxidharze: http://www.wecobis.de/jahia/Jahia/Home/Grundstoffe/Kunststoffe_GS/Epoxidharze_GS) (accessed 21st June 2012)

[35] http://academic.evergreen.edu/g/grossmaz/SCHROEBJ/(accessed 21st June 2012)

[36] D.A. Griffin, Blade System Design Studies Volume I: Composite Technologies for Large Wind Turbine Blades, Sandia report, SAND2002-1879, 2002

[37] Germanischer Lloyd, 'Rules and Regulations, IV-Non-Marine Technology, Part I: Wind Energy, Hamburg, Germany, 2003, pp. 5-19

Alternatives

Research for new materials is in progress towards the production of very large (>70m) wind turbine blades. Major aspects are the manufacturing process and the material row costs. Therefore, polyurethane is discussed as an alternative matrix material, with superior tensile fatigue and inter-laminar fracture toughness and fatigue crack growth compared to current resins.[38]

2.4.4 Adhesives

The state of the art research for adhesives is conducted in two major fields. Process wise it is very important to reduce the curing time, enhancing reduction in the mould life cycle, while at the same time prolong the pot life improving the application process. Further decrease of the exothermal reaction will mitigate the mould worn out reducing the investment costs. The other main direction is adhesives with higher elongation to breakage that can avoid early crack initiation.

The use of Nano-materials in adhesives to increase shear strength and the use of nano-fiber fabrics and nano-sizing of glass and carbon fibres will allow for better mechanical properties[39,40]. Currently those materials are still very expensive.

2.4.5 Core materials

In wind turbine blades core materials are used for the manufacture of spar caps, connecting the two GRP plies. The main mechanical purpose of the core material is to transfer existing load within the spar cap on to the load carrying laminates. The most common core materials used for turbine blades are balsa wood and low-density polymer foams such as polyvinyl chloride (PVC), polyethylene terephthalate (PET), polymethacrylimide (Acryl) and styrene acrylonitrile (SAN). Typically foams used for blade construction have a density between 60kg/m³ and 200kg/m³ and a shear strength of 0.3 to 3.9MPa.

End grain balsa is used to produce high quality composite cores with high shear and compressive strength. In addition the mechanical properties of balsa cores are not very temperature sensitive compared to foam cores. Due to their relative high density (minimum 100 kg/m³), balsa cores are generally applied to areas where weight reduction is not considered as a major design factor. Balsa wood is often used as local core reinforcement at the blade root section. With the huge increase in demand, availability of balsa wood might cause material supply issues based on the current growth rate of balsa trees. The majority of the worldwide balsa wood supply comes from Middle- and South America. Its fast growth rate allows 50% of the wood to be commercially sold after 5 years of its growth period[41].

[38] U. E. Younes, F. W. Bradish, "Polyurethane composites for wind turbine blades". JEC Composites Magazine (2012), No.70.

[39] "3B Fiberglass, Nanocyl to develop nano-sizing for glass". Composites World (2011), http://www.compositesworld.com/news/3b-fibreglass-nanocyl-to-develop-nano-sizing-for-glass (accessed 21st June 2012)

[40] "Hybrid glass/carbón nanofabric". Composites world magazine (2011), http://www.compositesworld.com/products/hybrid-fiberglasscarbon-fiber-nano-textile-fabric (accessed 21st June 2012)

[41] http://www.sharewood.com/index.cfm?sID=21&sprache=1 (accessed 21st June 2012)

Among the rest of applied core materials, PVC are most widely used for blade core production. PVC foams are closed-cell, moisture resistant, and have good physical properties when compared to other foams of similar density (50-150kg/m³). Generally PVC foams are distinguished between two main types: uncured and cured PVC foams. Uncured PVC foams, e.g. Airex R63, provide a higher toughness and better flexibility, and then can be easier formed under temperature increase. Cure PVC-foams have better mechanical properties, higher resistance to temperature and are harder. The main disadvantages of PVCs are the high material costs and the hydrochloride acid produced during heating. Overall, the manufacturing process is very energy intensive.

Polyethylene terephthalate (PET) foams are still relatively new on the market and is said to be the core material of the future[42]. It is one of the cheapest foam cores on the current market that can withstand high material processing temperature (150°C), having though a higher density (100kg/m³ [43]) compared to other foams. Wind-specific PET is offered by almost all of the major core material suppliers, where emphasis is made on material´s recyclability. PET is the most abundant polymer in the world and is the primary material for all water and beverage bottles. Table 12 shows some examples of typical prices from suppliers and are based on the minimum purchase quantity.

Table 12. Core material density and cost data

Type	Material	Density (kg/m³)	Euro/kg (m² by 10mm)
Baltek SB 100	Balsa wood	150	17
AirexC71.75	PVC	80	39
AirexT92.100	PET	105	15

2.4.6 Coatings

Surface protection for wind turbine blades are required to withstand the harsh environmental conditions both onshore and offshore, which lead to erosion or reduced power performance of the blades. Hence, special coating systems are applied to blade surfaces to enhance their operational lifetime, ability to withstand UV radiation and moisture, as well as to mitigate dirt on the blade surface with anti-fouling performance. Furthermore, the coating material should be non-toxic and should be harmless to the applicator.

Typically the manufacture of all blades requires an in-mould UV stable gel coat, as the finished blade surface or a process coat that is painted on to the blade after production, helping to protect the resin from unwanted damage-degradation effects like erosion and brittleness. Process coatings, when used as the final coating of the blade, will cause an increased processing cost due to their complex formulations. Hence, it is often considered to be more efficient and cost effective to use lower process coat, which provides a good sand ability and reparability.

Blade edges are prone to erosion faster than the rest of the blade. Therefore, special coating systems for the blade edges are required additionally to the full blade surface gel coat. While full blade coatings aim primarily to provide a smooth, aerodynamic and resilient surface over the entire blade, edge surface coatings are more focused on providing high strength and flexibility, UV stability and good impact and abrasion resistance[44].

[42] Jeff Sloan, Composite Technology, Wind foam sources: PET, SAN & PVC, January 2010, http://www.compositesworld.com/articles/wind-foam-sources-pet-san-pvc (accessed 21st June 2012)

[43] Kernwerkstoffe in Rotorblättern, Fraunhofer IWES internal report

[44] http://www.duromar.com/product-finder/wind-energy-solutions (accessed 21st June 2012)

The manufacture of surface coatings varies from company to company. Typically surface coating consists of epoxy resin and hardener. Due to the excellent adhesive qualities of epoxy resins, special care must be taken with regard to the mould preparation. Hence, high gloss finish mould release systems are applied to the mould surfaces.

An innovative approach for blade surface protection is to use protection tapes, which was introduced by 3M in 2007. They provide effective erosion control for the leading edge of turbine blades. The tape is made from a very tough, transparent, abrasion-resistant polyurethane elastomer that resists puncture, tearing and erosion. It can be applied at the OEM facilities or in an O&M situation, either on the ground or up-tower. Blade can be out into services 4hrs after application at 22°C. Direct application eliminates a coating step, which saves time while providing additional leading edge protection[45].

2.5 Manufacturing

The rotor blade production is manpower dominated while automation within the processes is still limited. The two most common manufacturing procedures used for rotor blade production are prepreg-auto clave and resin infusion methods such as Vacuum-Assisted Resin Transfer Moulding (VARTM) and Seeman Composite Resin Infusion Moulding Process (SCRIMP). These production methods have replaced the wet layup method, which was initially employed for turbine blade production.

Nowadays, the majority of blade manufacturers use VARTM due to its lower cost production costs compared to prepreg technology. In VARTM, the liquid resin is transferred into a closed mould to impregnate the fibre preform placed inside the mould cavity. To ensure complete wetting of the fibres vacuum is applied to draw the resin through the cavity. The resin is then cured and forming the final composite. The composites manufactured using VARTM methods have high fibre content with relatively few air voids. Due to the high moulding pressures and temperature the moulds can be relatively very expensive.

Prepreg sheets contain fibres pre-impregnated with uncured resin. Multiple fibre sheets are placed into the mould to build the required composite. The fibres are covered in a plastic bag, where air is removed using a vacuum pump. The composite is cured by placing the mould into an autoclave. Prepreg materials have optimized and consistent resin ratios. This method gives a composite with an optimized fibre volume content resulting in high stiffness and strength properties. By using vacuum bagging and autoclave, the health and safety issues are reduced. Prepreg materials are for example used by top manufacturers like VESTAS and GAMESA[46]. However, this manufacturing method requires high capital equipment cost and is labor intensive. Therefore, manufacturers try to avoid making costly design changes in order to maximize the use of existing tools, limiting possible design optimizations and variations for rotor blades.

The typical manufacturing (VARTM) process steps for a 60m blade are presented in Table 13, where the total cycle time is 23 hour[47]. Noticeable is the significant long curing time required, which accounts for almost half of the production time required. Hence, improvements in curing process technology are required in order to decrease overall production time and produce less

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[45] http://finance-commerce.com/2008/10/3m-taps-into-windpower-business-with-new-wind-tape8217/ (accessed 21st June 2012)

[46] Douglas S. Cairns et al, SANDIA report, Wind Turbine Composite Blade manufacturing: The need for understanding defect origins, prevalence, implications and reliability, February 2011

[47] SGL Rotec (Lars Weigel) - Wind energy components, Ways to manufacture rotor blades for MW turbines, IQPC Conference Bremen 2.2012

damage to the moulds due to wearing. The ageing process of the moulds can lead to vacuum leaks, making the moulds unusable and therefore requiring to be repaired.

Table 13: Blade production steps[47]

Process step	time [h]
lay up (glass and sandwich)	4
preparation for infusion	1
Infusion	2
Curing	4
web bonding	1
Curing	3
shell bonding	2
Curing	5
demolding and preparation of mould	1
Cycle time	23
Curing time	10

The future goal is to have more energy efficient and automated production processes, which lead to shorter production and processing times, higher productivity, reproducibility, process security as well as exactness in production i.e. meeting the required tolerances in positioning and material alignment. Many manufacturers are aiming to reduce or eliminate touch labour in some of the key time-consuming manufacturing operation, such as the glass layup.

The state of the art automated process in the wind turbine blade manufacturing include use of x-y ply cutting for material kits, automated ply nesting software, pick and place automation. The use of material transfer systems into open moulds is limited, primarily with semi-automated or driven A-frames and gantries. Although also limited advanced automated systems i.e. robotic arms are developed for the trimmining (root trim), drilling for T-bolts installation, application of coatings, surface grinding and finishing processes[48].

Blade parts like spar caps and root section appear as the next possible step for fully automated process.

Another crucial approach to increase the overall productivity will be to develop resins and master the processing technology around speeding up the curing process for the resins. The aim is to decrease the curing time from hours to minutes. One possible development for the next generation material systems are UV or electron curing resin systems. The use of liquid materials with near-to-zero emission will also provide a good working environment.

The production capacity of blade manufacturers depends on various factors, such as production technology used, size of the production facilities, number of moulds and existing manpower. Currently the typical production output is about one blade per day per mould. The continuous increase in blade length requires new and bigger moulds to be developed by the leading turbine OEMs and suppliers. However, this trend is not expected to have a major effect on the overall production capacity as new capacity requirements are expected to be achieved through either

[48] http://web.mit.edu/windenergy/windweek/Presentations/Nolet_Blades.pdf (accessed 21st June 2012)

retooling existing facilities or closing existing facilities with smaller blade sizes while establishing new facilities for longer blades[49].

In 2011 the global blade production capacity is estimated to be around 90GW from which over 60% of the capacity is produced in Asia pacific and the rest 40% is shared by Europe and America. Currently more than 10 of the 15 top turbine manufacturers fully or partially insource blades due to their strategic priority items in terms of technology and manufacturing ownership. This has resulted in a highly competitive market for independent blade manufacturers. However, the forecasted rapid growth of the wind turbine market and high manufacturing capital costs for localization is expected to increase hybrid sourcing strategy among turbine OEMs and increase the market opportunity for independent suppliers[49].

2.6 Blade failures

2.6.1 Manufacturing flaws

Manufacturing defects caused during blade production can lead to significant reduction in strength and lifetime of blade structure. Hence it is crucial to study the cause of these defects and improve existing manufacturing processes to reduce potential rotor blade defects. Nowadays rotor blade manufacture is still highly labour intensive, which leads to a lack of repeatability and accuracy. Manufacturing defects caused by human or material compatibility errors during production may occur randomly with respect to type, size and location and cannot be avoided.

Some of the major flaws are: dry spots, wrinkles, fiber misalignment, porosity, incompletely cured matrix and bonding errors i.e. lack of adhesive, kissing bonds. Depending on the size of the geometric imperfection, the global buckling resistance may also be greatly reduced.

One of the most common manufacturing flaws is dry areas, i.e. insufficient reinforcement impregnation. Dry spots can emerge due to different errors during the manufacturing process, i.e. contaminated reinforcing fibres, air voids, fault in the infusion process, etc. Air voids can be built due to un-tight vacuum bags, existing air at the resin front during the infusion process or insufficient resin degassing. This type of failure within the composites can significantly reduce the compressive strength of the composite structure.

For prepreg, the delaminations can also be a result of poor consolidation during the curing process. Under fatigue loading delamination can lead to high stress concentrations, which can result in further growth and major reduction in the blade fatigue life.

Insufficient or inaccurate bonding of the blade components is rather frequent e.g. voids in the bondlines, kissing bonds that emerge due to the adhesive contraction during the curing process, tolerance mismatch and drawbacks of the manual application of the adhesive e.g. material discontinuity. In addition, inappropriate adhesive mixing process and insufficient degassing will introduce air into the bonding paste affecting its bonding properties.

As blade length increases, thicker laminates are manufactured especially inboard, at root area. Due to the high material volume, the exothermic reaction, the high temperature during the curing process along with the different contraction performance amongst matrix and the fibres, results in local waviness i.e. undulation. Waviness within the laminate plies potentially causes instability issues i.e. buckling resulting in local or global failure of the blade. This critical flaw cannot be easily repaired. Material suppliers i.e. resin and fibres should coordinate the optimization of the composite system performance.

[49] MAKE Consulting, Supply Side, Market Report, June 2011

Inaccurate positioning and misalignment of the fibres will also cause a reduction in laminate stiffness and strength. These can be eliminated by using laser positioning method for the laminates, however the plies can be dislocated again during the vacuum infusion process.

It is rather difficult to identify visually this type of defect during the production process and therefore Non Destructive Techniques (NDT) e.g. ultrasound, tapping or shearography are implemented. All three methods are time consuming and require highly trained operators. For the future, faster and more automated inspection methods are desired, which will allow more blades to be inspected within less amount of time and providing more comprehensive results than the state of the art methods. For example, automated 3D visualisation technique such as computer tomography could potentially provide more detailed information concerning the specific size and location of the flaws.

2.6.2 Operational failure

During their operational life rotor blades are subjected variable load amplitudes and extreme environmental conditions, which often lead to small damages up to complete failure of the wind turbine. Some typical blade failures due to alternating or static loads are delaminations, trailing edge splits, panel cracks, buckling instabilities in panels or shear web, bondline cracking. Typical failures due to environmental conditions are leading edge erosion, lightning protection damage due to strikes and local surface cracks due to hail.

The data analysis of 45 blades showed that a large proportion of the blade damages are caused due to lightning and impact of foreign objects such as rain, hails and birds, which accounts for 36% of the blade failures[50]. These failures sources are highly dependent on the nature of the operating environment and cannot be eliminated. Blade failures caused by the tip hitting the tower are either due to overestimation of the blade stiffness or underestimation of the load imposed on the blade, which can be minimised by having adequate blade to tower clearance. Bondline failures within the blades usually develop with increasing number of operating cycles due to fatigue loading. Finally, as described above manufacturing defects such as air voids within the blade skin and core material and improper curing of the composite can also lead to blade failures. Main causes of blade failure are:

- Lightning (20%) & Foreign Object impacts (16%)
- Tip hits the tower (13%)
- Adhesive Bonding failures (20%)
- Voids in skin and core (18%)
- Improper Cure (13%)

For large offshore wind turbines the distribution of blade failures will be different due to the harsher operating environment and higher tip speed. Here, erosion protection of the leading edge is very important, as damage at the leading edge will result in uneven blade surface rotor imbalances and significant loss in power production. For offshore rotor blades, rain erosion emerges as a significant challenge for the surface coating as the blade is also exposed to the impact of salty sea water, which will accelerate the erosion process. Since there is no noise limitation for offshore wind turbines, the rotor blades operate at a much higher speed. The costs of repair for offshore wind turbine are significantly higher than for onshore wind turbines. Blade tip and leading edge erosion can especially be an issue for two bladed designs that run with high tip speeds.

Operational failures of turbine blades are very crucial as they impact the overall reliability of the wind turbines. Although wind turbines are designed for a lifetime period of 20 years, it is

[50] D. Hartman, Analysis of Wind Turbine Blade Failure Modes, Presented in Composites & Polycon 2006, Owens Corning

difficult to provide an accurate prediction of the expected life, due to the lack of operational data over the total life period for wind turbines. Harsh operational environment and existing manufacturing inaccuracies result in component failures prior the expected lifetime of wind turbines.

A ten year study program on turbine failure (1994-2004) revealed that the components with the highest exchange rates were blades (2.4%) and generators (2.2%). In addition, over the period of operating life no particular trend in the development of reliability for turbine blades can be observed. The number of annual incidents seems to occur randomly as shown in below in Figure 8 and Figure 9. Noticeable is the relatively high failure rates of turbine blades, which seem to be damaged at least once per year.

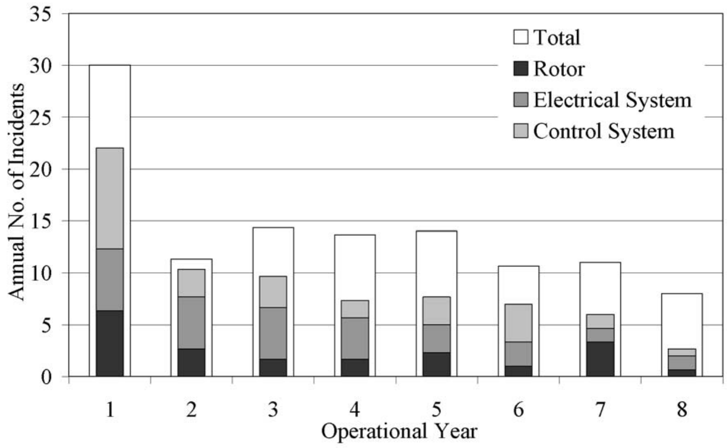

Figure 8: Example 1 of component failure rates of a MW wind turbine per year of operation[51]

(Copy right by ASME International)

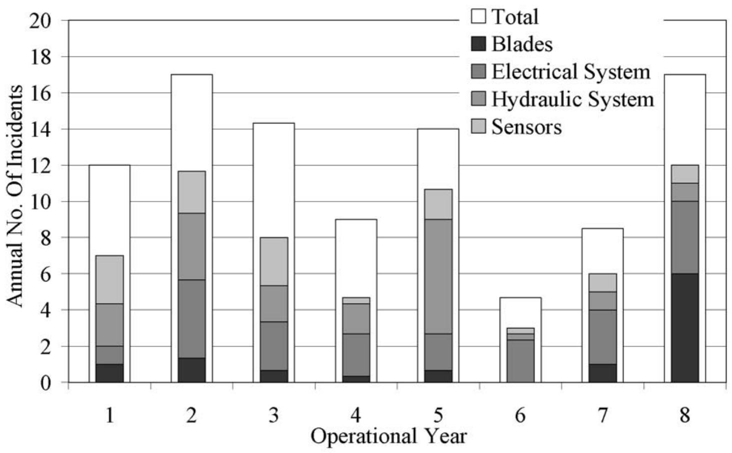

Figure 9: Example 2 of component failure rates of a MW wind turbine per year of operation[49] (Copy right by ASME International)

Turbines operating in locations with low temperatures and icing conditions will have to provide a suitable blade heating system. The system should to be suitable to be integrated in the large blade design. Developed ice on the blade surface would have a negative impact on the

[51] E. Echvarria et al, Reliability of wind turbine technology through time, Journal of Solar Energy Engineering, November 2008

aerodynamics and the power output of the turbine while changing the blade eigenfrequencies. This could result in significant fatigue loading and turbine imbalance.

