SIXTH FRAMEWORK PROGRAMME

Project no: **502687**

NEEDS

New Energy Externalities Developments for Sustainability

INTEGRATED PROJECT

Priority 6.1: Sustainable Energy Systems and, more specifically,
Sub-priority 6.1.3.2.5: Socio-economic tools and concepts for energy strategy.

RS 1a: Life cycle approaches to assess emerging energy technologies

Final report on offshore wind technology

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PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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Summary

The objective of this report, as part of the NEEDS project, is to provide data on costs and life cycle inventories for offshore wind energy technology. The focus is the present and long-term technological development of the offshore wind energy technology.

The first part of the report deals with the historical, technological background development as well as environmental problems related to the offshore wind technology.

The second part deals with future technological developments. This section discusses the technological and non-technological barriers and drivers. On the basis of these barriers and drivers three road maps are drawn based on a pessimistic, an optimistic realistic and a very optimistic scenario for the future offshore wind energy technology. The road maps describe in detail how the technologies of offshore wind could develop and how costs could develop in respect to projections of installed capacity and experience curves.

For example in the very optimistic scenario it is projected that offshore wind turbines will have an effect of 15-20 MW in 2025 and will be erected on concrete towers. Based on different scenarios for the global development in capacity, investment costs will have fallen from the present level of 1.8 million euro per MW to between 0.8 million and 1 million euro per MW.

Life cycle inventories for the present and future offshore wind energy technologies are described and analysed in the last section of the report.

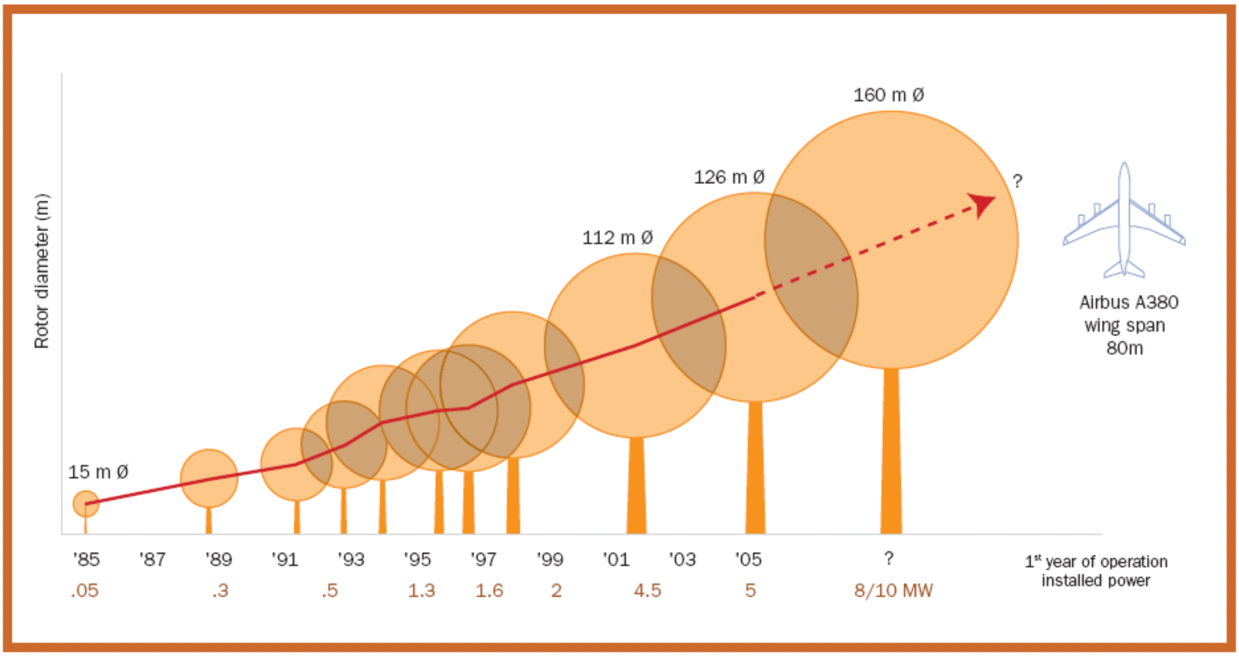
1. Introduction

This final report on offshore wind technology is the conclusion of a three year project period where methods and analyses have been developed in parallel in a number of working groups. Based on a number of earlier drafts this report sums up the final technology specifications, including the technical and financial screening of the current offshore wind energy technologies. Moreover, a number of drivers and barriers that form part of the road map for the future development are evaluated in the report. The report also contains the evaluated results of the Life Cycle Analysis of the current technologies as well as the future technologies envisaged for in 2025 and 2050.

2. Background

2.1 Historical development of wind energy technology

The technological development of wind turbines has been significant in the last two decades. It started in the early 1980s with wind turbines ranging from 20 kW to 30 kW with simple fixed-speed stall-regulated turbines with basic asynchronous generators. Today, wind turbines between 2 MW and 5 MW with more advanced variable-speed pitch-regulated turbines equipped with sophisticated generators and control systems are commercially available (figure 2.1).



Source: Jos Beurskens, ECN

Figure 2.1: The development in size of wind turbines from market introduction

The oil crisis in the1970s, the concern over environmental deterioration, high energy demands and as the national research and development programmes have played an important role in promoting the development of wind turbines towards more cost efficiency and reliability machines.

Due to this development in wind energy technology, the European wind power capacity has increased dramatically and wind power has developed into one of the most efficient sources of renewable energy. It is also proving to be a very fast growing industry in the renewable energy sector. For instance in 1994 there were 1,683 MW of wind energy installed across the EU and by the end of 2006 this figure had been multiplied 28 times to 48,027 MW (figure 2.2).

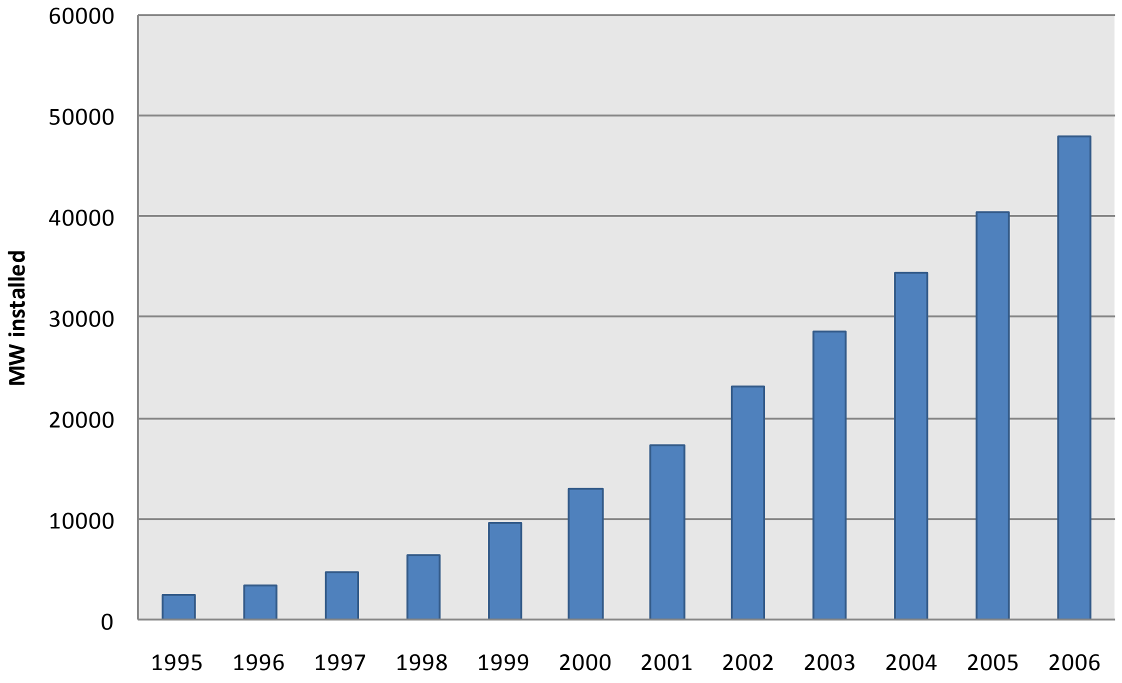


Figure 2.2: Wind energy installed across Europe [2]