2.7 Sub-component testing

Currently wind turbine blades are certified through material characterization tests and a single full scale blade test. Material characteristic data obtained from coupon tests are used for the design of blades. Full scale static and fatigue blade tests are required for the certification process and have to be preformed prior the actual production of a new turbine blade. This means when major changes in design, production or material are made in certified blades, new full scale blade tests have to be performed. With the increase in turbine blade size, the design, manufacturing, testing and operational costs will increase significantly, resulting in a drastically higher risk for the designers, manufacturers and investors. Hence, the importance of having an optimal and reliable blade design becomes even more significant. In addition, standard coupon tests and certification blade tests are not able to predict some of the occurring failure modes during the operational life of blades. Blade failures caused due to manufacturing, material defects or design faults cannot accurately detected using these current test methods.

Therefore, a reliability based certification methodology is needed, bridging the gap between the coupon scale and the full-scale testing with providing insight on the material structural performance, enhancing the validation of the actual calculation models.

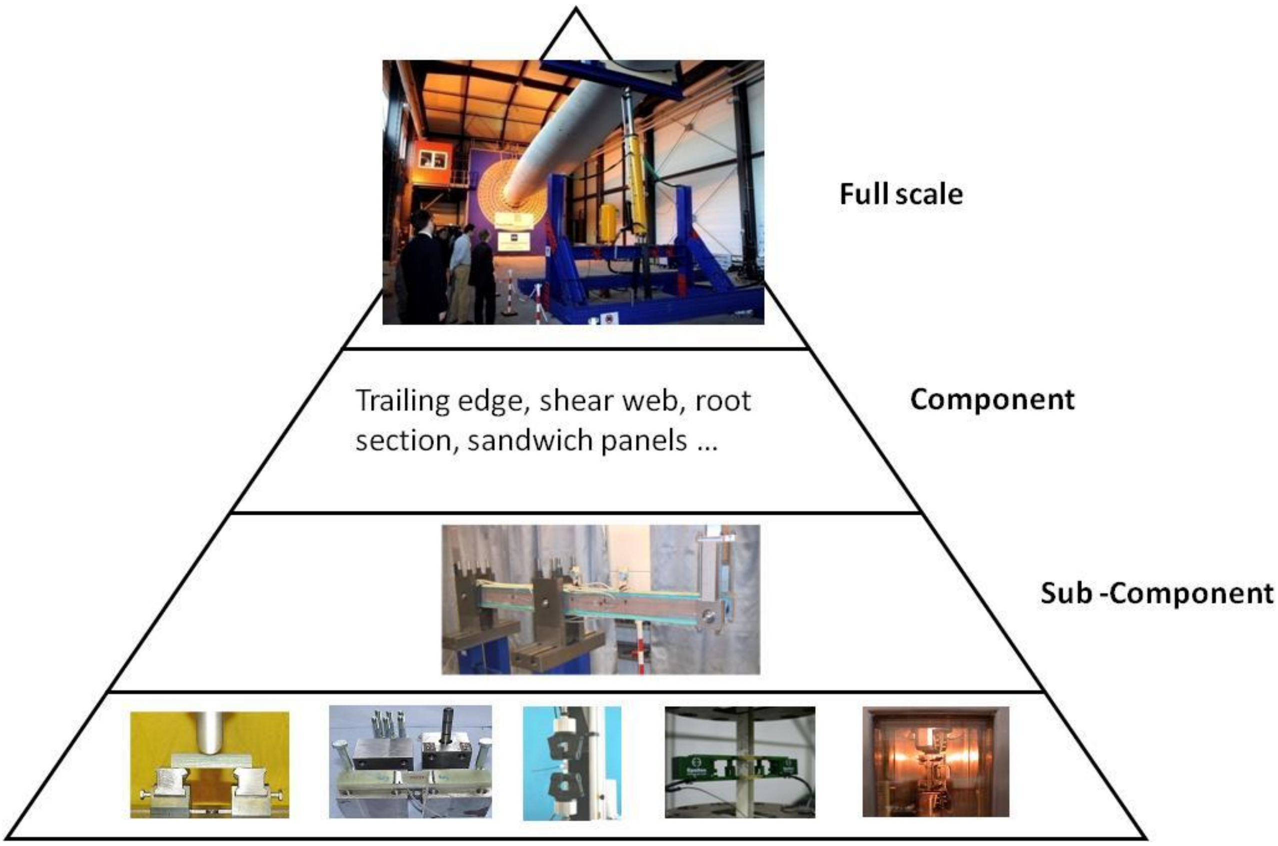

Figure 10. Incremental testing procedure from material properties to blade structure certification

Figure 10 shows a proposed test pyramid for improving structural reliability in wind turbine rotor blades, which is divided into four testing stage. Information obtained from material characterisation tests provides a basis for the proceeding tests. Sub-component tests are developed and performed for the investigation of the effect of specific complex stress states of structural failures while taking into account the material properties. The information obtained for structural failures can be used for optimising component testing for parts like blade root trailing edge and shear web to spar caps adhesive joints. Finally a full scale blade test is performed for the certification of the blade[52].

Overall sub component tests will enhance the design optimisation of different blade sections, as it allows design changes made to be investigated in more detail based on a series of tests, before testing the final blade design in full scale. Furthermore, sub-component testing allows manufacturing defects to be analysed systematically in terms of size and location and their effect on the overall structural performance. New conceptual designs can also be investigated and tested within the sub-component testing level.

The sub-component test idea is based on well established practices implemented in the aerospace sector. Moreover, in the wind sector there are also published studies, focused on the adhesive joints in specific parts of a wind turbine blade. Sayer et al[53] introduced an I-beam specimen investigating the structural strength of the bondline between shear-web and spar-caps. Samborsky et al[54] investigated the static and fatigue strength of structural details of wind turbine rotor blades.

2.8 Blade recycling

The average life span of wind turbines are 20 to 25 years. Efficient methods of recycling are necessary to avoid huge waste production from a non-renewable energy producer. Currently, there are two recycling methods for wind turbine blades such as mechanical recycling and thermal recycling.

Mechanical recycling is divided into three process steps. First the blades are removed and cut into smaller pieces at their operating locations. The small pieces of the blades are transported to a separate processing plant, where crushing hammer are used to smash the cut blades into much smaller pieces, while also serving to pound the resin out of the fibres. Producing two types of recyclates, where the finer pieces are separated from the coarser ones, as they have different applications. These recyclates may be used in various applications, such as an alternative to wood fibre in particle board, or as reinforcement in asphalt[55].

The finer recyclates have an especially low density which helps reduce the mass of its new construction, but the finer pieces also absorb more resin than others, which ultimately diminishes their performance. Though coarser recyclates absorb less resin than finer pieces, it is impossible to eliminate the entire resin residue. As a result, coarse recyclates have difficulty bonding with new materials. Mechanical crushing produces dust which is harmful[55].

Through the thermal recycling method, wind turbines are burned. The polymer within the turbine material is combustible and, when burned to 500 degrees Celsius, produces solid substances or liquid hydrocarbon products that can be turned into energy for the production of

[52] A. Antoniou, F. Sayer, A. van Wingerde, Application of sub-component tests to bond line investigation for wind turbine blades, Fraunhofer IWES

[53] F. Sayer, F. Kleiner, A. Antoniou, M. Trusheim, A. van Wingerde, Sub-Component Testing for Adhesive Bond lines for Wind Turbine Blades, DEWEK 2010, Bremen 2010

[54] D.D. Samborsky, A.T. Sears, J.F. Mandell, O. Kils; Static and Fatigue Testing of Thick Adhesive Joints for Wind Turbine Blades; 2009 ASME Wind Energy Symposium

[55] http://www.altfuelsnow.com/wind/wind-turbine-recycling.shtml (accessed 21st June 2012)

electricity. Leftover glass fibers may be used in glue, paints and concrete. Leftover carbon fibres may become part of new composite materials.

2.9 Logistics and Installation

Large size blades can hardly be transported on roads any more. Not only because of the length that requires reasonably straight trajectories even with steering on both ends, but also because of the flatness of the roads, limited slopes and hill tops that will be required to avoid contact of the blade with the ground.

Dedicated fabrication facilities close to ports or shippable rivers are required. Another reason for onshore transports to be unfeasible are the chord size of the blades that can’t even be overcome with turning mechanisms on the transport trucks to allow to turn the highest chord out of the way for the passage below bridges and other obstacles that limit height, but allow to turn the blade back into a position where the width of the transport is reduced.

Very large blades need special lifting devices to avoid damages due to installation. Single crane assemblies get more and more difficult. The large turning moments resulting from unbalanced aerodynamic loading during the lifting are difficult to control. Maximum wind speeds for installation are reduced even further and limited weather windows for installation are the consequence.

Split designs and material combinations (e.g. Enercon steel/glass fibre split blade) might overcome some of the issues for transport by limiting the size of the components again, but would also increase the preparation work for installation and would require additional resources for quality control. In case of laminated joints the environmental conditions for the manufacturing of these joints need to be controlled very carefully to achieve long lasting joints without quality issues.

3 Pitchsystems

3.1 General/Manufacturing

The stall system is not an option for turbines larger than approximately 1MW. Thrust loads are getting too big and consequently the towers and foundations will get heavier. In all large turbines the pitch regulated design is implemented nowadays.

Until Smart Blades design will implement passive control allowing for performance without pitch drives to achieve the speed control i.e. bend/twist coupling and flaps to limit the lift in very large blades, the conventional systems will have to be assumed for the future very large turbines. The weight of the blades and their inertia do play an important role for the dimensioning of the pitch systems and might get into issues with very heavy blades for very large rotor diameters. Individual pitch control will allow limiting the loads for the turbines and therefore as a direct consequence the weight of the components as base frames, towers and foundations.

In case of electric yaw drives with pinions, the lubrication of yaw gears and bearings will have to consider forced lubrication to compensate the limited movements of the rollers and the movements due to deformations and the play in the bearing races. This is especially important for the teething of traditional pinions of pitch drives that suffer from considerable wear otherwise due to the relative movement due to the deformations. This is also due to the fact that the gears only work on a very limited sector of the ring gear of the bearing and are engaged often in the same position for longer periods. The quality control for pitch teething on the bearings will also have to be rigorous to avoid premature wear and the surface hardness of pinion and ring gear has to be adjusted to each other. The bearing manufacturers usually assume a stiff connection surface for their bearings. In case of the blade connection this is not the case. Under the loads, the hub, the pitch bearing and the blade root undergo a cyclic loading that results in relative movement of the pitch gearing. The lubrication medium easily gets pressed out of the contact area of the teeth and needs to be pressure fed to avoid damage to the tooth surface. Also for the bearing the lubrication needs to be addressed to avoid premature wear.

In case of the hydraulic pitch systems the gearing issues are not relevant. There the questions are more with the complexity of accumulator systems and possible leakages on the hydraulic system. The bearing issues though apply as well.

The size limitation in manufacturing is not as dramatic as the stiffness challenge resulting in deformations at blade root hub connection and the related consequences for the bearings.

3.2 Logistics/installation:

The logistics for the bearings is not more complicated than that of the hub, since the connecting diameters will have to match.

4 Hub

4.1 Manufacturing

Founding of large pieces has technical difficulties to it. There is only a limited number of suppliers that can provide large foundry pieces with the technical specifications that a wind turbine hub requires. Different designs with new materials (fibre reinforced materials) might provide a possibility to resolve this. To maintain the rigidity of the hub with increased blade root diameters will be an issue, since the blade bearings mounted to the hub will suffer from increased relative movements. Bearing issues will result from excessive load induced deformations. These have been addressed already in medium size turbines with additional webs parallel to the pitch bearing planes or additional stiffening of the bearing with steel plates between blade and hub[56].

4.2 Logistics/installation

The size of the hubs and the fact that they can't be divided makes them difficult to transport on the road, as soon as their diameter exceeds certain values. Combined with the information that foundries are scarce and not always placed close to the sea requires special attention to the transportability of those components. There is no split hub design. The new proposed hub materials from reinforced fibre materials or from fibre reinforced cast materials, to replace the current cast iron designs will possibly gain some stiffness to reduce the pitch bearing movements, but will still be large undivided structures that, due to their dimensions and rather spherical shape will reduce the transportability a lot. Height restrictions on roads will affect every land transport. Since foundries for very large cast components are scarce and the foundries are not always located nearby shippable rivers or have otherwise access to offshore ports this might form an issue for large diameter hubs, as long as no large item forgeries with access to the sea can be encountered.

[56] BVG Associates. (2010). Towards Round 3: Building the Offshore Wind Supply Chain - A review for The Crown Estate on how to improve delivery of UK offshore wind. The Crown Estate.

5 Drive train

Two different concepts are dominating the state of the art market. One configuration consists of a gearbox connected to the generator. Up to now it is mostly used for the offshore wind turbines. A low speed shaft connects the rotor to the gear box i.e. 30-60 rpm and then a high speed shaft increases the rotational speed about 1000 to 1800 rpm, the rotational speed required for most generators. The other concept has a direct drive from the rotor to the generator.

5.1 Gearbox

No new development is usually considered for the baseline case of a 3 stage gearbox. As improved concepts against this baseline often just single-stage medium speed gearboxes, multi generator drive path concepts and direct drive (DD) turbines are considered for drive train improvements.

But the traditional gearbox concepts are being improved as well. The main failure modes encountered in the traditional designs are addressed and solutions proposed in new designs.

Ricardo suggests a low weight compact design for a 10MW variable ratio split path drive train (4 generators), that is able to shave the load peaks by having part of the torque being converted by a hydraulic system. To avoid peak loads that exceed nominal load and could cause damage to the equipment temporary peaks in hydraulic pressure can be stored in accumulator systems and be converted later on when the peak has been passed, keeping the efficiency high**Error! Bookmark not defined.**.

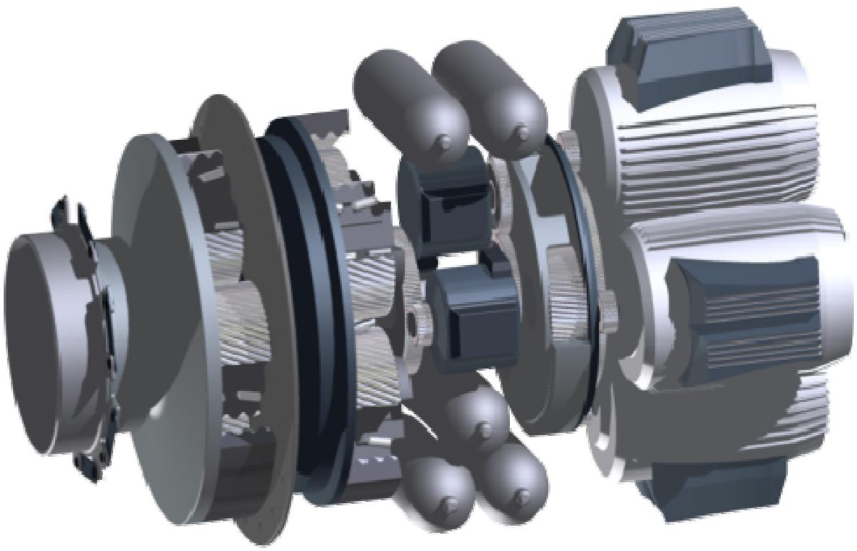

Figure 11 10MW gearbox from Ricardo

Voith proposes a hydodynamic WinDrive system that is added to the conventional step up gearbox adding to the overall ratio and has the same ability to avoid peak loads and to survive overloads. It is able to keep the output speed constant. The system therefore enables the use of synchronous generators and to get rid of the converter systems, which is known to be a system that has reliability issues as well. Since only a small part of the transmitted power goes over the hydrodynamic torque converter the overall efficiency is kept high[57].

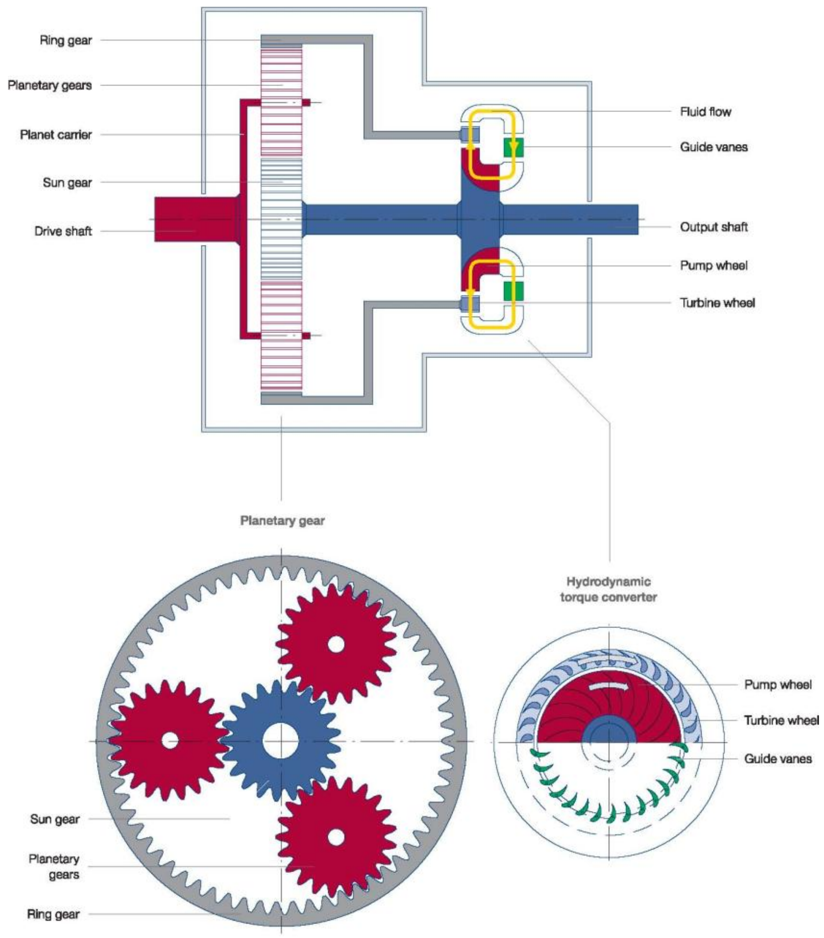

Figure 12: WinDrive system Voith[58]

Mitsubishi Power Systems Europe bought Artemis Intelligent Power Ltd. and their continuous variable transmission system (CVT) based on a digital displacement hydraulic system in 2010. This system does improve the efficiency of a hydraulic system especially at partial load, because

it can turn off some of its cylinders. The Mitsubishi 7MW turbine will still have a 165m rotor. The 7MW system also goes for a multi generator design (2 generators)[59, 60].