2.1.1 Wind energy technology

Modern wind turbines are basically classified by the orientation of the drive shaft, which can be horizontal axis turbines or vertical axis turbines. Horizontal axis turbines with two or three blades are the most common types used today.

Currently, there are two ways of transmitting wind energy from the rotor to the generator; via a gear or a direct drive generator (gearless).

Transmission of wind energy to the generator using a gearbox has been known for a while and is still widely used. On the other hand, direct drive generators or gearless transmission systems are technologically feasible and have the advantage of avoiding the expenses and maintenance in connection with the gearbox. However, the direct drive system has proved to be heavier than the traditional gear drive system. In a competitive international market the choice between two solutions like these is usually a question of finance. So far the gear solution is still the most competitive; however, this may change through technical improvements and cost reductions in future.

2.1.2 Offshore wind turbines

The success story of onshore wind energy has led to a shortage of land sites in many parts of Europe, particular in northwestern Europe, and has spurred the interest in exploiting offshore wind energy. Offshore sites also enjoy the advantage of having significantly higher wind speeds and more stable winds than onshore sites. This stable and higher wind speed leads to higher energy production at sea (see table 2.3) and a longer turbine life. In addition, modern offshore wind turbines can also be remotely monitored and controlled, which gives unique advantages when regulating the power output.

Table 2.3: Comparison between the annual production of an offshore and onshore wind turbine

Type of wind turbine	Site	Full load hours/year	Production [MWh/yr]
2 MW offshore	Horns Rev (DK)	4,044	8,088
2 MW onshore	Tjaereborg (DK)	2,817	5,634

Due to economies of scale, wind farms consisting of multiple wind turbines all connected to a single transformer station are more financially viable than individual turbines. Therefore in future, offshore wind turbines are only considered for erection in wind farms where multiple turbines connected to one transformer station are categorised as one offshore wind power plant.

2.1.3 Monitoring control systems in the nacelle

Monitoring systems

As wind energy moves offshore the turbines become less accessible and operation and maintenance (O&M) costs increase, and thus offshore turbines need to be more reliable than their onshore counterparts. Therefore, the turbines are equipped with monitoring systems which detect any unusual events and report them to the control centre via a wireless link. Such early warnings of an impending failure allow remedial action to be taken and in most cases prevent complete failure.

Control systems

The modern wind turbines we see today are highly dependent on their control systems to operate successfully. The control system basically uses the output from the monitoring system and decides which action to take; eg by examining wind speed output from the nacelle anemometer, the control system will change the pitch angle of the blade to extract the maximum possible energy form the wind. On the other hand, it will also pitch the blades out of the wind to reduce the load on the blade when the wind speed is found too high. In fact the modern wind turbine with a prospective lifetime of 20 years would simply not be possible without the load-reducing functions of the control system.

As wind turbines grow in size, it will be necessary to develop new technologies to reduce the overall load. A new method for early warning gust detection is being considered at the moment where an approaching gust can be detected using sonar. A monitoring device of this type allows the control system to take preventive action by pitching the blades out of the wind, thus reducing the impact of a high load case situation.

A comparison between the lifetime of car and a wind turbine:

In terms of working hours an offshore wind turbine is expected to operate for 20 years at 4000 hrs/year, which amounts to 80,000 hours during its useful lifetime. That is a highly impressive achievement compared to a car. Eg if the average car drives 12,000 miles per year at an average of 30 mph (motorway and city driving), it would run for 400 hours a year and in the unlikely case the car lasted for 20 years, it would have operated for 8,000 hours. This is 1/10 of the time that a wind turbine is expected to operate. Within the first two years, the offshore wind turbine will have operated for a period equivalent to the entire lifetime of most cars.

2.2 Specification of reference technology

Today, the basic concept of the offshore wind energy technology is generally the same from one competitor to the other, however, there are different design concepts and the choice of a specific technology in the actual project will depend on its efficiency, reliability and costs.

Among current commercially available wind turbines, the 3-blade upwind pitch-regulated turbine with a horizontal axis is the dominant type compared to 1- or 2-blade turbines [3]. Even though the main problems with the 2-blade wind turbine, noise and visual impact, can become less important when the turbines are installed offshore, it seems unlikely that they will pose a serious challenge to the 3-blade turbines in future.

Therefore, the reference technology for the present wind energy technology is 2 MW turbines with 3-blade upwind pitch-regulation and horizontal axis. Horns Rev Offshore Wind Farm has been chosen as representative for the contemporary European offshore wind farm (figure 2.4). It is situated in the North Sea approx 14 km off the coast of Blaavands Huk in Denmark [1]. Figure 2.4 also shows the system boundary for the LCA (Life Cycle Analysis).

At the moment offshore wind turbines the size of 2 to 3 MW are currently available and have been installed in some parts of Europe. There are also some larger turbines of which some are commercially available, others are still prototypes presently undergoing testing such as:

- Siemens 3.6 MW with 107 m rotor diameter
- General Electric 3.6 MW with 104 m rotor diameter
- Vestas V120 4.5 MW with 120 m rotor diameter
- Enercon E-112 4.5 MW with 114 m rotor diameter
- Repower 5 MW with 127 m rotor diameter
- Enercon E-126/6 6MW with 127 rotor diameter

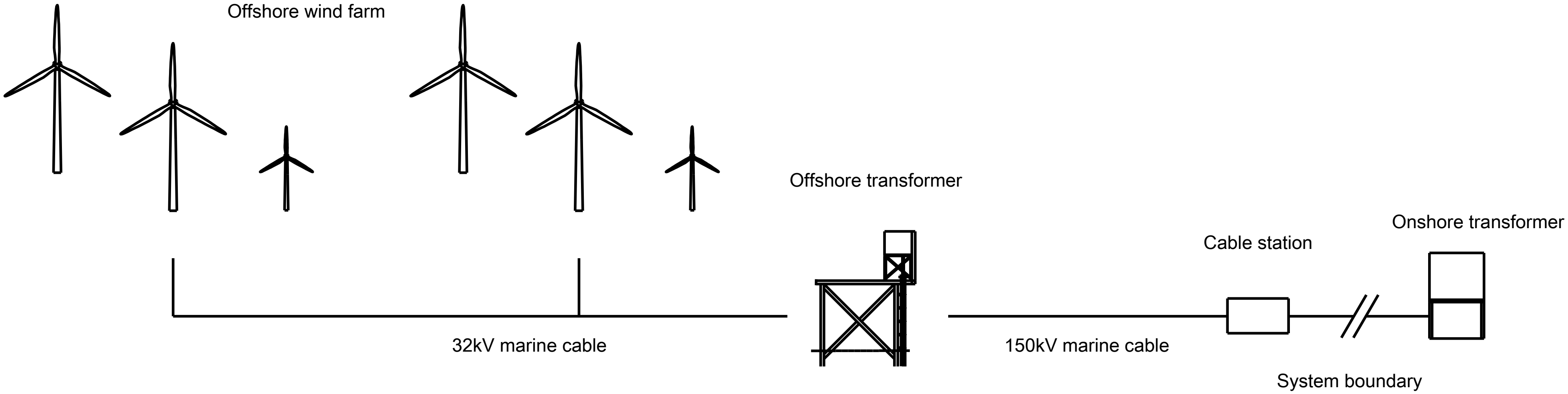


Figure 2.4: Simplified illustration of Horns Rev Offshore Wind Farm and its grid connection system