[57] http://voith.com/en/products-services/power-transmission/variable-speed-gearboxes-windrive-9747.html

[58] http://www.voithturbo.com/applications/vt-publications/downloads/990_e_cr355_en_voith-windrive-for-wind-turbines.pdf

[59] http://www.artemisip.com/Pictures/SeaAngel%20Brochure2.pdf (accessed 21st June 2012)

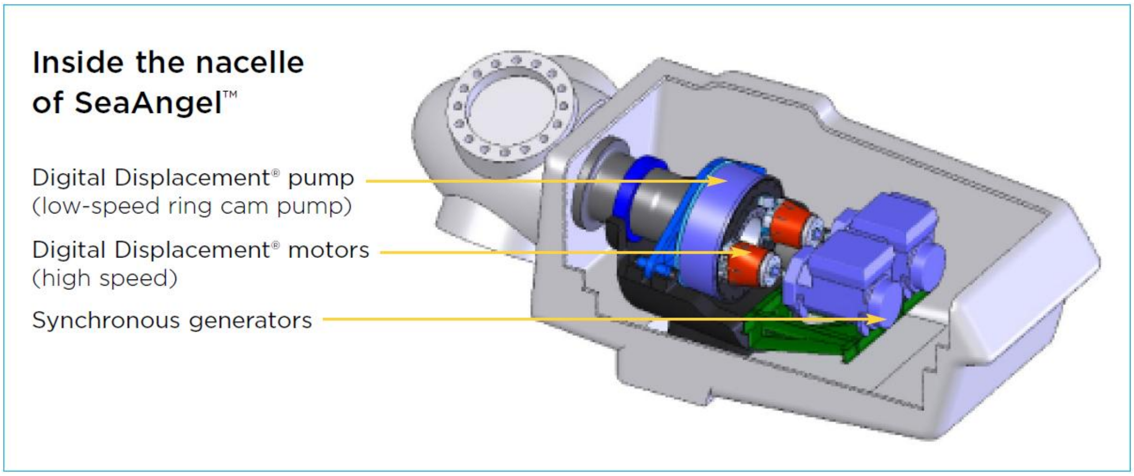

Figure 13 Digital Displacement technology Mitsubishi Power Systems Europe/Artemis Intelligent Power

The systems will not necessarily be all lightweight for a 10MW scale.

The torque resulting from a 160m diameter rotor ("Upwind, design limits and solution for very large wind turbines" EWEA 2011 6th framework Programme) that would have to be transferred through a gearbox is enormous and consequently the deformations of the carcass of the gearbox does become an issue as well as the perfect decoupling of any other forces but the torque being introduced into the gearbox has to be avoided.

Many failures in the past could be tracked back to alignment errors that caused uneven load distribution and therefore excessive wear on bearing races. Over-load on the bearing races typically is limited to the zones that due to their position carry most of the load anyway. New concepts to turn also the raceways of the bearings by simple mechanisms driven by the oil pressure inside the bearing or with the help of motors are planned to extend the life time of the bearings by distributing the wear equally over the complete raceway. (Multi-life bearings Ricardo 2011[61]).

The overload also causes the misalignment of some components, distorting the structural components of the gearbox or movable parts inside and affects consequently the gears due to the undesired load distribution they are not designed for. Overload on the gear surface causes micro cracks.

The missing lubrication of the gears is also one of the typical failures encountered in older designs, especially the planetary stages suffered from zones with insufficient lubrication and subsequent superficial damage as grey staining and micro pitting that develop into more serious gear damages over time. Together with the effects of design flaws in the gear geometry that result in high deformations of the teeth and subsequently in cracks that result in mayor damages over time.

Structural defects of the material of the gear teeth can also result from inadequate surface treatments. Special quality control can detect those failures and avoid the implementation of faulty parts. There is a series of different methods that can be applied for this purpose. For very

[60]http://www.artemisip.com/Pictures/Artemis%20EWEA%20Offshore%20brochure%20300dpi.pdf (accessed 21st June 2012)

[61] http://www.all-energy.co.uk/userfiles/file/paul-jordan-190511.pdf (accessed 21st June 2012)

large turbines the component cost will get less relevant and a thorough quality control for the complete unit will get crucial to avoid exploding maintenance costs due to the elevated costs for component exchanges offshore in combination with production losses for such large units.

Even more advanced pressure lubrication systems that forced oil into all critical bearings and gear meshes did not completely resolve all lubrication issues. Oil is aging and losing additives due to the very high local oil temperatures encountered in the zones with very high pressure on the bearing raceways and gear mesh on very highly loaded components.

Modern Condition Monitoring systems allow controlling the oil quality and encountering impurities from degenerating components and the state of the art maintenance scenarios foresee the revision of the most critical oil quality parameters and allow in combination with vibration sensors to observe the gearbox conditions.

Timely oil change and remediation through the timely exchange of damaged components in early stages have therefore resulted in a considerable improvement of gearbox reliability avoiding catastrophic failures and the necessity for costly exchange.

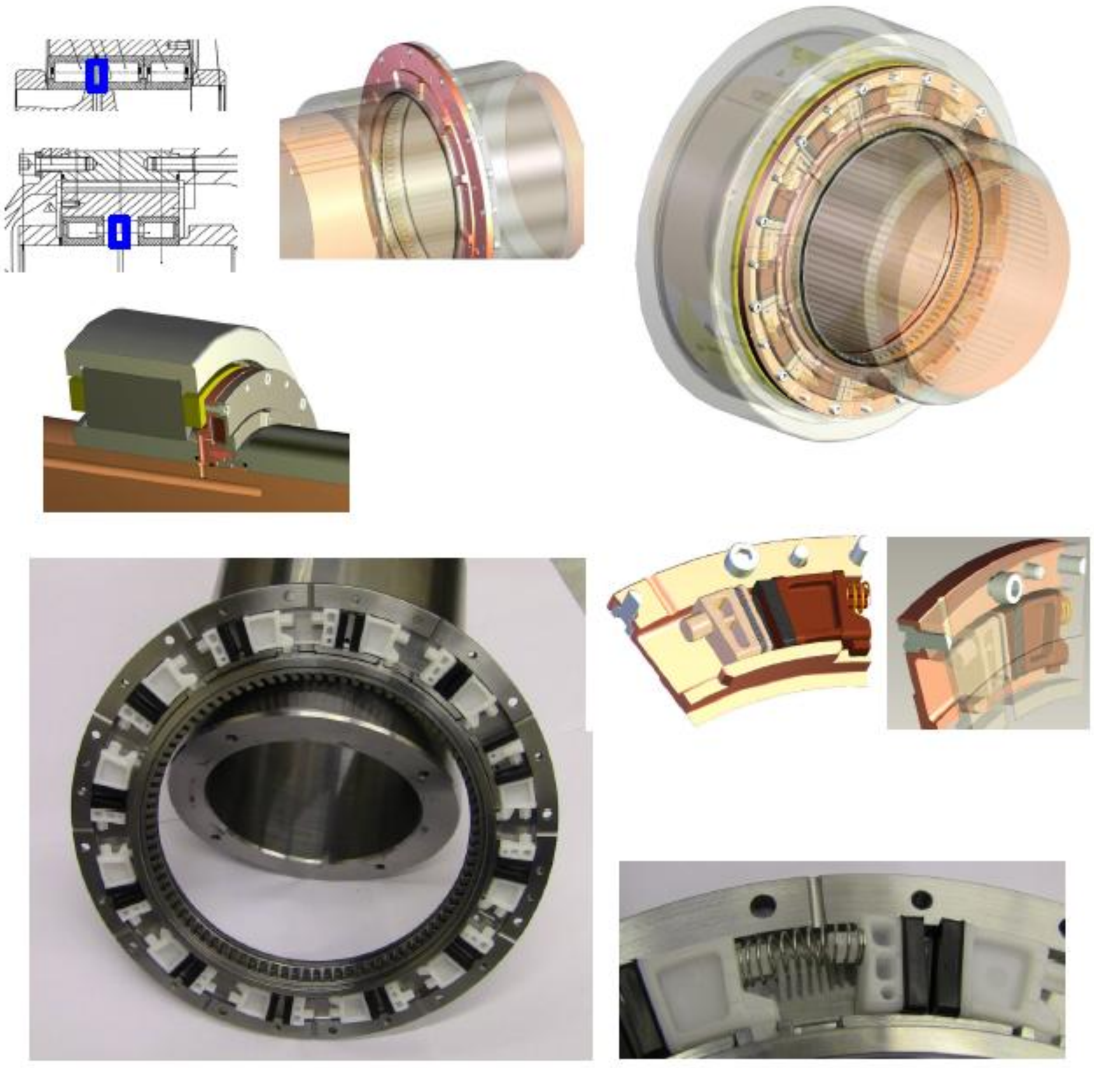

Figure 14. Multilife bearings Ricardo

5.2 Generator

5.2.1 Materials

For large DD generators there are severe restrictions for the use of wound stators due to the fact that the increased diameter will add significantly to the weight. They can be replaced by PM but this will imply a significant rise in cost for the generator since the cost for rare earth metals is likely to remain on a high level for several years to come. The fact that electric automotive industry, other electric motors and generators, MRIs are going to use as well permanent magnets and that diodes use rare earths as well, will only be compensated by the fact that additional mines will be economically viable again, after they had to close down after Chinese mines did produce far cheaper in the last decades. Alternative manufacturing methods allow to reduce the Dysprosium content in PMs. Dysprosium is currently used in all PM that are used in Wind Turbine Applications. The content can be reduced from approximately 8% down to 2% if the material is only used in the outer shell not in the centre of the magnets, still providing the corrosion resistance and the temperature properties searched for[62].

The bearing concepts for the large diameter DD generators will have to be adapted to guarantee the required air gap dimensions. Structural changes to the design of the turbines would be required to allow for different bearing concepts.

5.2.2 Cooling systems

Most of the generators today are air cooled, mainly by convection, with the rotation of the machine itself pushing the air flow through the generator parts. Increasing the generator power capacity increases the heat density inside the generator which will decrease the generator efficiency (see **Error! Reference source not found.**).

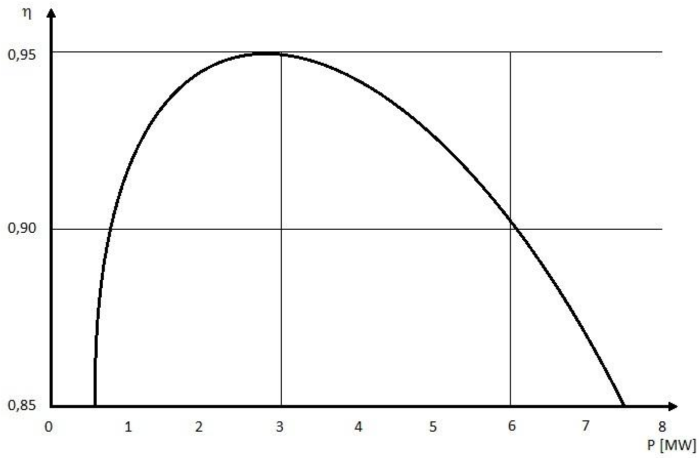

Figure 15 – Generator power vs. efficiency[18]

It is necessary to avoid the increase of the temperature on the generator in order to keep efficiency. This means that the cooling system must be able to withdraw the produced heat from the generator. There are mainly two solutions for this, improve the cooling system or increase

[62] Bloomberg New Energy finance, Wind research note 2012, Is the magnetic attraction of rare earths reversing, January 2012

the areas for better heat dissipation (both solutions can be used together or separately). Improving the cooling system will imply more expensive systems (different coolers can be used as for example, water) and may require a power supply (decreasing the production overall efficiency). Increasing the areas for better heat dissipation can be done by increasing the conduction surface area which will result in larger and heavier generators and thus transforming the thermal problem in a logistic problem.

5.2.3 Electromagnetic limitations

There are mainly two electromagnetic issues at the generation level that can limit the upscaling of the power generated by each wind generator.
The first issue is the flux density. An iron-based magnetic flux has a maximum flux density limit that can only be increased by increasing the amount of iron in the generator. Increasing the amount of iron will consequently increase the generator size and fall in the problem of the logistic limitations.

The second issue is connected to the currents in the generator. It is possible to increase the generator power production by increasing the current density in the generator. This can be done by increasing the current in the conductors in each one of the slots or by increasing the number of conductors in each slot. The first will lead to an increased generation of heat (due to losses) which will require an improved (better or different) cooling system as it will be further explained in the thermal limitations chapter. The second will lead to increased height of the slots which will cause excessively leakage inductance and reduce the generator efficiency.

5.3 Expected technological breakthroughs

The wind technology has been evolving considerably and new features are being brought forward constantly. Although many things could be pointed out, the most prominent developments for the near future in the generator technology regards the integration and ironless generators.

5.3.1 Integration

Integration is the expected next big step in the development of wind generators. Zhang et al.[63] points out this factor as being an important in order to reduce the generator mass and size.

One of the main problems in wind generators is that rated power and mass do not grow in the same proportions. For example, a 10MW machine has more than 3 times the mass of a 4 MW machine. This has had a close eye by the industrial and academic communities where efforts are being made to reduce the size and weight with the integration of the generator into the turbine (see **Error! Reference source not found.**), decreasing the top head mass and increasing the potential of better cooling.

[63] Zhang Z., Matveev A, Øvrebø S., Nilssen R., Nysveen A., "State of the art in generator technology for offshore wind conversion systems", IEEE International Electric Machines & Drives Conference (IEMDC), 2011

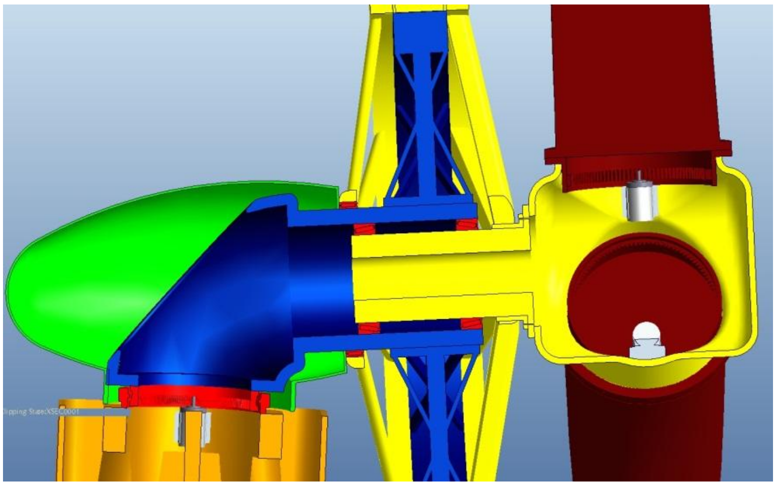

Figure 16 – NTNU reference turbine without nacelle

5.3.2 *Ironless generators*

Iron-based generators are exposed to extreme magnetic forces due to the proximity between the magnets in the rotor and the iron in the stator and rotor. These forces end up by increasing the requirements for the bearings and the system structure.

The ironless generator has an air core. The air core means there are no magnetic forces of attraction, no distortion of the structure and zero cogging torques[64]. The only force will be the electromagnetic force for torque and energy production. The air core also implies a lot less iron in the generator components and a possible modulation of its structure. This not only causes the system to become a lot lighter but allows installation, maintenance and reparation at the site with possible transport of modules by helicopter (making the usual expensive large barges with cranes unnecessary).

5.3.3 *Alternative generators*

Superconducting Generators (SC) or Ceramic High Temperature Superconducting (HTS) Generators would allow significant weight advantage, but are not readily available on the market. Thought there are several research projects underway their applicability for wind turbines is still to be demonstrated their reliability as well.

Table 14. Projects on Superconducting Generators

Year	Institution	Country	Power / MVA	Speed / rpm	Fe poles	Inductor	Armature	Status	Ref. #
2009	Tecnalia	Spain	10	10	Yes	MgB2	Copper / air gap winding	design study	65
2010	AMSC/ Teco Westinghouse	USA	10	10	No	2G HTS	Copper / air gap winding	??	66

[64] Wind Energy Update, "Offshore wind game-changer: Air-cored axial-flux generator", April, 2012

[65] PTC/ES2009/070639 "DIRECT DRIVE SUPERCONDUCTING GENERATOR FOR A WIND TURBINE

[66] AMSC SeaTitan™ Wind TurbineTechnical Innovation For Large-Scale Offshore Wind Turbines. A White Paper. November 2010

2009	AML Energy	USA	10	10	No	MgB2 (double-helix winding)	MgB2 (double-helix winding)	design study	[67]
2009	Converteam /Zenergy Power	UK/Germany	8	12	No	2G HTS	Copper / air gap winding	??	[68]
2008	RISO-DTU	Denmark	10		No	1G HTS	Copper / air gap winding	design study	[69]
2011	GE	USA	15	10?	?	HTS	?	?	[70]

American Super Conductor AMSC is in the process of developing a HTS generator for wind turbines with commercial production forecast in 2016. There are several European projects that have the same aim to get a HTS system running. This might release the demand on Neodym, but would in term raise the demand for Yttrium, which is used for the superconducting wires and which is often classed as a rare earth metal as well due to its similar characteristics[71].

5.4 Manufacturing

Large forged components are having a rather high market concentration since there is a very limited number of forgeries that are able to forge very large main shafts or axles. Components as couplings and brakes are not an object of preoccupation, neither manufacturing nor logistics or installation are critical, even for very large turbines. High market concentration exists especially for large size gearboxes. Limited operational reliability of existing units and missing testing facilities for large size gearboxes form a risk for the development of large sizes.[72]

A study from Delft University concluded that a drive train composed of a gearbox and a double-fed induction generator is the most economical concept in term of energy yield to cost ratio, but that the direct-drive is the one that raises the highest energy yield[73]. Also worth to mention, permanent magnet generators have better efficiency than induction generators, with 3-4% gain overall[74].

[67] P. Masson. Wind Turbine Generators: Beyond the 10 MW Frontier. (2011) Contribution to Symposium on Superconducting Devices for Wind Energy Systems. Barcelona,Spain.

[68] C. Lewis et al. A Direct Drive Wind Turbine HTS Generator. Power Engineering Society General Meeting 2007 , 1-8 (2007).

[69] A.B. Abrahamsen, N Mijatovic, E Seile, T Zirgibl,C Traeholt,P B Norgard, N F Pedersen, N H Andersen an J Ostergard. Superconducting wind turbine generators. Supercond. Sci. Technology. 23 (2010) 034019

[70] http://www.rechargenews.com/business_area/innovation/article275513.ece

[71] Bloomberg New Energy finance, Wind research note 2012, Is the magnetic attraction of rare earths reversing, January 2012

[72] BVG Associates. (2010). Towards Round 3: Building the Offshore Wind Supply Chain - A review for The Crown Estate on how to improve delivery of UK offshore wind. The Crown Estate.

[73] Polinder, H., van der Pijl, F., de Vilder, G.-J., & Tavner, P. (2006). Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines. Energy Conversion, IEEE Transactions , 21 (3), 725-733.