2.2.1 Foundations

One of the present and future challenges in connection with offshore technology is the type of foundation and the material used to build it (concrete, steel, etc), especially in deep water. Currently, there are several different types of offshore foundations used either in the offshore oil and gas industry or in the offshore wind industry, viz:

- Monopile
- Tripod
- Gravitation foundation
- Suction bucket
- Jacket
- Floating foundation, anchor chain mooring
- Floating foundation, tension mooring
- Pile foundation within sheet pile foundation
- Guyed foundation

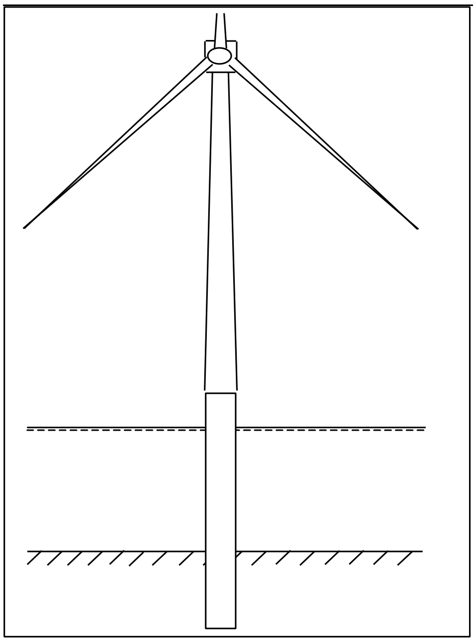


Figure 2.5: Monopile foundation

Some of these foundation types are already used in offshore wind projects, eg the monopile, gravity foundation and suction bucket. However, at the moment the other foundation types are known in the offshore oil and gas industry.

One of the foundation types widely used in modern wind technology is the monopile. It is a single large steel pile driven into the seabed (see figure 2.5) and it features the following advantages compared to the other types of foundations: it is a well-known technology and cost effective up to a water depth of 30 metres (depends highly on the actual soil conditions), not especially sensitive to scouring and seabed changes and requires only modest maintenance.

The focus has been on reducing the weight and size of the foundation units. When moving further offshore into deeper waters, the installation process becomes more challenging and the installation vessels put a size limit on the type of foundation applied.

The other foundation types, which are presently known in the oil and gas industry, may also prove to be useful for the offshore wind industry in future. Table 2.6 summarises the current and future foundation types for offshore wind farms. Although it is difficult to foresee the kind of foundation that will be used in 2050, the experts believe – regardless of the size of the wind turbine in 2050 – that the type of foundations used in 2025 will also be used in 2050.

Table 2.6: Current and possible future foundation types

Foundation type	2005	2025	2050
Monopile	X	X	
Tripod		X	X
Gravitation foundation	X	X	X
Suction bucket	X	X	X
Jacket		X	X
Floating foundation, anchor chain mooring		X	X
Floating foundation, tension mooring		X	X
Guyed foundation		X	X

Source: DONG Energy, department for Wind Power Technology.

2.3 The potential of offshore wind energy

According to two studies described in Global Wind Energy Outlook [14], the global wind resources are extremely large and wind is not likely to be the limiting factor in the development of wind power. One study [21] suggests that global wind resources can produce approx 53,000 TWh/year, another study [22] finds that a potential production of 39,000 TWh/year is realistic in the long-term. This is three to five times more than the global electricity consumption of 13,663 TWh in 2003, or between one and a half and two times more than the demand expected in 2030: 25,667 TWh. [14]

These findings are confirmed by a recent report from Stanford University, based on data from 8,199 sites globally at 80 metres height. [23]

2.4 Quality of wind energy

Wind energy is an abundant renewable energy source that is primarily limited by the availability of wind farm sites and the acceptance of the public. The wind resource as such is free, and once the wind farm is installed the effect on the environment is limited.

Unlike other energy forms, wind[1] energy. ie electrical power, cannot be stored yet for optimal use without considerable efficiency losses or relatively high costs eg via batteries or transformation to hydrogen or methanol. Therefore, wind energy is transformed simultaneously and fed into the power grid along with several other power types. The power grid has a limited capacity and is physically restricted to keep a balance between the supply and the demand in order to uphold the frequency.

2.5 Economics of wind energy technology

2.5.1 Definitions

The economics of production units such as wind turbines and other energy technologies are normally described by fixed and variable costs. Fixed costs are defined as costs that do not fluctuate according to production, eg investment, insurance, etc, whereas variable costs are defined as costs fluctuating according to production, eg fuel, maintenance etc.

Usually a wind power project is described by its specific investment costs (ie euro/MW installed electrical capacity), which are fixed, and its O&M costs, which contain elements of both fixed and variable costs related to the production, eg insurance, administration, maintenance, repair etc. O&M costs are usually calculated in relation to the power produced (ie euro/MWh).

[1] Plus solar and wave energy

2.5.2 Economics of wind power

Wind power is characterised by relatively high fixed costs, ie the investment and low variable costs per kWh. Even though the specific overnight construction costs in euro/MWe are about the same as for coal-fired power plants, the costs of wind power are considered to be relatively high because of the lower capacity factor, ie less productive hours per year. The capacity factor has increased, however, with improving technology over the last decade and further improvements are expected as wind energy move offshore where the wind potential is greater.

A wind power plant consists of a number of elements which in addition to multiple turbines and foundations also include investments for a shared grid, a transformer and a cable transmission station. In the Danish offshore wind farm Middelgrunden the turbines accounted for approx half of the total investment whereas the grid and the foundations accounted for the majority of the remaining half (see figure 2.7). The wind farm consists of 20 2 MW Bonus turbines. The specific costs of the installed wind farm (turbines, grid, foundations etc.) amounted to 1,250 euro/MW. The investment costs of most installed wind farms are listed in table 2.9.

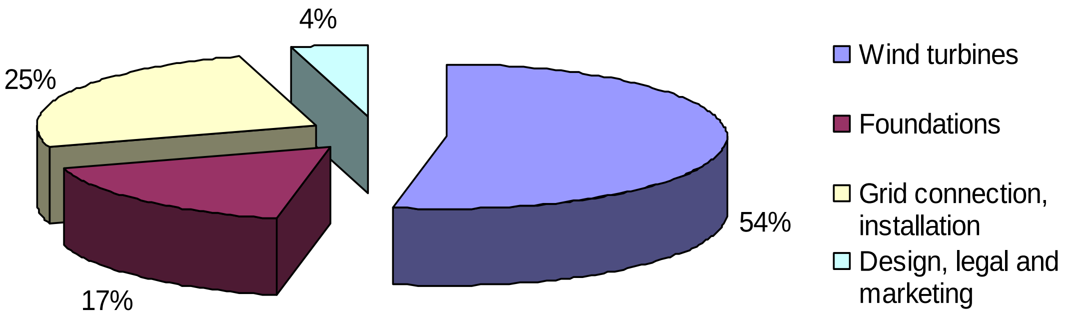


Figure 2.7: Investment costs for Middelgrunden[2]

The O&M costs of wind power are lower than fuelled energy technologies since the “fuel” – ie wind – is free, and most turbines are now designed to operate with only one inspection and one service-stop a year. However, the O&M costs of wind power have increased as wind power plants have moved offshore, eg because of the more challenging transport of the O&M teams and the new conditions for the equipment. Usually the O&M costs are considered confidential and only few wind farms go public with these figures. For the Danish wind farm Middelgrunden (installed 2001), the figures are publicly available as it is a cooperative of several investors, including small private investors. In 2005 the total O&M costs for Middelgrunden amounted to 8.6 euro/MWh (see figure 2.8). The wind farm is situated in coastal waters and O&M costs are higher further offshore. For the large offshore wind farms installed today the total O&M costs are approx 10-15 euro/MWh.