[74] Wong Too, P., Jamieson, P., Manins, O., & Thorp, W. (2009). Trends in Wind Turbine Technology. Garrad Hassan

5.5 Logistics/installation

Dedicated manufacturing at offshore port sites is required to optimize the logistics for the manufacturing of the units. However, the size of the large gearboxes is not so critical and therefore they could be assembled in dedicated manufacturing facilities. Their weight and dimensions would otherwise for most concepts still be manageable in respect to road transport.

More power implies bigger and larger generators (as well as blades and other equipments used). This means that generators will take more copper and more iron and their weight and dimensions will increase considerable. For example, the Enercon E-126 7.5 MW turbine, which is the largest model build and running up to date, has a generator that weighs 220 tons with an external diameter of 12 meters (126 meters blade diameter). With today technology, the generator must be placed as unique module at the top of the towers which implies raising this 220 tons piece (at least if the generator doesn't need to be coupled with other equipment at that time) up to 130 meters. This task might look simple but carries several complications, namely moving a large piece (12 meters diameter is considerable taking in account that for logistic purposes it is not practical to have generators over 8 meters[75]) into such a big height (a Liebherr 750-tonne crane can lift 100 tons up to 120 meters[18]).

For wound generators the diameter of the generator will increase even further and will require the development of the appropriate new installation equipment that can handle the dimensions and weights.

Few ports are adapted to the dimensions that are required for larger turbines, limiting installation capacity in most markets. Ports fitted turbines require stronger quays, deeper ports for bigger ships, more space, larger cranes, a longer installation period storage and preassembly for offshore wind[76,77].

[75] Semken R., Polikarpova M., Röyttä P., Alexandrova J., Pyrhönen J., Nerg J., Mikkola A., Backman J., "Direct drive permanent magnet generators for high-power wind turbines: benefits and limiting factors", IET Renewable Power Generation, Vol. 6, Iss. 1, pp. 1-8, 2012

[76] BVG Associates. (2010). Towards Round 3: Building the Offshore Wind Supply Chain - A review for The Crown Estate on how to improve delivery of UK offshore wind. The Crown Estate.

[77] Emerging Energy Research, Global Offshore Wind Energy Markets and Strategies, 2008–2020 March 2008 Section 5 Competitive Trends in Offshore Wind Supply

6 Yaw system

6.1 Manufacturing

Yaw moments for very large rotor diameters will increase with the amount of asymmetric loads onto the rotor plane, caused from the incident wind field or the wake effects. There is also the effect of rotor torque in case that the rotor axis is tilted, contributing to the yaw moment. The harmonics in the out of plane bending moment of the blade cause also harmonics in the nacelle and the yaw system. Certain systems like individual pitch control and Lidar systems on the hub to "foresee" the upcoming wind loads might be appropriate methods to resolve part of this issue to certain extend. Forced lubrication will have to be considered for the yaw gears and bearings, so as to compensate the limited movements of the rollers and the movements due to deformations and tolerances in the bearing races. This is especially important for the teething of traditional pinions of yaw drives that suffer from considerable wear otherwise. The same as for gearbox gears is applicable also for the yaw drives. The quality control for yaw gears will also have to be rigorous to avoid premature wear. Other friction bearings will have to be considered as well. Their design might overcome some of the issues in relation to relative movements of raceway and rollers. Both systems don't actually have manufacturing limitations due to the size. The limitations for lifetime of the bearings are of less concern. The size of the yaw drives also will not be a limiting factor for 10MW turbines. The current turbine systems show that the number of yaw drives can be increased. The soft yaw drive systems have already been using hydraulic couplings on the yaw gearboxes. This system approach would allow for improvements on the wear of the reduction gears of the yaw drives independent of their size independent of the use of hydraulic brake systems.[78]

6.2 Logistics/installation

Traditionally the bearing manufacturers are very seldom located close to offshore ports, which resulted in the development of split bearings for large diameter bearings for transportation reasons. The large diameter bearings for the yaw drives could be done in segments as well to allow for transportation, but would also increase the preparation work for installation and would require additional resources for quality control.

[78] Engström, S. (2001) Soft Yaw Drive for Wind Turbines. DEWI Magazine, No. 18 (Feb. 2001)

http://www.dewi.de/dewi/fileadmin/pdf/publications/Magazin_18/09.pdf (accessed 21st June 2012)

7 Tower

7.1 Manufacturing

Tubular towers for monopiles are typically manufactured from steel plates which are then rolled and welded into appropriate sections. These sections are assembled, typically by welding or occasionally also bolted together. Assembly can be performed at the onshore site, or in the port.

Manufacturing of large tubes is not a critical item. The flange production for large diameters is also a less critical item. The main issue here is to maintain the flatness and waviness of the flange and to avoid distortions of the flanges to achieve the basis for properly tightened flange connections between the different tower sections and the foundations. A good quality control after manufacturing and before the use of the components must be in place to detect possible issues and to avoid long term issues with the bolt connections in between the tower segments.

7.2 Logistics/installation

Storage and handling of large diameter tower sections without causing deformations. This is especially important for the flanges again, that also should not be distorted during the handling operations. The risk for any kind of distortions is rising with increased diameters. Lifting equipment and storage equipment has to be adapted to the very large diameters.

8 Substructures

8.1 General

The main function of the support structure is to support the wind turbine rotor at sufficient height that it can operate effectively. In other words, the support structure has no intrinsic function in power production. However, it also serves the secondary function of providing protection for equipment and personnel, it provides secure access to the nacelle, and it can be subject to aesthetic considerations.

A great variety of support structure concepts exist, each with different merits. It is not the goal of this report to give a comprehensive overview of all possible concepts, but it is advisable to distinguish a number of distinct categories. The main distinctions are between onshore and offshore support structures, and the latter can be further subdivided into bottom-fixed and floating support structures. The main categories considered are:

- Onshore support structures
  - Tubular tower
  - Lattice tower
- Offshore bottom-fixed support structures
  - Monopiles
  - Jackets
  - Gravity-based solutions (GBS), e.g., monopods
- Offshore floating support structures
  - Spar type
  - Semi-submersible
  - Tension-leg-platform (TLP)

A number of interesting support structure concepts are not present in this list. These include guyed turbines, tripods, tripiles and barges, but also more recent developments. In particular during the Offshore Wind Accelerator (OWA) initiative a number of future alternative support structure concepts are currently being developed (twisted jackets, suction bucket foundations, etc.) that will not be considered specifically. Although typically wind turbines offshore are built in a hybrid way, where a traditional tubular tower is connected to one of the above concepts by way of a transition piece (including boat landing), alternatively it has also been suggested to replace the tubular tower by a lattice tower going all the way from seabed to the nacelle[79]. These interesting concepts, as well as support structures for vertical-axis wind turbines, will not be explicitly considered here, although the remarks below are general enough to apply to these as well.

Onshore, lattice towers were the predominant support structure until the early 80s, and were then quickly replaced by tubular towers, which are more efficient and have a better aesthetic impact. Nevertheless, recently manufacturers have adapted the former concepts to current wind turbines of the 2.5 MW class[80].

[79] Muskulus M., The full-height lattice tower concept. *Energy Procedia*, in press

[80] Ruukki: *Ruukki wind towers – Reaching the heights with Ruukki*. Product brochure, Rautaruukki Corporation, 2011. Available from: http://www.ruukki.com/Products-and-solutions/Infrastructure-solutions/Wind-towers [Accessed 25 April 2012]

8.2 Manufacturing

Manufacturing processes are to be established for serial production. Currently the manufacturing of large numbers of floaters has not been undertaken[81].

For multi-member structures such as offshore jackets and semi-submersibles, a large number of welds are needed and manufacturing cost is a limiting factor. However, this is a general problem with this kind of support structures and not especially affected under upscaling to larger wind turbines. The main limitation here arises because of larger dimensions of the assembled structure, which can be problematic for workshops, paint shops and loadout facilities. Cost reduction of multi-member structures is a current research priority, and innovative solutions such as modular jackets (Weserwind) and joint detailing are currently being evaluated.

With regard to supply chain issues, it has been noted by the European Wind Energy Association that "… technical barriers to manufacturing are not very high. New production facilities can be set up fairly quickly"[82]. The alternative of new materials for support structures (concrete, aluminum is also under investigation.

8.3 Logistics/installation

Some suggestions for the main requirements for port infrastructure have been given recently[83]:

- water depth > 10m
- storage area > 25ha
- quayside bearing capacity > 15-20 t/m^2
- waterway clearance > 150-200 m (for horizontal transport of rotors)

Ports can be utilized both as manufacturing (assembly and loadout) and mobilization (installation vessel base) ports, and optimal strategies depend on site and port distances, and are currently being investigated. With regard to installation vessels, an increased demand for offshore wind specific vessels with better adapted lifting and positioning capabilities has been noted[83]. The major players such as A2SEA, MPI and new entrants such as Fred Olsen Windcarrier are all developing and/or constructing more suitable installation vessels.

Transport onshore is a limiting factor that will become more critical for larger rotor blades. Again, this is one of the points that render offshore wind energy projects attractive, where complex road transport is avoided to a large degree.

Bottom-fixed and floating offshore wind turbines are typically assembled portside and either loaded on barges or special installation vessels, or self-floating. In the latter case, sufficient draft is required (typically at least 15m). Larger wind turbines are expected to increase these requirements to a certain degree, depending on the specifics of the design.

Piling for bottom-fixed support structure can be either performed previous to installation (pre-piling) with subsequent installation by way of pile sleeves, or during installation. Larger pile diameters will require longer and therefore more expensive operations. Advances in sizing of piles (which are currently thought to be relatively conservative designs) are thought to potentially mitigate this factor. Ramming of piles implies environmental issues and handling of

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[81] Emerging Energy Research, Global Offshore Wind Energy Markets and Strategies, 2008–2020 March 2008 Section 5 Competitive Trends in Offshore Wind Supply

[82] Azau S., Beneath the surface. *Wind Directions* **30** (2011), 38-40

[83] EWEA: *Wind in our sails – The coming of Europe's offshore wind energy industry*. Technical Report, European Wind Energy Association, Brussels, Belgium, 2011

piles gets an issue with larger diameter, due to high weights. The bigger the diameters of the piles the more handling issues arise.

Floating foundations are consisting of very heavy components and thus difficulties are emerging for load out procedures if the manufacturing is not performed in a dry dock. Their installation requires large weather windows with special ambient conditions to be towed out. Possible manufacturing facilities do in many cases match with large ship yards. Floating foundation suppliers are till now the same with Oil&Gas suppliers. Actually they do not have the manufacturing facilities to supply with larger quantities.

The towing of floating structures over large distances is sensitive to weather delays and drives the cost and planning uncertainties up. Cranes (max height) will have to be able to handle the weight of the 10MW turbines. Otherwise modular installations would be required that will cause issues with pre-commissioning and could cause potentially quality issues if no additional resources for quality control are employed.

8.4 Design process and tools

Preliminary design is an art in itself, and little publicly available recommended practice exists. Typically, companies have developed their own in-house approaches to support structure preliminary design, often based on spreadsheet analysis and semi-analytic formulae, which are continuously being refined. The certification analysis, on the other hand, is highly regulated. According to the relevant IEC standard[84], e.g., a large number of load cases need to be evaluated in time-domain analyses that fully account for the nonlinearities in the system.

In between the two extremes of preliminary (spreadsheet-based) conceptual design and full certification analysis designers will typically need to evaluate dynamic response of the wind turbine for a selection of load cases, e.g., with regard to extreme environmental conditions.

Recent experience has shown that accurate results can only be achieved if the complete wind turbine is simulated in an integrated way[85,86]. Although this concerns all kinds of support structures, it is of particular relevance to multi-member structures such as jackets and lattice towers, which consist of a large number of members and joints in a complex geometry. Local out-of-plane vibrations of jacket braces have been found both in simulations and measurement data, and have the potential to influence fatigue lifetime of welded joints significantly.

Two important issues arise: First, often offshore support structures are designed not by the turbine manufacturer but by a separate company or contractor, and the interaction between support structure and wind turbine manufacturer is critical. Especially small support structure developers are not able or willing to share all details of their product with third parties, but prefer to perform certification analysis themselves. Likewise, turbine manufacturers are not willing to share details of the wind turbine with the support structure designers. The classical solution to this dilemma has been to perform sequential analysis for the support structure. The support structure is thereby reduced to a simplified model that the turbine manufacturers use in their simulations. The time series of the resulting forces and moments on the connection points

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[84] IEC: Wind turbines Part 3: Design requirements for offshore wind turbines. International standard IEC 61400-3. International Electrotechnical Commission, Geneva, Switzerland, 2009

[85] Seidel M, Foss G: *Impact of different substructures on turbine loading and dynamic behaviour for the DOWNVinD project in 45m water depth.* In: Conference Proceedings EWEC 2006, Athens, Greece, 2006

[86] Cordle A, Kaufer D, Vorpahl F, Fischer T, Sørensen J, Schmidt B, et al: *Final report for WP4.3 – Enhancement of design methods and standards.* UpWind deliverable D4.3.6 (WP4: Offshore foundations and support structures). Garrad Hassan and Partners Ltd, Bristol, UK, 2011

are provided to the support structure designer, who performs analysis of the support structure only, using these forces, with a detailed model. Major drawbacks of this approach are that global vibration modes that couple rotor excitations with support structure excitation are suppressed[87], and that the environmental loads on the support structure (e.g., due to waves for an offshore turbine) need to be exactly the same in both analysis runs, which typically means that the same analysis software needs to be used by both companies. Recent suggestions for future solutions include the development of encrypted "black-box" models of both support structures and wind turbines that can be distributed to turbine manufacturers or support structure designers, respectively.

Another issue of current interest is that present software tools are limited in their capabilities to simulate complete offshore wind turbines. For onshore turbines, the presently existing models, e.g., the de-facto industry-standard Bladed by GL Garrad Hassan (2011)[88], are in principle sufficient to perform comprehensive design and certification analyses. Many manufacturers have also developed their own in-house codes. For offshore turbines, the accurate representation of wave loads for bottom-fixed turbines has been only recently implemented. For floating wind turbines, no such integrated tool is commercially available currently[89]. The existing software either originates from marine engineering and does not yet feature the necessary capabilities for complex aerodynamic load calculations (e.g., SIMO/RIFLEX), or originates with the onshore wind industry and does not feature the necessary capabilities for large-volume rigid body excitations, detailed mooring systems, and second-order wave forces (e.g., Bladed). Many universities and research institutions have addressed this need for suitable simulation tools by investing large amounts of resources into the development of their own in-house computational codes. Due to the size of these investments, it is unlikely that these tools will be publicly available and accessible to most researchers. One exception is the tools developed at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. Being developed with support from government grants, these tools are available for the general public. However, the present FAST and AeroDyn codes presently do not allow for accurate simulations of multi-member support structures, and many developments necessary for floating wind turbines are not finished yet. Thus, one obstacle at least for research environments studying the design of future large wind turbines is the easy accessibility to a comprehensive, well-validated simulation tool.

As larger turbines are likely to be more complex, reduction of the cost for the support structure, although paramount, will be challenging too. One area of current interest is the automatic optimization of support structures by computer algorithms. Although present wind turbines have to a large extent been designed semi-manually in classical design loops, the complexity of support structures for deeper waters (e.g., with thousands of parameters and dimensions for a typical offshore wind turbine jacket or semi-submersible floater) implies that not all possible savings will be realizable. The use of automatic optimization algorithms is therefore an interesting potential field for future research. First pilot studies are underway[90], but are far from being useful for realistic design projects. As in the previous paragraph, the main limiting factor for the realization of better designs by automatic methods is the existence of suitable software tools and methodologies to achieve accurate fatigue predictions efficiently and quickly.

[87] Seidel M: *Advanced design methods for monopiles of large wind turbines in deeper waters.* In: Proceedings of EWEA Offshore, Amsterdam, The Netherlands, 2011

[88] Garrad Hassan: *Bladed User Manual,* Version 4.2. Garrad Hassan & Partners Ltd, Bristol, UK, 2011

[89] Muskulus M: *Designing the next generation of computational codes for wind-turbine simulations*. In: Proceedings of Twenty-First (2011) International Offshore and Polar Engineering Conference, ISOPE 2011, pp. 314-318

[90] Zwick D, Muskulus M, Moe G: Iterative optimization approach for the design of full-height lattice towers for offshore wind turbines. *Energy Procedia,* in press

Likewise for floaters, automatic optimization of designs has been investigated[91], subject to the same limitations.

A final remark about simulation tools: it is at present unclear how well current simulation models capture all relevant aspects of large wind turbines. Although software has been validated by comparison of results between different codes (OC3/OC4), comprehensive validation with real-world experimental data has not been performed. The German RAVE project has instrumented two offshore wind turbines in the Alpha Ventus testfield, and performs a detailed measurement campaign. However, it is at this stage too early to judge how well our current simulation models perform.

As detailed previously, the main issues for the support structure when upscaling wind turbines result from an increase in top weight that needs to be accommodated. This implies an increase in dimensions and size of the substructure which is typically slightly larger than linear. Technologically, this does not present a limiting factor. However, additional factors need to be considered.

Frequency constraints: for larger machines both the rotor frequency and the support structure fundamental frequency is expected to be smaller. Increases in tower top mass likewise lower the fundamental frequency, and at some point this could be potentially limiting. This will either lead to less weight savings than potentially possible for a given wind turbine, or would need specific control strategies to traverse wind speed regimes too close to the eigenfrequency quickly, but poses no specific technological problem.

With regard to world-wide markets, the effect of marine growth can influence the local vibrational behavior of jacket support structures, which can limit their use for certain countries close to the Equator (e.g., southern California and Offshore West Africa, according to DNV 2008) due to significantly increased fatigue damage. This effect is, however, less pronounced for larger support structures.

For monopiles beyond 25m and/or for larger wind turbines, wave forces incurred on secondary structure (e.g., boat landings) can excite global vibrations. Active-idling strategies need to be implemented for load mitigation outside of the operational range[85]. This is not a limitation if alternative support structure concepts offer competitive costs.

For floaters, a major challenge is the design of a suitable mooring system. Deep water floaters as the spar type are relatively straightforward in their response and system properties. However, semi-submersible floaters are thought to be applicable to water depths starting at 60m. A satisfactory performance of a catenary mooring system for these depths can be difficult to realize with the present technology. Thus, lack of an optimized design could make the wind turbine inefficient due to highly increased costs. This problem could be more critical for larger wind turbines but currently there are no studies available addressing this issue.

[91] Fylling I, Berthelsen PA: *WINDOPT – an optimization tool for floating support structures for deep water wind turbines.* In: Proceedings of the 30th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2011), Vol. V, 2011, pp. 767-776

9 Electrical infrastructure-Grid

9.1 Manufacturing

A high market concentration of manufacturers is currently observed, while only a limited number of suppliers for sea cable are available in the market[92,93].

9.2 Logistics/installation

Inter Array cable: The Limited number of installation vessels for installation of sea-cables forms a serious threat to all offshore wind projects. This will affect the 10MW turbines as well.
Substation: Very heavy component needs special ambient conditions to be installed. Limited number of installation vessels for installation of high weight of Substations available. No particular challenge for 10MW turbines, since this is already true for current designs.
Sea cable: Limited number of installation vessels for installation of sea- cable requires special dredging equipment[94,95].