[2] www.middelgrunden.dk

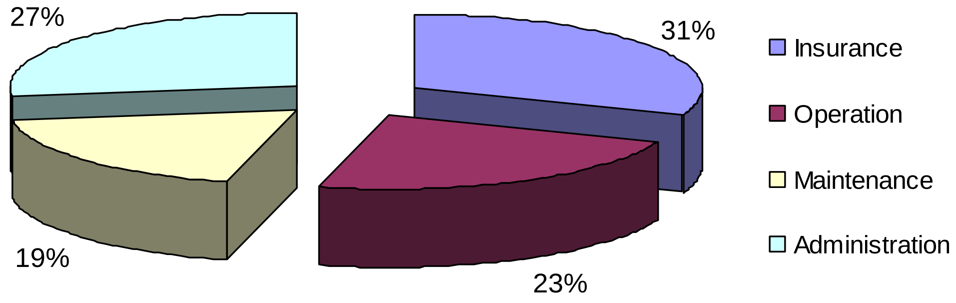


Figure 2.8: O&M costs for Middelgrunden[3]

Keeping the O&M costs from increasing with increasing distance to shore and increasing complexity of the wind farms will be one of the major challenges in the future. Great savings/earnings can be made by optimisation of the maintenance and repair phase, eg by monitoring of tear and wear of the equipment so that parts can be exchanged before they cause a failure. Also the logistics can be improved, eg by moving from boat transport to a combination of boat and helicopter transport in connection with repairs. This will also result in higher availability of the wind farm.

2.5.3 Historical cost development

The largest development within commercial offshore wind power technology has taken place over the last five years, but the first offshore wind power plants were installed already in the beginning of the 1990s.

Table 2.9 displays selected information on investments, capacity, location, etc of the European offshore wind farms commissioned from 1991 to 2005. The information is collected by reviewing our own projects, the Internet, magazines and other publications. Some information has been published during the planning phase of the wind farm, other after finalisation.

The Vindeby wind farm in southeastern Denmark, installed in 1991, was the first commercial offshore wind power plant in the world. It consisted of 11 450 kW stall-regulated[4] Bonus turbines, situated 1,5 kilometres from the shore, with a total installed overnight cost of about 10 million euro, ie a specific cost of approx 2100 euro/kW.

Throughout the 1990s another five offshore wind power plants were established with slightly decreasing investment costs. In 1996, a large wind power plant consisting of 28 wind turbines was established at Dronten in The Netherlands. The wind farm was placed in an inland sea only 20 metres from the shore; however, this is not considered a typical offshore plant.

After the first ten years with offshore wind energy, the limits were challenged again in 2000 and 2002 with the Danish wind farms Middelgrunden and Horns Rev at sizes of 40 and 160 MW, respectively. The specific overnight costs were 1250 euro/kW for the 20 2 MW Bonus turbines at Middelgrunden and 1675 euro/kW for the 80 2 MW Vestas turbines at Horns Rev. Compared to Middelgrunden, the turbines at Horns Rev were erected at greater depths, ie up to 14 metres and further from the coastline, ie 15 kilometres.

[3] www.middelgrunden.dk

[4] Prior to the pitch regulated turbines the stall regulated turbines were directed in a fixed position to the wind

Table 2.9: Offshore wind farms commissioned from 1991 to 2005 (status per 1 January 2007)