9.3 Grid General

In order to make use of the electric power generated by wind turbines, they have to be connected to electricity grids for transmission and distribution of the power.

If the wind farm is located close to an existing electricity grid of sufficient stiffness, the grid connection can be done relatively easy and cheap. However, wind resources are in many cases located in rural areas with weak electricity grids, so that reinforcement of the grid is required before a wind power plant can be connected.

In the coming years, a majority of new wind power capacity will be installed offshore due to e.g. higher wind speeds, more available space and less public conflicts than onshore. For offshore locations, there are generally no nearby electricity grids to which the wind farm can be directly connected. An exception is wind farms located very close to shore. This means that new transmission grids have to be built between the wind farm locations and the onshore grids. For shorter distances to the onshore grid, AC transmission is the most economical solution, while for longer transmissions distances or large amounts of power DC becomes more economical. It is expected that many future large offshore wind farms will be located far offshore with DC transmission to shore.

The largest wind turbines are mainly developed for installation in offshore locations. Therefore, a main focus in this document is restrictions and barriers related to grid connection of offshore wind farms.

[92] BVG Associates. (2010). Towards Round 3: Building the Offshore Wind Supply Chain - A review for The Crown Estate on how to improve delivery of UK offshore wind. The Crown Estate.

[93] Emerging Energy Research, Global Offshore Wind Energy Markets and Strategies, 2008–2020 March 2008 Section 5 Competitive Trends in Offshore Wind Supply

[94] BVG Associates. (2010). Towards Round 3: Building the Offshore Wind Supply Chain - A review for The Crown Estate on how to improve delivery of UK offshore wind. The Crown Estate.

[95] Emerging Energy Research, Global Offshore Wind Energy Markets and Strategies, 2008–2020 March 2008 Section 5 Competitive Trends in Offshore Wind Supply

9.4 Grid capacity in connection points

Grid capacity in the connection point to the grid is an important challenge for both onshore and offshore wind farms, especially for large wind farm sizes. Often, the best wind resources are located in areas with weak grids, far away from the load centres and the large conventional power plants. Then the development of wind power will be limited by the amount of power that can be injected into the grid. Wind farm developers can be required to cover parts of the costs for reinforcement of the grid, increasing the total project costs. Lack of public information on available grid capacity, absence of master plan for grid extensions and uncertainty regarding how the grid connection costs should be shared, have been identified as important barriers for the grid connection of wind farms by the WindBarriers project[96].

9.4.1 Grid codes for wind turbines

Grid codes states technical requirements which the wind turbines or farms have to fulfil. As long as the wind power penetration level is low, it has little influence on the power system operation, and can be easily integrated into the power system. Wind turbines could then have less strict requirements, as system services (frequency control) could be provided by the large conventional synchronous generators. The most important in the early stage of wind power development was to provide voltage/reactive power control capability, as this need to be done locally.

However, with increased penetration level and possible substitution of conventional power plants, the impact from the wind power on the system becomes significant and the integration more challenging. This has led to development of grid codes into a direction where wind power plants are required to behave more like conventional power plants, with both frequency (active power) and voltage (reactive power) control capabilities[97]. In addition, most grid codes require that wind turbines are able to operate through voltage dips in the grid, low-voltage ride-through capability.

Up to now each country generally have had its own grid code, with significant variations between the different countries. Also, no grid codes for offshore wind have been available, so the requirements have had to be agreed on with the relevant network owner/operator. Technical requirements are needed for the planning of wind farms. They will govern design of components, choices of technology, design of compensation units and filters etc. Grid code requirements have been driving the development of wind turbine technology, for instance regarding low voltage fault ride through capability. Due to grid code requirements, there is a trend towards variable speed wind turbines with power electronics interfaces to the grid, where frequency and voltage can be controlled separately. These turbines are more expensive than turbines connected directly to the grid, so the grid code requirements have contributed to more expensive wind turbines.

ENTSO-E has prepared a draft Network Code[98] upon request from the European commission. The network code is planned to be implemented in the member countries within a few years,

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[96] AEE, EWEA, and DWIA, *WindBarriers. Administrative and grid access barriers to wind power*. 2010. Available from: www.windbarriers.eu/index.php?id=21. (accessed on 21st June 2012)

[97] Hansen, A.D., *UpWind Work Package 9: Electrical grid. Deliverable D 9.4.4. Evaluation of power control with different electrical and control concept of wind farm. Part 2 - Large systems*. 2010: Roskilde, Denmark.

[98] ENTSO-E, *ENTSO-E Draft Network Code for Requirements for Grid Connection applicable to all Generators*. 24 January 2012: Brussels. Available from: www.entsoe.eu/resources/network-codes/requirements-for-generators/.(accessed on 21st June 2012)

and thus the different countries will have a common grid code. A separate section on offshore power generation is included in the network code. One main objective behind the network code is to facilitate the development of renewable generation. An interconnected European transmission system with cross-border trading of electricity is assumed necessary for integrating large amounts of renewable power generation into the grid, for instance power from large offshore wind farms. In addition it is assumed that a common grid code will lead to cost reduction through technical standardization, for instance of wind farm components.

9.5 Collection grid

Up to now, wind farms generally have AC collection grids operating at medium voltage (MV) level. The voltage level depends on the power rating, and for some example wind farms of rating 200-400 MW the collection grids voltage levels were 33-36 kV. The same frequency as in the onshore grid is used. The wind turbines are connected to radial feeders, and large wind farms have many such radials. Usually each wind turbine has a step-up transformer for increasing the voltage to medium voltage level. When choosing the same conventional technology as used in onshore MV grids, the benefit is that standardised equipment can be used. The radial grid structure is common in the onshore MV grids. A meshed grid would provide higher reliability, but also higher cable costs. Saving of cable costs is assumed to be the reason for having radial collection grids. As most offshore wind farms up to now have AC transmission to shore, it is beneficial to use AC also in the collection grid.

With a development of wind turbine with higher ratings, higher transformer rating is also required. Conventional 50/60 Hz transformers are available in a large range of ratings, and are thus not representing a limiting factor. The main challenge offshore is the size and weight of the transformers.

The same type of collection grids can still be used. However, the voltage level might have to be increased[99], possibly also on the generator side. Due to thermal limits (4000 A_{rms})[100] of conventional medium voltage switchgear, it can be necessary to split the collection grid into more radials and branches when each turbine becomes larger.

If DC transmission is used it has been suggested to also have an internal DC collection grid, and considerable research is going on. This will save the need for an offshore HVDC terminal, and it is suggested that this solution be cheaper than the combination of an AC collection grid and a HVDC transmission. However, experience with operation of DC grids is lacking, as no such grid exists up to now. The technology is not mature, and there are still challenges related to DC/DC transformers and DC breakers. If these technological challenges are solved, this might be the solution for future far offshore wind farms.

9.6 Power transmission

A significant amount of the largest wind turbines are assumed to be installed in wind farms located far offshore. As no offshore grid exists, new transmission grids have to be built for each new wind farm project, adding extra costs. An overview of the relative share of offshore wind

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[99] UpWind FP6 project, *UPWIND Final Publication*. 2011. p. 98-102. Available from: www.upwind.eu. (accessed on 21st June 2012)

[100] Breuer, W. and N. Christl. Grid Access Solutions Interconnecting Large Bulk Power On-/Offshore Wind Park Installations to the Power Grid. in The Great Wall Renewable Energy Forum. 2006. Beijing, China.

power grid connection costs collected from different sources are given in[101]. The costs are taken from existing offshore wind projects, and range from 9 to 26 % of the total costs. These are of course depending on the distance to shore, power and voltage ratings and so on. These costs represent a significant limiting factor for the development of offshore wind. Up to now point-to-point connections between the wind farms and onshore grids have been built. The possibilities for developing larger offshore grids interconnecting several wind farms and countries have been investigated in e.g. the OffshoreGrid project[102]. One finding was that it is beneficial to connect wind farms located in the same geographical area together, and use one common transmission line to shore.

Power can be transmitted as either AC or DC. Generally, AC is more economical for shorter transmission distances, while for transmission of large amounts of power over longer distances, HVDC is required. The reasons for this division are both economical and technical, and there is no fixed limit for when DC will be used instead of AC transmission. AC cables will have a physical limitation around 120-150 km, where the capacitive charging current becomes higher than the transmitted active current[100]. The charging current is increasing with the cable length, and in addition the relative cable capacitance is increasing with the voltage level. For the longest distances compensation of reactive power becomes challenging both technically and economically[100]. For HVDC large and costly offshore converter platforms are required, contributing to larger investment costs than for AC. Also, the converter components require more maintenance than AC substation equipment. Each case should be analysed specifically in order to find the best transmission solution. However, AC will generally be used for distances less than 50-100 km, while DC will be used for distances longer than 80-120 km[100,103]. These numbers apply to cable transmission.

Connections to offshore wind farms have up to now been AC, as the sites closest to shore have been developed first. However, the BARD Offshore 1 wind farm, currently under development in the German North Sea, will have a HVDC connection to shore, via the BorWin1 converter platform. ABB's HVDC Light technology (VSC) is used[104]. BorWin1 is located 125 km from shore, and this will be the wind farm with largest distance from shore up to now. The power rating of the DC connection in 400 MW, and the voltage is +/-150 kV. Many offshore wind projects with HVDC transmission to shore are planned in the coming years. Examples are the 800 MW, +/- 320 kV DC DolWin1 connection planned for commissioning in 2013, and the 900 MW, +/-320 kV DC DolWin2 connection planned for commissioning in 2015[104]. The BorWin2 HVDC converter platform is planned for commissioning in 2013, for connection of wind farms in the same area as BorWin1. Siemens will deliver the converters (HVDC Plus, VSC technology), while Prysmian will deliver the cables. The power rating will be 800 MW, and the voltage level +/-300 kV DC[105]. These projects give an idea about the available power and

[101] Weissensteiner, L., R. Haas, and H. Auer, Offshore wind power grid connection - The impact of shallow versus super-shallow charging on the cost-effectiveness of public support. Energy Policy, 2010. **39**(8): p. 4631-4643

[102] 3E, et al., OffshoreGrid: Offshore Electricity Infrastructure in Europe, Final Report. 2011. www.offshoregrid.eu. (accessed 21st June 2012)

[103] Morton, A.B., et al. AC or DC? economics of grid connection design for offshore wind farms. in The 8th IEE International Conference on AC and DC Power Transmission. 2006

[104] ABB. ABB HVDC reference projects in Europe. [cited 2012 April 17.]; Available from: www.abb.com/industries/ap/db0003db004333/25de433ebeefd7e0c12574ad0027a678.aspx.

[105] Prysmian. Prysmian secures BorWin2 project for the grid connection of offshore wind farms in the North Sea. [cited 2012 April 17.]; Available from: www.prysmian.com/archive/highlight/BorWin2_project.html.

voltage ratings for VSC HVDC. The projects also follow the concept of connecting a cluster of wind farms within the same geographical are via a common HVDC transmission link.

It is also possible to develop a meshed offshore grid for connection of offshore wind farms. Much research is going on within the topic of Multi-terminal-HVDC grids, which can be one such solution. This will however not be further discussed here.

9.6.1 HVDC transmission

The majority of existing HVDC links utilise the LCC HVDC technology (thyristor-based converter), which is a mature technology. However, LCC is not very suitable for connection of offshore wind farms, as a strong grid is required for commutation, and it has large reactive power consumption. The alternative technology, VSC HVDC, can be used in weak grids, both offshore and on mainland, and also has black-start capability. Unlike LCC HVDC, active and reactive power can be controlled independently. The VSC requires a smaller converter station than LCC, which is beneficial for offshore applications. VSC HVDC is thus suited for connection of offshore wind farms[106].The drawback is that VSC is a relatively new technology, and much less mature than LCC HVDC.

An offshore converter station is required, which adds extra weight and cost. As it is a new technology, the number of suppliers is limited and the technology is expensive. These costs increases the overall wind farm development cost, and thus represent a limiting factor for the development of offshore wind.

9.7 Protection and fault handling

For conventional AC transmission and generators connected directly to the grid, protection and breakers exist, and the technologies are mature. However, protection of grids dominated by power electronics interfaced generators (e.g. full power converter wind turbines) is challenging, due to low fault current levels. The main challenges are detection of faults and selectivity, while conventional AC breakers can still be used.

For HVDC transmission, which will be required for large wind farms far from shore, there are limits in the protection and breaker technologies. Protection of converter dominated network is challenging due to low short-circuit capacity. Protection of DC grid is challenging, e.g. due to lack of DC circuit breaker for high ratings.

[106] Koldby, E. and M. Hyttinen. *Challenges on the Road to an Offshore HVDC Grid*. in *Nordic Wind Power Conference*. 2009. Bornholm, Denmark.

10 Operation & Maintenance

10.1 General

IEC (International Electrotechnical Commission) defines Operation and Maintenance (O&M) as follows:

Operation (IEC 60050-191-01-12)

The combination of all technical and administrative actions intended to enable an item to perform a required function, recognizing necessary adaptation to changes in external conditions

Maintenance (IEC 60050-191-07-01)

The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function

In the context of offshore wind power this means that all normal, daily work done off- or onshore to enable the turbines to produce electricity is regarded as operation. Included in these activities is surveillance of the wind farm in an onshore control centre. Maintenance, on the other hand, is about repairing faults (minor and major) and carrying out preventive maintenance on the equipment to improve its condition. Depending on the number of failures, maintenance on a turbine should normally be done only a few times each year.

10.2 Principles of offshore wind O&M

Operation and maintenance strategies which maximise the energy yield from turbines while minimising O&M costs, are essential for the commercialisation of offshore wind power. The strategies should take advantage of advanced condition-based and risk-based maintenance philosophies in order to improve operational efficiency and reduce costs. They should also address the challenge of access, developing and testing novel systems and vessels to deliver a variety of access options.

A maintenance strategy is defined as *"maintenance method used in order to achieve the maintenance objectives"* (European Committee for Standardization, 2001). A more descriptive definition is found in [107]:

"A long-term plan, covering all aspects of maintenance management which sets the direction for maintenance management, and contains firm action plans for achieving a desired future state for the maintenance function".

It is important to refer to the system level in question when discussing a maintenance strategy. On component level the maintenance strategy may either be preventive or corrective (see Figure 17) and each of these two groups may further be divided into several sub-categories (scheduled, condition based, etc).

Each component can be subject to one of the following maintenance strategies:

[107] http://www.maintenanceresources.com/referencelibrary/maintenancemanagement/keyterms.htm (accessed 21st June 2012)

1. **No maintenance**: Neither preventive nor corrective maintenance are carried out (requires redundancy). Major overhaul may be carried out after a predefined time interval.
2. **Corrective maintenance** (run to failure): No preventive maintenance is carried out, but repair is carried out as soon as possible after a component failure.
3. **Preventive maintenance**: Can be subdivided into several categories:
   - **Calendar based (scheduled) maintenance**: Preventive maintenance carried out in accordance with an established time schedule or established number of units of use.
   - **Condition based maintenance**: Preventive maintenance based on performance and/or parameter monitoring, i.e. on the observed condition of the component. A more advanced CB strategy may be called **Predictive maintenance**, which is condition based maintenance carried out following a forecast derived from the analysis and evaluation of the degradation of the component.
   - **Opportunity based maintenance**: Preventive maintenance carried out when the system is down due to preventive or corrective maintenance on other components.

On the system level there will always be a mix of the component maintenance strategies, simply because the components that form the system have different failure types and consequences, thus have different criticality, and should therefore be maintained differently.

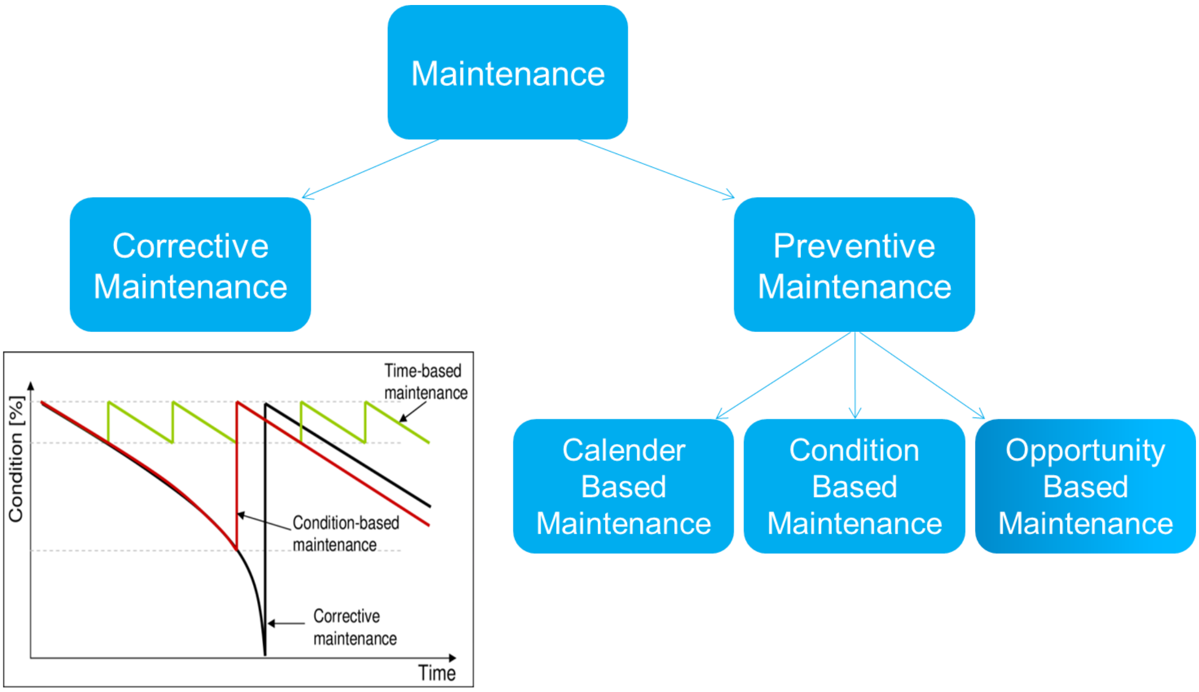

Figure 17 Maintenance terminology and maintenance strategies

In principle, the O&M plan should consider the risk of failures, taking into account both the probabilities and consequences of failures. In addition, the possibilities for discovering on-going failure propagation will decide whether a component should be subject to a condition based strategy or not.

The consequences of a failure can be grouped in different classes:

- Economic losses (lost production and repair costs)
- Negative impact on safety level
- Weakened reputation
- Negative environmental impact

Traditionally in other industries these considerations are taken care of using Reliability Centred Maintenance (RCM) or similar methods. In addition, the weather (particularly the wave conditions on the site) plays a significant role when designing the maintenance plan for an offshore wind farm. Normally, the weather conditions at sea are better during summer than in the winter, thus most of the preventive maintenance activities are done during the summertime.

10.3 O&M strategy trends and outlook

The maintenance regime applied offshore is in many instances adopted from land-based applications, and the long-term effects of a saline atmosphere may not be covered by these established maintenance regimes. Historically, most of the maintenance done in the wind power industry has been corrective ("run to failure")[108]. For offshore wind farms this is considered too unpredictable because the weather conditions play such a significant role when it comes to possibilities for carrying out repair actions. Thus, a shift to more preventive maintenance, and even condition- or opportunity-based, is foreseen.

Vestavind Offshore's Havsul project in Norway has put pressure on cost reduction, mainly by using simpler and more effective installation methods. From www.arenanow.no: *"The assignment involves the development of a solution for design, assembly and installation of foundations, towers, and wind turbine generators. Vestavind Offshore requires known technology to be assembled and tested onshore and then installed in one single operation at offshore site: a dramatic development upon the five-six offshore operations that are typical for installations today. This will set a new industry standard for offshore wind with considerable cost reductions and a more efficient project execution."*

Going further offshore have some implications that will effect also the operation and maintenance. When it comes to planning and design it will be profitable to invest in more redundancy in some of the less costly but still critical components (e.g. sensors, instrumentation and communication). Generally, more robust components (even if more expensive) should be considered for improving the reliability, and also more use of condition monitoring and remote presence.

It is known from the oil and gas sector that offshore supply vessels are one of the most costly resources in the supply chain, and the investment and operation costs of the offshore wind farm vessel fleet can therefore be expected to constitute up to over 30% of the total cost of energy for a far offshore wind farm. This means that large savings can be obtained if the vessel fleet is optimised with respect to size and vessel characteristics, and the fleet is operated efficiently.

Going more than about 20 km from shore, a living platform may be a relevant solution. Even a so-called mother/daughter ship may be profitable if the wind farm is large enough. A mother

[108] Bratland, S: *HyWind – The world first full scale floating wind turbine.* Presentation at the conference "Operation & Maintenance excellence for offshore wind". London, 2010

ship serves as living quarter for the maintenance crew, and at the same time it can be used as a crane ship when heavy lifting within the wind farm is required. Even if such a ship is very expensive (≥ 100 mill. €) it can still be profitable due to the combination of functions it provides. With a living platform or mother ship dedicated to a wind farm, the implications for the daily O&M tasks will be comparable with near shore wind farms since O&M personnel and spare parts are already on site. When it comes to replacement of bigger and heavier components it is always a question of storage space, and with a far offshore wind farm it will of course take more time to get a spare part to the turbine if it is not available on site. Thus, faster and bigger access vessels may be a solution far offshore.

Furthermore, safe working conditions are an important part of the scope, including safe access to turbines, safe launch and recovery of daughter vessels and safe deck layout /work areas on vessels. The evacuation time in case of emergency will also be longer far offshore than near shore, especially if the evacuation for some reason is not possible by helicopter.

Sea-sickness may be a problem if people need to be transported more than 0.5 hour in significant wave heights above 1 m[109]. The implication of this "trivial" phenomenon may be that the mobilisation time will be increased by the personnel recovery time before they can start working.

The cost-benefit of all measures and investments for better reliability should of course be carefully analysed, and it all comes down to maximising the profit of the wind farm in a life cycle perspective.

10.4 Technology and resources

10.4.1 Reliability of large wind turbines

Table 15 gives an overview of some of the most central sources for reliability data for wind turbines, including the data collection period and number of turbines. Apart from Windstats, which not contains very detailed data about failures, the most comprehensive data source is the German WMEP database.

Table 15. Overview of databases in Europe that collect reliability data for wind turbines[110]

	Country	Time span	Number of turbines	Turbine-years of experience
WMEP	Germany	1989-2006	1500	15.000
LWK	Germany	1993-2006	241	5.719
Windstats	Germany	1995-2004	4285	27.700
	Denmark	1994-2003	904	18.700
VTT	Finland	2000-2004	92	356
Elforsk	Sweden	1997-2004	723	4.378

[109] Cockburn, C: *Accessing the far shore wind farm.* Presentation at the conference "Operation & Maintenance excellence for offshore wind". London, 2010

[110] Faulstich 2009 - Reliability of offshore turbines - identifying risks by onshore experience

Even if the data collection of these databases ended several years ago and only includes onshore wind turbines, lessons can be learned from WMEP and others that can give an indication of the development in reliability figures also today. It seems for instance that the failure rate increases with the turbine size, Figure 18

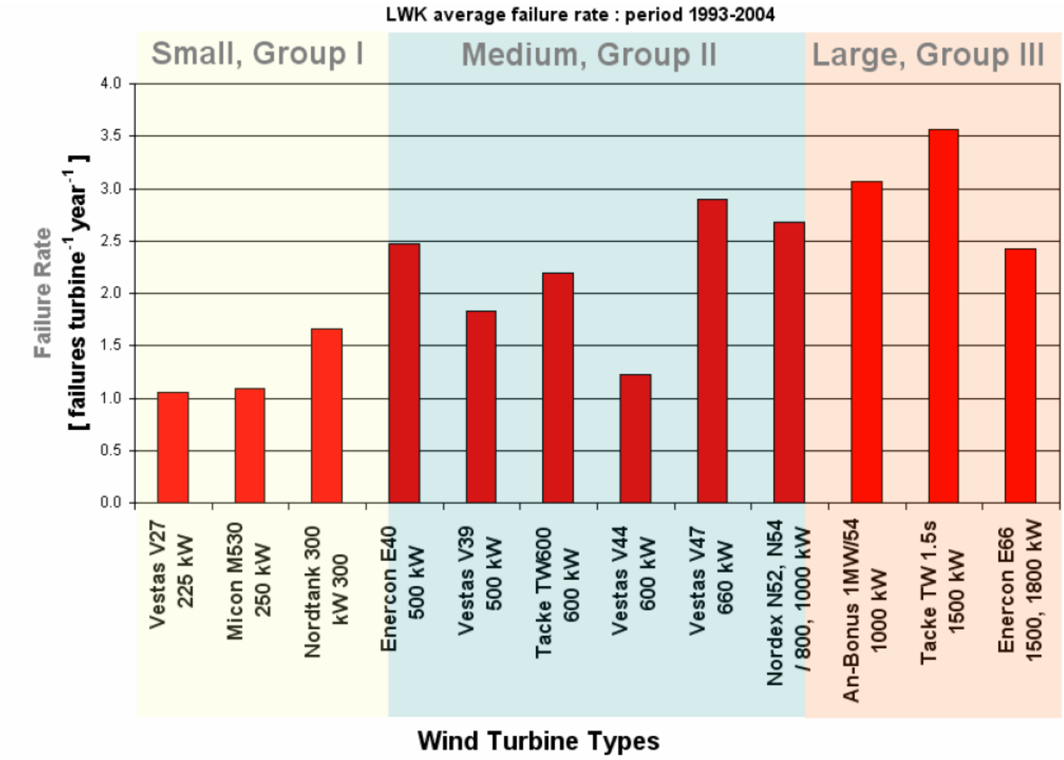

Figure 18. Failure rates and downtimes depending on the turbine size [111]

Even if the data collection period in Figure 18 is as far back as 1993-2004 there is a clear trend that larger wind turbines have a higher failure rate than smaller turbines. This can also be seen from Figure 19, which is extracted from the WMEP database. The reasons for this trend can be many, but more complex design (electronics, pitch system, etc.), higher wind speeds and immature technology are important factors.

[111] Tavner,P. et. al.: *Reliability analysis for wind turbines*. Wind Energy, Volume 10, Issue 1, 2007

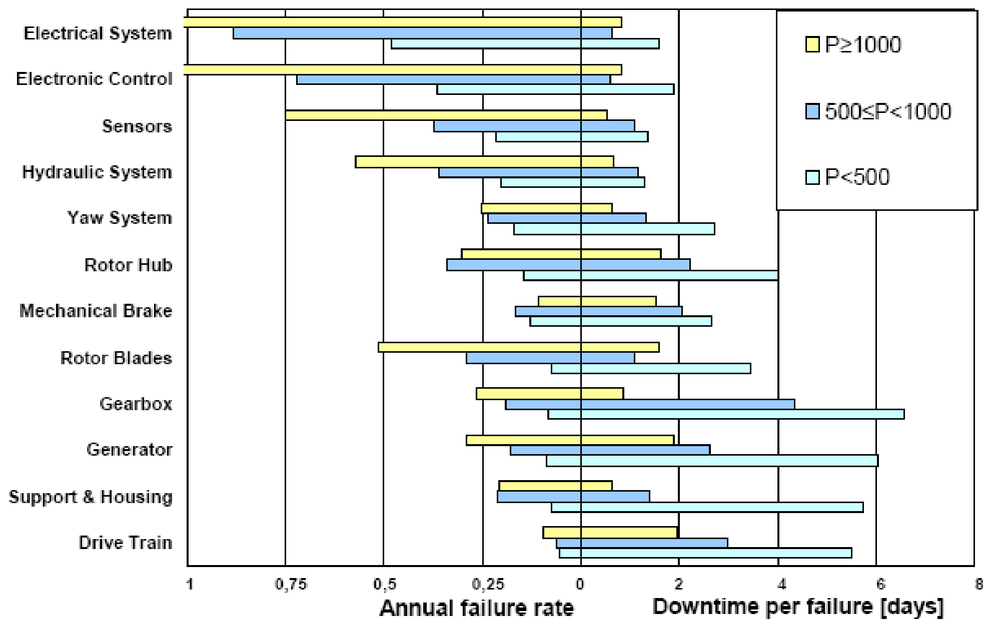

Figure 19. Failure rates and downtimes depending on the turbine size [112]

However, even if the failure rate is increasing with turbine size, Figure 19 also clearly illustrates that the downtime per failure typically decreases with increasing size. There may be many explanations for this, but the main reason is probably the increased focus on repairing faults and getting the turbine up and running again as soon as possible due to higher downtime losses for the larger turbines. Another possible explanation is that the infrastructure (availability of maintenance personnel, more comprehensive surveillance and monitoring systems, etc.) is superior for larger turbines.

In addition to the size of the turbines, the concept or design obviously also has an impact on the reliability. In the UpWind project[112] wind turbines were divided into 4 different concepts as shown in Table 16, where the characteristics of the concepts are also illustrated.

Table 16 Characteristic features of different wind turbine concepts [112]

	Simple Danish concept	*Advanced Danish concept*	*Variable-speed concept*	*Direct-drive*
Exemplary turbine groups (WMEP)	AN Bonus 100/150 Vestas V 17/20	Vestas V 25/27/29 Ventis 20-100	Vestas V 63/66 Enercon E 32/33	Enercon E 40 Enercon E 66
Control	Stall	Pitch		
Speed characteristic	Constant		Variable	
Gearbox	Gearbox			Direct-drive

[112] Faulstich, S. et. al.: *Comparison of different wind turbine concepts due to their effects on reliability.* UpWind Deliverable 7.3.2, 2009

These concepts illustrate to a certain degree the development of the turbine technology over time. This reference was written in 2009, and today there is of course a clear trend towards more direct-drive turbines.

Figure 20 shows the failure rate per component for the different concepts as derived in the UpWind project[112] For most components there is a trend towards higher failure rates for larger and more recent turbines. The general trends are marked with arrows in the figure for clarification.

It should be emphasized that the statistical basis especially for the direct-drive turbines were not very solid in 2009, when this comparison was done. There is also a general tendency that the failure rate declines with turbine age due to elimination of design and mounting failures, and this will probably be the case for larger direct-drive turbines as well.

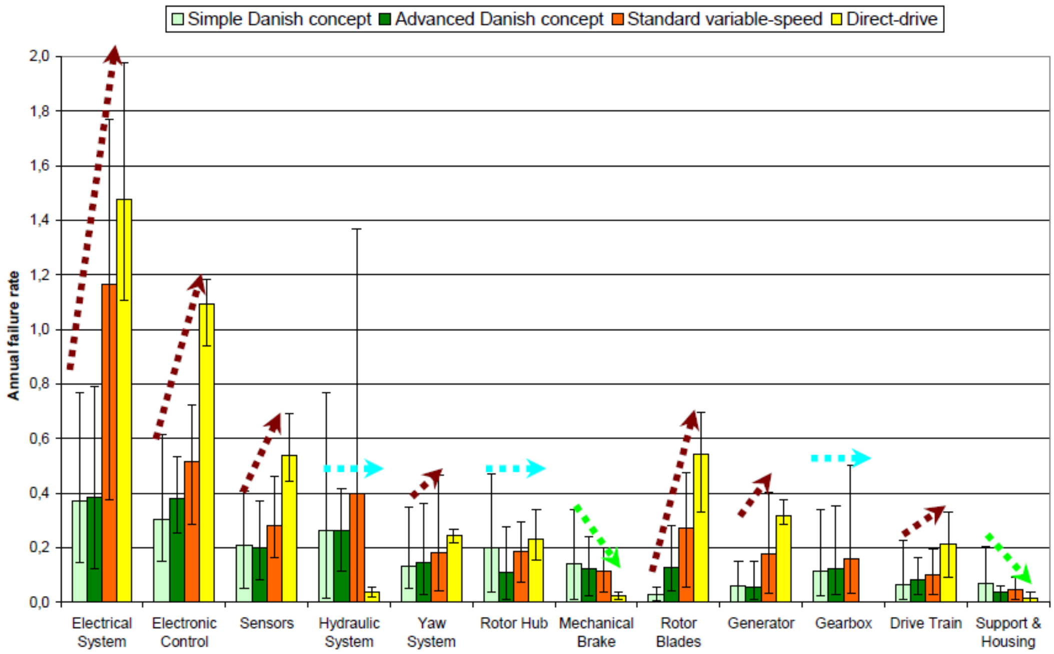

Figure 20. Failure rates for components of the four different concepts [112]

Application of historic reliability data (mostly collected for onshore turbines) must be subjected to engineering judgement in order to predict the reliability of large offshore turbines. For the time being, the only conclusion that can be drawn is that the negative impact of turbine size on the reliability indicates that substantial effort must be given in order to reduce the failure rate of larger offshore turbines. Nevertheless, an increasing failure rate does not mean necessarily an increased total number of failures at a wind farm level. If larger wind turbines are used, fewer turbines are needed for the same production capacity. This can lead to a lower total amount of failures, dependent on the increase of the failure rate per wind turbine.

10.4.2 Vessels for O&M

Operation and maintenance of an offshore wind farm requires several types of vessels – both for transport of technicians, lifting operations and accommodation if the wind farm is far offshore.

Most of the vessels used for transport and installation are also relevant vessels for performing O&M tasks. Vessels considered are[113]:

- Towing tug
- Cargo barge
- Jack-up
- Construction vessel
- Crane barge (sheer leg)
- Crane barge (derrick)

Main types of ships regarded as relevant for the installation of wind turbines:

1. Installation ship - typically large jack ups with strong cranes
2. Service vessels - for use during unscheduled maintenance
3. Service vessels - for use during scheduled maintenance
4. Cable laying vessels
5. Construction support ship / supply vessels
6. Survey vessel: bottom surveys
7. Crew boats – fast travelling boats

An example of a vessel fleet has been presented by Pieterman et.al.[114], as part of a case study of a 520 MW wind farm consisting of 130 wind turbines of 4 MW rated capacity. The wind farm is located 120 km from the nearest harbour and the water depth is 30 m. The vessels needed for operation and maintenance of this fictitious wind farm are listed in the following table.

Table 17. Vessels used in a 520 MW wind farm (the pictures serve only as illustrations)

3 workboat access vessels for transferring technicians and transporting small components	 *the WindCat MKIII* http://www.windcatworkboats.nl/

[113] Herman, S.E.: *Offshore wind farms – Analysis of transport and installation costs.* ECN 7.4130, Energy Research Centre of the Netherlands, 2002.

[114] Pieterman et.al: *Optimisation of maintenance strategies for offshore wind farms.* EWEA Offshore 2011, Amsterdam 2011

1 jack-up vessel for transporting and hoisting large components	 Jack Up Vessel JU004 www.4coffshore.com
1 mother ship for accommodation of technicians and storage of small components	 http://www.houlderltd.com/
1 cable lying vessel for replacing power cables	 CTC Marine Projects http://www.maritimejournal.com

2 diving support vessel for underwater inspections and repair	 OffshoreWind – InWater Service http://www.nordseetaucher.de
2 helicopters for transporting technicians for specific types of maintenance and emergency evacuation	 Bond Aviation Services http://www.flightglobal.com/news/articles/winds-of-change-361819/

Technical restrictions for O&M based on upscaled wind turbines are similar to the challenges in the installation phase of the wind turbine. Especially, exchanging and therewith hoisting of large and/or heavy components is a challenge for O&M when upscaling wind turbines.

The service vessel segment for current wind farms, based on an onshore O&M base is regarded to be covered by the industry and research. However, several aspects are lacking to meet the requirements of the market for far offshore wind farms that require an offshore O&M base / mother ship to drive a cost efficient industry development:

- Detailed functional requirements and capacities (operational range, speed, dynamic positioning, stability, passengers, work shop, storage, crane etc.)
- Health, safety and environment (HSE) accept criteria for all relevant functions and operations
- Safe and robust launch and recovery systems for daughter vessels (of size 24 m / 12 passengers or bigger)

10.4.3 Access to and working at wind turbines

Access to the turbines for maintenance purposes is critical both regarding safety of personnel and unplanned downtime of a turbine. **Error! Reference source not found.** gives an overview of the most typical access methods and the weather restrictions for accessing the wind turbines.

Table 18. Characteristics of typical access methods

Type	Significant wave height in metres	Average wind speed in m/s (1hr at 10 m height)	Example of application	Advantages	Disadvantages
Direct boat landing	0.5 - 1.5 (rubber boats) 2.5 (SWATH)	10	Nysted (rubber boats) Bard 1 (SWATH)	Simple	Sensitive to marine growth and icing
Boat landing with motion compensating	2 - 2.5 (OAS) 2 - 3 (Ampelmann)	11.5 (OAS) 14 (Ampelmann)	Tested	Not sensitive to marine growth	Installation of additional equipment on the vessel required
Hoisting by crane	2.5	?	None	Not sensitive to marine growth	Remote control of crane Maintenance offshore required
Helicopter	-	15 - 20	Horns Rev, alpha ventus	Not sensitive to waves Fast transport	Expensive

Limited access exists in months with more challenging met-ocean conditions with the existing solutions of access vessels that operate from nearby ports. The most used access methods up to date are direct boat landings and helicopters. Helicopter access is a solution but is expensive and also depends on the visibility conditions. The main reason why oil and gas companies are going away from helicopter access in the recent years in the North Sea is exactly the loss of working hours due to the waiting hours in helicopter-terminals of the personnel. Therefore, the development of access methods is going into the direction of motion compensated access methods to allow for access from boats in larger significant wave heights. New specialized access systems were developed (Carbon Trust access initiative) and successfully tested on fixed and floating foundations and ship to ship transfer.

Icing will only form an issue for certain locations with icing conditions. Then it will have serious consequences for maintenance. Ice formation in the water and on the structure will lead to limited access to the wind turbines.

After entering the wind turbine, the wind speed is a constraint for the different maintenance activities, as illustrated in **Error! Reference source not found.**.

Table 19. Wind speed constraints[115]

Wind speed [m/s]	Restrictions
> 30	No access to site
> 20	No climbing turbines
> 18	No opening roof doors fully
> 15	No working on roof of nacelle
> 12	No going into hub
> 10	No lifting roof of nacelle
> 7	No blade removal
> 5	No climbing MET masts

These wind speed restrictions are independent of the size of the wind turbine. The same is valid for the restrictions for accessing a wind turbine. These are solely dependent on the access technology used and not on the size of the wind turbine. Therefore no limiting technical barriers have to be expected from the access methods when upscaling wind turbines.

10.4.4 Manned offshore platforms and mother ships

Maintenance and service operations involve the transport of crew and equipment to the location. Due to weather window restrictions and the travelling distance from shore, it can be worthwhile for remote wind farms to reduce travelling times by installing an accommodation platform or using a mother ship as part of the wind farm. Until now, this concept is only applied at Horns Rev 2, where an accommodation platform is installed alongside the offshore substation (Figure 21).

Figure 21. Offshore substation with accommodation platform alongside[116]

[115] McMillan, D.; Ault, G.: *Towards quantification of condition monitoring benefit for wind turbine generators.* University of Strathclyde, 2007.

[116] Source: www.dongenergy.com (accessed 21st June 2012)

Horns Rev 2's utilization strategy of the accommodation platform is shown in Figure 22. Basically, the platform is manned around the clock with maintenance personnel in the summer period, whereas it is not used in the winter period due to low accessibility of the offshore wind farm in the winter months. The low accessibility implies that fewer maintenance tasks can be carried out and therefore the benefit of shorter travel times is reduced in this period.

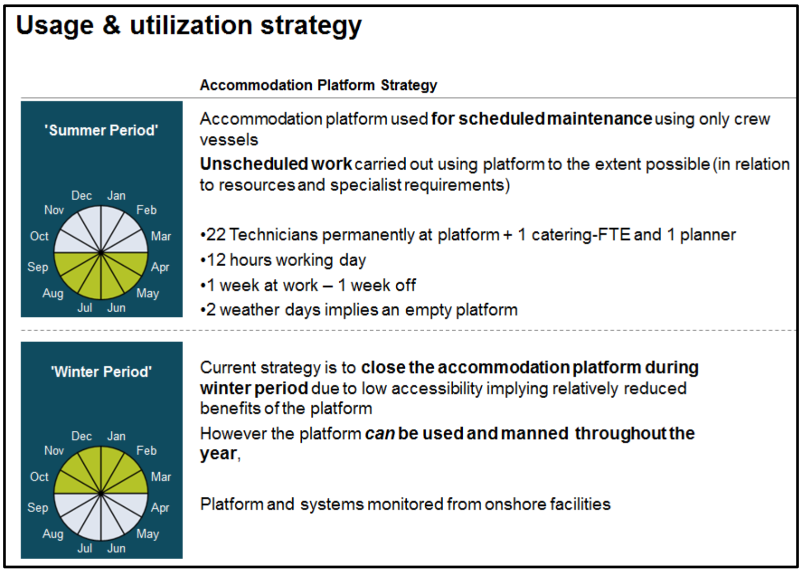

Figure 22 Support and crew vessels, and usage strategy for the accommodation platform at Horns Reef II [117]

There are several advantages with coupling an accommodation platform to the sub-station, as for example the utilisation of common infrastructures like power supply and telecommunication, as well as sharing of the same helicopter deck and common access facilities for vessels. In addition, the maintenance crew will have very easy access for operation and maintenance of the critical components on the sub-station itself. It is expected that future far offshore wind farms have to apply some kind of offshore accommodation concept to be able to carry cost effective maintenance operations.

Another possibility are mother ships that can be implemented in the future to allow reduction of the travelling times towards the far offshore farms were the 10 MW turbines most likely will be implemented. The mother ships can store access vessels on board and will have the advantage of bringing the transport times down to a minimum and also offer the possibility to store certain amounts of spare parts and consumables that will be required for O&M work. Different shift systems are enabled with the elimination of long travelling times.

The benefit of an offshore accommodation platform and mother ships is dependent on the distance to harbour and the total number of maintenance tasks. If larger wind turbines lead to fewer single maintenance operations, the benefit of offshore accommodation may be reduced. But more research is needed to conclude on an optimum solution for an offshore wind farm with upscaled wind turbines and different concepts as accommodation platform or mothership

[117] Andersen, M: *The History & Practical Experience of Offshore Accommodation at Horns Reef 2* Dong Energy, EWEA Offshore 2011

dependent on the distance to shore. However, these concepts should not be regarded as technical barriers, but rather possibilities to improve the cost-efficiency of O&M far offshore.

10.4.5 Technology trends and outlook

The innovation within O&M for offshore wind farms is considerable and the support vessel that is planned by SeaEnergy can serve as an example of this (Figure 23).

Figure 23 Planned support vessel from SeaEnergy[118]

The drivers for development and innovation is of course cost reduction and maximising the electricity production, mostly related to the possibility of accessing the turbines in bigger waves heights, to operate in deeper waters and at more distant locations, and the increase in wind farm sizes that is expected (e.g. UK Round 3).

WindServer by Fjellstrand is another example of one promising concept. WindServer is one of the vessels shortlisted by the Carbon Trust Offshore Wind Accelerator in the UK[119].

Figure 24 The Fjellstrand WindServer access vessel [120]

[118] Source: www.seaenergy-plc.com (accessed 21st June 2012)

[119]http://www.carbontrust.co.uk/emerging-technologies/current-focus-areas/offshore-wind/Pages/offshore-wind-access-shortlisted.aspx#vessels (accessed 21st June 2012)

[120] Source: http://www.fjellstrand.no/ (accessed 21st June 2012)

Condition Monitoring (CM) systems will be prerequisite for preventive maintenance and repair to achieve optimum power production of the wind farm. For 10MW turbines the CM systems will need to be improved to also control subsystem component level to allow encountering as well indicators for pending failures for the subsystems that affect the operation of the system.

A major issue for all offshore wind farms will be the recruitment of experienced/educated maintenance personnel. The strong growth in offshore wind will cause an increased demand that so far no educational programs seem to be adapted to.

Some other expected technology developments are, as also partly mentioned earlier:

- Access vessels with motion compensation operating in above 3 m significant wave heights
- Motherships and living platforms for reduction of travelling time to far offshore wind farms
- Reduction in the number of maintenance visits due to:
    - More advanced sensors, condition monitoring equipment and prognostic tools
    - Remote operations and fault correction (automatic/remote re-setting, etc.)
    - More robust and fault-tolerant components in the turbine
- More sophisticated and robust access facilities (from boat to turbine)
- New designs with relative weight decrease are necessary for e.g. the lifting of heavy components

Part B: 10MW Potential Markets

Executive Summary: Part B

This document is describing a Market trade off study for 10MW wind turbines on fixed or floating foundations from a European manufacturer or developer's viewpoint along with an analysis of the associated site conditions. An Excel spread sheet has been developed as a tool with a weighted set of questions in order to investigate the suitability of a list of countries for the implementation of very large wind turbines. The questions the evaluation criteria and their scaling methods are described in detail. The associated site conditions for 10MW turbines were determined for On- and Offshore implementation.

The list of countries that has been retrieved from the 'Trade off' table was not altered by the 'Definition of associated site conditions' for the 10MW turbines. The common understanding is that the technical limitations for the site conditions are very much compensated by the wide variety of design possibilities.

If all the filters are applied, then the most promising markets for the offshore wind farms with 10MW turbines would be **Australia, Belgium, Canada, France, Germany, Ireland, Japan, Netherlands, Norway, Portugal, Qatar, Republic of Korea, Spain, United Kingdom, United States, Hong Kong and Taiwan**.

Definitely, some other considerations as the likelihood of occurrence for hurricanes and typhoons would need to be taken into account for some of those countries. To get a better understanding a risk assessment would need to be done for the sites in more detail, considering wildlife protection zones or nature preservation areas. Moreover, the analysis of the shipping routes, military exclusion zones, fisheries zones and other alternative uses of the coastal and far offshore waters would need to be performed.

The questions of national or local laws concerning construction permits, or permitting systems, for the regulations for network requirements and the responsibilities for the provision of the offshore connection to the parks would need to be investigated for each location to get deeper understanding of the advantages and disadvantages of the identified countries.

The restrictions for the associated site conditions of offshore floating or fixed platforms are not driven by the turbine size.

Introduction: Part B

This document investigates the potential markets for 10MW wind turbines on fixed or floating foundations from a European manufacturer and developer's point of view.

An Excel spread sheet "10MWPotentialMarkets_TradeOff.xls" has been created with a set of questions for which all member states of the United Nations have been evaluated towards their suitability for the implementation of very large wind turbines. The posed questions, concerning technical and supply chain set of requirements and a general set of political and socio/economic requirements to identify possible markets, are described. Moreover, scaling and filtering procedures that were used to sort out the research outcome i.e. the most suitable markets for the installation of 10MW wind turbines are explained.

1 General information

The list of countries in the Excel spread sheet are the member states of the United Nations based on the press release ORG/1469 of 3 July 2006[121]. That is, 192 states are considered for the trade-off.

Additionally 10 other countries, Aruba, Cayman Islands, French Guiana, Hong Kong, Jersey, Kosovo, Macau, Puerto Rico, Taiwan and West Bank with Gaza, were also considered that are not part of the list of the United Nations.

There are two types of questions, "go/no go" and scaled. If the type of question is "go/no go", then a possible answer to the question is only "TRUE" or "FALSE". Only countries that have "TRUE" as answers to all "go/no go" questions are considered in the questions of type "scale". In some cases the scale was used as a basis to set a threshold and then use that threshold to achieve a "go/no go" result.

Countries without coastal area are directly disregarded. The same was done for all countries that don't provide sufficient politic stability and those that don't have sufficient wind resources in their coastal areas.

In the first three "go/no go" questions, already a very large number of countries are excluded from the possible markets. These are considered the basic three that were investigate first and are always applied during the further filtering questions. Since they form the basis for a possible market, already excluded countries after these initial questions were not investigated further with respect to all the following scalable questions.

The rest of the criteria are scalable, or "go/no go" based on scales that allow threshold tuning. Due to the difficulty to compare countries with available and with not available information respectively, decision had to be made on the comparison procedure. In the case of doubt the countries where no information could be found, the go criteria was chosen as defect and the country in question stayed in the evaluation. Therefore, if not all filters are applied, the results for the listed countries has to be evaluated for the existence of data for each of them.

For some of the questions no information could be retrieved for certain small countries or islands. In this case it was stated that data for this questions was missing. In the following filtering these countries were not excluded due to lack of information. Therefore, it is necessary to check the remaining countries for the existence of data concerning all questions, especially if not all filtering questions of the spread sheet were applied.

[121] This press release is available is at: http://www.un.org/News/Press/docs/2006/org1469.doc.htm. (accessed 21st June 2012)

2 Questions for country evaluation

In the following the evaluation criteria are listed with the corresponding sources that have been chosen to retrieve the data.

2.1 Coastal Area?

Type of question: go/no go

Whether a country has a coastal area or not is answered based on “The World Factbook” of the CIA[122]. If a country has a coastal line greater than 0 km, it got a “TRUE” as answer. After that only 152 of the original 192 states remain for further evaluation, or 162 of the total of 202 investigated countries.

2.2 Politic stable country?

Type of question: go/no go based on scale

The politic stability of a country is based on the political stability risk index (R_P) and the operational risk index (R_O) of the Economist Intelligence Unit[123]. Both risk ratings are spanning on scale from 0 to 100 where 100 means highest risk. A combined risk parameter (R) was derived with the following formula:

$$R = \frac{2}{3} 2 \times R_P + \frac{1}{3} \times R_O \qquad \text{(Eq. B1)}$$

All countries with a risk value R of 40 or better (means below) are assessed as political stable.

Political stability risk definition:

"… addresses the degree to which political institutions are sufficiently stable to support the needs of businesses and investors. It covers the following issues: What is the risk of significant social unrest during the next two years? How clear, established, and accepted are constitutional mechanisms for the orderly transfer of power from one government to another? How likely is it that an opposition party or group will come to power and cause a significant deterioration in business operating conditions? Is excessive power concentrated or likely to be concentrated, in the executive, so that executive authority lacks accountability and possesses excessive discretion? Is there a risk that international disputes/tensions will negatively affect the economy and/or polity?"

Operational risk definition:

"The operational risk model considers ten separate risk criteria:

- security
- political stability
- government effectiveness
- the legal and regulatory environment

[122] https://www.cia.gov/library/publications/the-world-factbook/ (accessed 21st June 2012)

[123] http://viewswire.eiu.com/index.asp?layout=homePubTypeRK&rf=0, visited 26.03.2012

- macroeconomic risks
- foreign trade and payments issues
- labour markets
- financial risks
- tax policy
- the standard of local infrastructure"

After application of this go/no go criteria only 77 of the 202 countries from the beginning remain. This question is considered an important one due to the potential impact that political instabilities would have on these major investments.

2.3 Existing wind resources?

Type of question: go/no go

To determine whether there are wind resources existing in the remaining countries the wind resource simulations by VORTEX[124] has been used.

Vortex uses a supercomputer cluster to run a non-linear flow model (WRF) that scales large atmospheric patterns (NCAR-NCEP) down to fine spatial resolutions (SRTM), generating simulated wind data suitable to be used as an alternative to actual wind data where and when no measurements are as yet available.

VORTEX shows an approximately 200km wide coastal area in front of all coasts that allows to judge on base of the colors the available annual average wind speed at 80m height.

A minimum threshold for average annual wind speed is set to 7m/s to be sufficient as a minimum for the economically viable implementation for 10MW turbines. This value is chosen based on the experience for wind farms with large turbines on- and offshore.

The data is analysed in a 200km coastal area in front of each of the countries remaining after applying the first two filtering questions. Each country that did have wind resources of 7m/s or above, even in a limited part of its coastal water was evaluated positively and taken along in the further analysis. This positive evaluation is regarded as a “go” criteria.This way of analysis allowed a fast evaluation of potential resources. It is though recommended to verify with more precision, if the 7m/s threshold will be viable for a 10MW turbine site.

Only countries which did not have wind resources of at least 7m/s are excluded. After the application of this question there are still 71 of the 202 countries left.

2.4 Existing ports?

Type of question: go/no go

A significant criterion for the construction and deployment of 10MW and larger offshore wind turbine projects is the existence of suitable deepwater ports in a given country. A suitable port must possess a number of criteria, as defined below.

[124] http://www.vortex.es/ visited 27.03.2012

- Adequate harbor size as to accommodate the large components of the turbine and support structure
- Adequate degree of shelter as to allow for careful deployment and loading of turbine equipment and support structures
- Limited entrance restrictions such as ice or heavy swell
- Limited overhead restrictions as to allow for large components such as support towers to be moved by barge or other installation vessel
- Adequate depth as to accommodate the draft of the turbine support structure and installation vessels
    - Includes listings in the main channel, at the anchorage point, and alongside the wharf
- Adequate wharf side equipment such as cranes and lifts as to accommodate the large turbine components

The exact criterion for grading the ports is shown in below.

Table 20. Port grading criterion

Category	4	3	2	1
Draft in Channel	>15.5m	>12.5m	>=11.0m	<11.0m
Draft at Wharf	>11.0m	>9.4m	>=9.4m	<9.4m
Harbor Size	>=Medium	>=Medium	>=Small	<Small
Shelter	>=Good	>=Good	>=Good	<Good
Crane capacity	>=50 Tons	>=50 Tons	>=25 Tons	<25 Tons
Railway	>=Small	>=Small	>=Small	<Small
Access limitations	No Ice limits	Ice Limits	Ice Limited	N/A

This criterion corresponds roughly to similar criteria given by EWEA recently[125]; the main difference being that EWEA recommends the ports having a minimum depth of 10m and does not distinguish subcategories of suitability. The above variables correspond more naturally to the available data.[126]

According to the aforementioned question, Denmark was eliminated because all Danish ports are very shallow. Of course countries like Denmark could use ports from neighboring countries due to the geographical circumstances without major issues. This shows that the filtering results, though the criteria have been objectively applied to all countries will have to be analyzed with caution.

[125] EWEA, 2011, Wind in our sails, Available from www.ewea.org

[126] Data source: World Port Index 2011, National Geospatial-Intelligence Agency, The United States Government

2.5 Existing infrastructure, supply chain, marine industry…?

Type of question: go/no go

The question about the existing infrastructure, supply chain and marine industry needed to be broken down in several questions. Therefore it was chosen to investigate 5 different indicators for the general suitability of the country to support the supply chain, construction and installation for offshore wind farms. The experience in the offshore sector for oil and gas was one of the indicators that were chosen due to the many possible synergies in respect to manufacturing and installation.

- The first to indicators chosen were the existence of ship yards that do have the ability to do new builds[127].
- Next the existence of oil and gas industry in the country was investigated [128]
- The production of oil and gas production in each country was determined and was evaluated without respect of the actual amount of production[129].
- The question if there is an existing supply chain for offshore wind was tied to the existence of offshore wind projects in the country.
- For the supply chain a second question was chosen, whether wind turbine manufacturers or wind turbine components manufacturers exist in this country.

For each of the indicators one point was given. All countries scoring at least 1 point were taken along into the next round of the analysis. The more points obviously the better the suitability for the implementation of very large turbines in this particular country. Only countries that did not score one point in even one single category were excluded from the further analysis.

2.6 Future electricity demand?

Type of question: scale

The future electricity demand (D_{future}) is based on several parameters:

1. GDP-growth from 2009 to 2016 (source: International Monetary Fund, World Economic Outlook Database, September 2011)[130] – GDP_{growth} [%]

2. Electricity consumption 2009 (main source: IEA (2011), Electricity information)[131] – E_{cons} [TWh]

[127] www.ship2yard.com visited 16.04.2012

[128] https://www.cia.gov/library/publications/the-world-factbook/index.html, visited 04.04.2012

[129] http://www.subsea.org/company/ visited 19.04.2012

[130] www.imf.org, visited 02.04.2012

[131] Missing data were supplemented with data from the CIA World Factbook, https://www.cia.gov/library/publications/the-world-factbook/index.html, visited 04.04.2012

3. Net import of electricity 2009 (main source: IEA (2011), Electricity information)[5] – E_{imp} [TWh]

The following formula is used to estimate a possible future electricity demand. The future electricity demand was calculated for the period 2009 to 2016 due to the fact that most of the data only were available for 2009.

$$D_{Future} = E_{Cons} \times (1 + GPD_{growth}) + E_{imp} \quad \text{(Eq. B2)}$$

Scale: TWh (2009 – 2016)

2.6.1 *Cost of energy production?*

Type of question: scale

The electricity price exclusive taxes is used as an approximate for the cost of energy production in a country. Incipiently, different sources of electricity and their specific generating cost were considered for the calculation of the cost of energy production. However, since the generating costs for the same source are differing between countries and a lack of country specific data for these values exists, the aforementioned concept was disregarded. The electricity prices without taxes are for the year 2010 and based on an average price (P) of the price for households (P_h) and industry (P_i). All data are collected from IEA statistics (IEA 2011, Energy prices and taxes, fourth quarter 2011). If prices for the year 2010 were not available, the prices from earlier years were updated with a price index for electricity for the specific country. Price data without taxes were not available for some countries (India, Republic of Korea, Singapore, South Africa) and we used therefore the price with taxes. The newest data for South Africa are from 2006. The following formula was used to derive average electricity prices:

$$P = \frac{(P_h + P_i)}{2P} \quad \text{(Eq. B3)}$$

Scale: USD/MWh (2010)

2.6.2 *Political & public acceptance & willingness to use incentives for renewables?*

Type of question: scale

For the evaluation of the overall acceptance and willingness to use incentives for renewables of the countries three major contributing factors are chosen, where each accounts for 1/3 from the total weighting scale of 0 to 100:

- The public attitude towards whether the efficient use of natural resources will boost country´s economic growth, i.e. public acceptance

- Governmental set renewable energy target until 2020

- Existing governmental policies or schemes to support the development of renewable resources within the countries

The data for the public acceptance towards the employment of renewable energy was obtained from the results of public surveys carried out within the countries[132]. In the EU, over 83% of the population thinks that the efficient use of natural resources can boost economic growth in the EU. Very high public acceptance of wind energy can be observed in Korea and in New Zealand, where over 88% of the populations expressed support of wind farm constructions.

The political acceptance and willingness to use incentives for renewables was judged based on the existing renewable energy targets and governmental policies to enhance the use and

[132] Eurobarometer, Attitudes of European citizens towards the environment, August 2011

technological development of renewable energy within the countries. Most of the countries have national energy targets for 2020 produced by renewable energy targets. Depending on the type of renewable energy source, e.g. wind, solar, hydro, biomass etc. different regulations and support scheme are applicable. Market-based incentive policies such as subsidies and taxes may be used to promote renewable energy and to correct for market failures that lead to underinvestment in energy efficiency. Subsidies in from the governmental provide financial support and hence a higher attractiveness companies to invest in renewable resources. Subsidies are provided very commonly in for of a feed-in tariff (FIT), which offers long-term contracts to renewable energy producers based on the cost of generation of the technology used. Generally technologies such as solar and tidal power are awarded a higher per-kWh price than wind power, due to the higher production cost. By implementing carbon tax on industries that emit the most CO2 will create incentives to use less energy and emit fewer emissions. Due to the fast variety in energy regulations within the different countries, the political incentives supporting renewable energy use was judged based on the existence of energy policies, not differentiating between the types of policy employed.

Due to the fact that the public acceptance of deployment of renewable energy lies mostly within the region of 80 to 90%, it is not suited as a meaningful differentiating factor for the different countries. Political incentives of each country on the other hand cannot be directly compared due to their complexity. Hence, the most sensitive factor, which differentiates the final result, is the set energy target from the government.

2.6.3 Economic ability to support incentives for renewable energy?

Type of question: scale

The data is based on the 2010 GDP (gross domestic product) of each country per capita. In case of not available data, 2009 values are used[133].

20.000 US-Dollar GDP per capita is chosen as a lower threshold value. This reflects the fact that developed countries will have a 39.000 US-Dollar GDP per capita according to the UNCTAD data and approximately half of that is assumed to allow also less developed countries to be considered. A further reduction of the threshold to 15.000 US-Dollar will only result in one additional country (Malta) and is therefore not chosen. In case the data could not be retrieved from the UNCTAD archive additional sources are used[134].

Countries with a rather small GDP/capita could still decide to use their funds to create incentives to support offshore wind. For example countries as Brazil that invest in offshore oil and gas, Chile with perfect resources and marine infrastructure and India that has a large onshore wind market is currently investigating the offshore wind resources for future offshore wind farms. All three would be countries with rather small GDP/capita that would be disregarded because of the limit that was set. India is even the third lowest GDP/capita of all remaining countries after applying the first three basic questions.

A short test was performed to see how many countries would be considered additionally, if the GDP/capita question would not be applied, just to see, whether there would be a significant change in resulting countries. In case that all other go/no go criteria are applied the GDP/capita value only excludes 3 additional countries. These are Chile, Namibia, and South Africa. If the corruption perception index is not considered another 4 countries would need to be added: Angola, Brazil, India and Panama have to be added to the list of countries that would have to be

[133] http://archive.unctad.org/en/docs/tdstat36_en.pdf visited 11th of April 2012

[134] https://www.cia.gov/library/publications/the-world-factbook/geos/xx.html visited 11th of April 2012

considered as potential markets if the GDP/capita criteria of is not used. Therefore, the threshold could be ignored and this parameter not applied to the selection of countries.

But the risk in those countries that no incentives will be given is much higher than in countries with very high GDP/capita. The scaling of the answer will allow evaluating the economic possibilities. The comparison of the GDP/capita of the countries after applying all the other questions will indicate that these with low GDP/capita are more unlikely to have the economic power to support incentives.

2.6.4 Electrical infrastructure, possibility to connect to grid?

Type of question: scale

The scaling is based on the following three criteria:

1. Electricity consumption /population (kWh/capital) [1]
   The electricity consumption per inhabitant is assumed as a scaling factor describing the development level of the electrical infrastructure, even though there is no one-to-one connection.
   Scale is set from 0 to 100, where 100 correspond to 6000 kWh/capita or higher. This was chosen because many eastern European countries have consumption slightly above 6000 kWh/capita, and it is assumed that these countries should have full score on electrical infrastructure.
   The countries with consumption less than 6000 kWh/capita were given a score as a fraction of 6000, that is the country's consumption divided by 6000 and multiplied by 100.

2. Electrification rate (%) [1]
   Electrification rate, the percentage of the population with access to electricity, is assumed as a factor describing the development of a country's electrical infrastructure.
   Scale is set from 0-100 %. When generic data is missing for some industrialised countries, the rate is set to 100 % by default.

3. Existing transmission grid close to the coast? [2], [3]
   Maps of transmission grids were studied. Scale is set at 0, 50 to 100. This is the simplified solution since a more detailed judgement requires much more time, and maybe better maps. 0 means no transmission grid, 50 means weaker grid with few lines and lower transmission voltages, and 100 means strong grid. For some countries information about the transmission grid is not found. If the electricity consumption and electrification rate was known, a number is assumed in order to complete the data set. For industrialised countries the scale is then set to 100, while for developing countries it is set to 50.

Due to the made assumptions the results are not definite but could be used as a guideline. Different assumptions would lead to different results.

2.6.5 Corruption Perception Index?

Type of question: go/no go based on scale

The data are retrieved from transparency.org and the corruption perception index[135]. The scale is from 0 (worst) to 10 (best). Data is based on a series of sources given with a confidence level.

[135] http://cpi.transparency.org/cpi2011/results/ visited on 11th of April 2012

Since most of them are based on perception this is no hard based evidence data. The threshold for the go/no go criteria has been set to 4 (every country that scored below 4 has been excluded). A series of small (island) countries were not found in the index. The table format easily allows to change the threshold level and to see the impact on the country list. It is found that certain European countries are affected by this threshold.

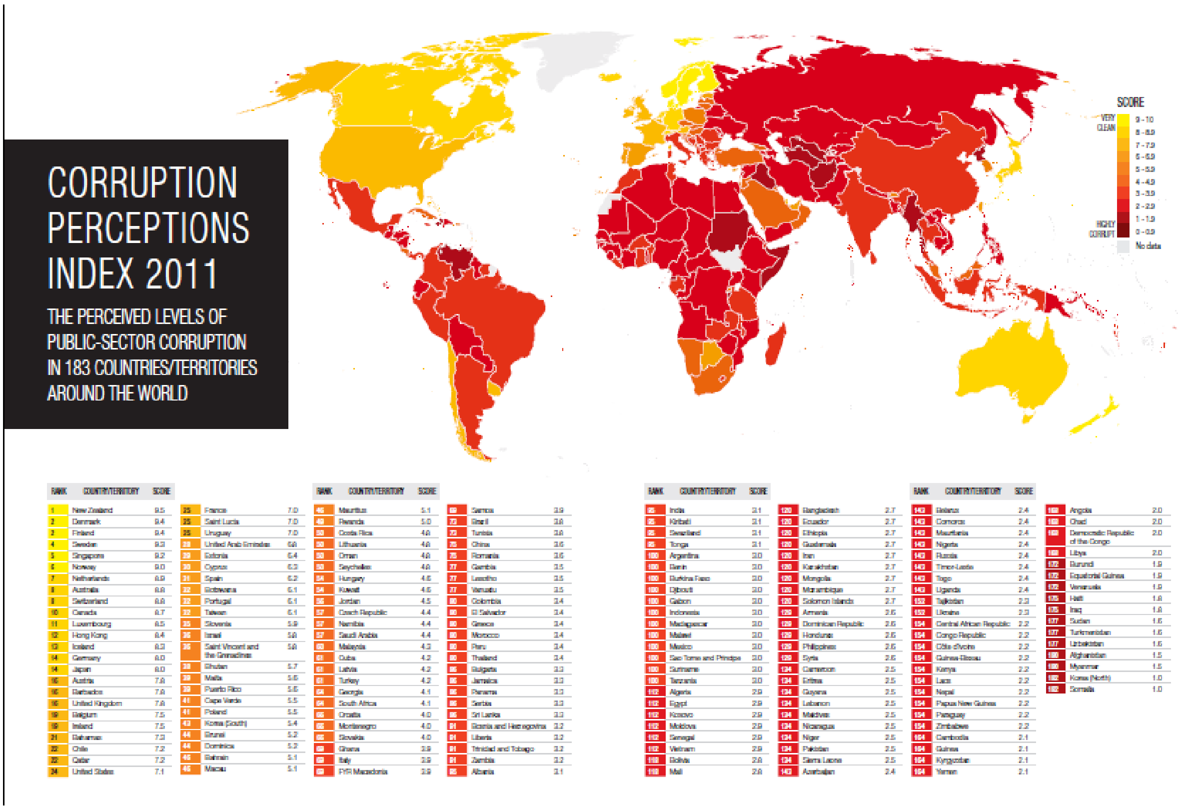

Figure 25: Corruption perception Index 2011[136]

[136] http://cpi.transparency.org/cpi2011/results (accessed on 21st June 2012)

3 10 MW Potential Markets –Definition of associated site conditions

There are three basic methods to install wind turbines of very large scale. The first one would be to install them onshore at easily accessible sites. The second one would be to install them offshore on fixed foundations and the third and last one would be to install them offshore on floating foundations. The last option seems to be the one that is applicable to most of the investigated countries, while the first and the second would be limited to very few countries of the potential markets.

3.1 ONSHORE

The potential Sites for the installation of 10MW turbines are very much limited onshore. The main restriction factors have been discussed already in Part A and are mainly connected to transport and installation factors.

3.1.1 Transport

The restrictions in height, waviness and curvature of the roads limit the transport of very long or very large components. The weight is an additional limiting factor. There is not too many split or modular designs that would allow for road transport e.g. large components as hubs are limiting the sites that can be reached by road transport. Therefore, the onshore site will need either to be easily accessible from coastal or shippable river harbors or to be installed near to the manufacturing facilities avoiding long road transportation. Towers would need to be manufactured in split designs from concrete to allow for road transport. Only a very limited number of locations would allow for the implementation of those 10MW turbines onshore.

3.1.2 Installation

Most of the installation concepts for those very large turbines are developed for the offshore fields and do not foresee onshore installation. To get offshore weather windows used as effectively as possible and to avoid long installation times most designs foresee an installation in very limited number of hoisting operations with very powerful cranes available on specialized vessels or barges.

The wide variety of foundation concepts already developed would allow building on various different offshore soil conditions. These are not a limiting parameter for the onshore implementation.

3.2 OFFSHORE

The offshore locations would need to be divided again into fixed and floating locations. The requirements for fixed locations are not so much different from actual conditions for the 5-7MW class. The water depth is a limiting factor. In case of gravity based foundations also the seabed roughness and inclination is a design parameter.

3.2.1 Transport

For the floating foundations a limiting factor is the water depth. In case of shallow waters, very long mooring chains will have to be implemented and the tidal influence is becoming more critical. The current state of the art does limit the implementation of floaters for water depths below 80m. The cost of the mooring line would direct the floaters implementation at rather deeper water depths. The same is valid for the Tension Leg Platforms (TLP) as for the Semisubmersibles and Spars.

3.2.2 Installation

In case of the Spar design the length of the submerged part already limits the water depths for the installation of the turbines on the Spar. Very shallow coastal areas would not be indicated for this kind of foundation, since the installation of the turbine would require that the Spar would be brought into an upright position. This could also be done in an installation facility offshore but due to weather restrictions this kind of installation would be of a high risk. Semisubmersible platforms and TLPs can also be towed with lower water depths. Their installation would also require deeper waters as mentioned before.

There are no real limitations for the annual wind speed that would be required for those turbines. However, the Cost of Energy (CoE) would require a certain minimum depending on the turbine type to make the projects economically viable. This report drew the line for the annual average wind speed at 7m/s as a minimum requirement as exposed in the prior potential market analysis part.

Several installation scenarios are considered, where part or the whole assembly is performed on offshore installation facilities, sort of artificial ports. This is already under discussion between manufacturers, towards avoiding the current limitations of the port size and availability of suitable port conditions for current large scale offshore wind parks.

Turbines can be installed also from rather far off shore port facilities, either by ship/barge transport, or by towing of floating platforms from further off shore production facilities to the installation site. Both options are of course apart from being time consuming and costly. The towing operations can usually only be performed with very restricted met ocean conditions.

Marine infrastructure in the form of ports is therefore no final argument in the definition of suitable markets. But of course their costly implementation or the increased installation cost in the absence of existing ports make markets definitely less attractive for the installation of 10MW turbines and the required investments to achieve the infrastructure or to perform costly transports.

The more limiting requirements for the implementation of offshore wind parks are not necessarily bound to the size of 10MW. The existing shipping routes, the existence of oil and gas installations and their pipelines as well as nature reservation zones and other dedicated zones such as military exclusion zones define where potential offshore wind parks could be installed. And considering those exclusion zones some areas will have to be discarded.

For a series of countries that are under the remaining countries with market potential it was possible to study the incentive system that has been established for the development of offshore wind. The following table gives an overview of the results.

Table 21: Table with the planned incentives for a selection of countries from Europe and Americas for Offshore wind

EUROPE						
Belgium	2.1 GW	10.7 ct/kWh up to 216MW per OWP† 9 ct/kWh for each additional MW in same OWP 4 ct/kWh market price for electricity = 13.0 to 14.7 ct/kWh	20 years	YES	PD/TSO‡ TSO will assume 1/3 of connection costs, up to max. EUR25m	NO
		green certificates (for the lifetime of the installation, bankable for 5 years; min. price 107 €/MWh for less than 216 MW rated, otherwise 90 €/MWh - guaranteed for 20 years - buying obligation on Elia and resell obligatory in regional markets				
Denmark	1.4 GW	(for a total on-+off-shore of ≈4GW in 2020) 6.94 ct/kWh (Horns Rev 2) 8.43 ct/kWh (Rødsand 2)	50,000 full load hours	YES	TSO	NO
		Tender Process Prioritised access also applies to electricity from tendered offshore wind parks in accordance with the RE Act, as this can only happen with a deregulation of certain wind farms under special circumstances and against compensation for operational loss. A balancing subsidy of 2.3 øre (1 øre=1DKK/100) per kWh is granted to new wind turbines erected outside the tendered offshore wind farms as balancing costs tend to be especially high for wind turbines. With tendered offshore wind turbines, the electricity produced would normally be included in the tender amount. Energinet.dk must also provide support to the owners of older wind turbines				
Germany	10 GW	EEG bonus 2009 ct/kWh: Starting bonus (2 ct/kWh extra for turbines connected until 31.12.2005) 13 ct/kWh Base bonus: 3,50 ct/kWh Digression: by 2014 0%, from 2015: 5%	Initial tariff 12 years (plus extension, depending on location)	YES	TSO	NO
France	6 GW	1) 10.7.2006: 0.13€/kWh for the next 10 years, then between 0.03 and 0.13€/kWh for the next 10 years depending on the plant. 2) 17.11.2008: 0.13€/kWh for the next 10 years, then between 0.028 and 0.082€/kWh five years depending on the plant. Allocation of connection costs. Call for tenders for the construction of offshore wind parks are under preparation (for selected areas optimising the connection conditions)	15-20 years depending on tariff regime and plant	YES	PD (changing)	YES
United Kingdom	13GW	12.22 ct/kWh certificate price for 2 ROCs (Renewable Obligation Certificate) 5.79 ct/kWh market price for electricity including LEC = 18.01 ct/kWh ROCs for 20 years (2 ROCS from 1 Apr 2010)	20 years	YES	Offshore Grid Develloper	YES

Country	2020 Target	Current Support (EURct/kWh)	Term	Subsidies	Grid Connection	Tax Incentives
EUROPE						
Ireland	555MW in scenario1 2.4GW in export scenario	REFIT (feed-in tariff) will cover offshore wind, wave and tidal (CER - regulator license and approval needed) approved in 2009, but subject to state aid clearance offshore wind: 14.0 ct/kWh	15 years	YES	All Island Grid Study - generation portfolio and investment needs; strategic infrastructure planning development (TSO) - streamlined consent procedure, specialised decision in planning board	NO
Netherlands	5.2 GW	FIT (Feed In Tariffs) less market price Tender process Scheme for Sustainable Energy Production (SDE): An Offshore Wind category (opened up in January-February 2010) of the subsidy scheme (budget of EUR 5.3 billion for offshore projects) exists. But no prices indicated. Guarantee of premium prices usually 10-12 years (differing for each category)	10-12 years	YES	PD/TSO Phase 2 (950 MW): Costs for cable between wind farms and national HV network included in SDE subsidy. Socialisation of cables not yet under consideration. Due to WF size and distance from shore, clustered installation is not most cost-effective in phase 2. Phase 3 (4800 MW) designation of additional wind energy areas, the costs for connecting phase 3 WFs to power grid can be presented more accurately. An overall decision can be taken for most cost-effective construction of offshore grid. National TSO no legal obligation to construct an offshore grid. The Minister	YES
Spain	0.6GW en PER (3GW en PANER)	Sale on the organised electricity market. Remuneration is the price on the organised market (or freely negotiated price), supplemented by a specific premium for each renewable technology area. premiums vary on the basis of per-hour market prices: – In the event of low market prices, the remuneration scheme guarantees a floor price meaning that the owner of a renewable installation can be assured a minimum return. – The scheme also provides for a ceiling premium payment, which means that no premiums are paid when market prices are high, thus helping keep system costs at bay. 2010 for offshore wind: 8.9184-17.3502 c€/kWh	20 years	YES	Specific planning of electricity transmission infrastructures linked to marine projects (wind, wave energy, etc.) taking account of progress in administrative procedure. Possibility of establishing offshore electricity transmission corridors to offshore project site. (planned for time period 2011-2020)	
Sweden	182MW	4.36 ct/kWh market price for electricity 2.4 ct/kWh certificate price = 6.76 ct/kWh (not differentiated by RES technology)	15 years	YES	PS	YES
AMERICAS						
USA		2.2 USDct/kWh Federal Corporate Tax Credit (recently extended until end of 2012)	At least for the first 10 years of operation			
Maine	5 GW	The 5 GW target is revisited by the newly elected republican government and major uncertainties prevail over the future development of deep offshore in this state				
Massachusetts		Cape Wind PPA was recently fixed to 18.7 USDct/kWh, with a 3.5% escalator in each of the 15 contract years				
Rhode Island		Deepwater project PPA was recently fixed to 24.4 USDct/kWh, with a 3.5% escalator in each of the 20 contract years				
CANADA		Program ecoENERGY (incentive of 1CADct/kWh) was recently cancelled by the federal government				
Ontario§		19 CADct/kWh (subject to consumer price index inflation)	20 years			

As can be easily seen in some countries like the USA the different states do not pursue a common politic towards the offshore wind incentives.

The incentives in other countries also depend partly on the current government and are subject to changes in respect to future plans for incentives and the way in which they are provided.

Since it the information could not be retrieved for all countries this information could not be introduced into excel sheet for the comparison of the markets.