Location	**Country**	**Commissioning**	**No. of** turbines	**Turbine capacity (MW)**	**Total MW**	**Water depth (m)**	**Dist. to shore (km)**	**Cost M€**	**Cost €/kW**	**Manufacturer**
Vindeby	DK	1991	11	0.45	5	3-5	2	10	2071	Bonus
Lely	NL	1994	4	0.50	2	5-10	1	5	2250	NedWind
Tunø Knob	DK	1995	10	0.50	5	3-5	6	10	2080	Vestas
Dronten	NL	1996	28	0.60	17	5	0	21	1220	Nordtank
Bockstigen, Gotland	SE	1997	5	0.55	3	5.5-6.5	4	5	1709	WindWorld
Utgrunden, Kalmarsund	SE	2000	7	1.50	11	8-10	8	14	1324	GE
Blyth	UK	2000	2	2.00	4	8.5	1	6	1580	Vestas
Middelgrunden	DK	2000	20	2.00	40	4-8	2	50	1250	Bonus
Yttre Stengrunden	SE	2001	5	2.00	10	<5	5	13	1300	NM
Horns Rev	DK	2002	80	2.00	160	6-14	15	225	1406	Vestas
Samsø	DK	2003	10	2.30	23	11-18	3	35	1522	Bonus
Frederikshavn	DK	2003	2	3.00	6	1	1	na	na	Vestas
Frederikshavn	DK	2003	1	2.30	2	1	1	na	na	Bonus
Frederikshavn	DK	2003	1	2.30	2	1	1	na	na	Nordex
Nysted	DK	2003	72	2.30	166	6-10	10	245	1476	Bonus
Arklow Bank	IRL	2003	7	3.60	25	2-5	12	73	2897	GE
North Hoyle	UK	2003	30	2.00	60	8-12	8	111	1851	Vestas
Emden	D	2004	1	4.50	5	3	0	na	na	Enercon
Scroby Sands	UK	2004	30	2.00	60	2-12	2	104	1733	Vestas
Kentish Flats	UK	2005	30	3.00	90	5	10	148	1644	Vestas
Barrow	UK	2006	30	3.00	90	15-20	7	na	na	Vestas

Table 2.10: Offshore wind farms under construction or in the planning phase (status per 1 January 2008). NB: List is not exhaustive.

Location	Country	Commissioning	No. of turbines 1st phase/total	Turbine capacity MW	Total MW	Water depth metres	Dist. to shore km	Developper
Lillegrund	SE	under constr.	48	2	96	na	7	na
Culemborg	NL	under constr.	2	3	6	na	na	Nuon
NSW (Egmond aan Zee)	NL	under constr.	36	3	108	18	10-18	NoordZeeWind (Shell&Nuon)
Zutphen	NL	under constr.	3	3	6	na	na	Nuon
Butendiek	D	under constr.	80	3	240	20	34	Bürgerwindpark
Burbo	UK	under constr.	25	3.6	90	5-15	5	na
Barrow	UK	under constr.	30	3	90	na	na	na
London Array	UK	under constr.	271	na	na	0-23	20	na
Thornton Bank	B	planning ph.	60	3.6	216-300	19-24	27	Interelectra, SIIF energies etc.
Q7 WP	NL	planning ph.	60	2	120	20-25	23	E-Connection (consortium)
Cathedral Rocks	Aus	planning ph.	37	1.75	66	na	na	Hydrotasmania / EHN
Kriegers Flak	D	Constr. starts 2010	80	3,6-5	330	20-35	31	Offshore Ostsee wind AG
Kriegers Flak 2	SE	planning ph.	128	5	640	na	na	Vattenfall
Klutzer Winkel	D	planning ph.	1	na	na	na	5	na
Baltic 1	D	Constr. starts 2009	21	2.5-5	na	15-19	15	na
Arkona Becken Südost	D	planning ph.	80/201	4-5	na	23-36	34	AWE GmbH EON Energy Projects
Ventotec Ost 2	D	Constr. starts 2009/2010	50/200	3	na	21-34	104	Arcadis Consult
Geofree	D	Constr. starts 2009	5	5	na	20	20	Geo
Wilhelmshaven	D	planning ph.	1	5	na	5	<10	Bard Engineering
Sandbank 24	D	Constr. starts 2009	80/980	3-5	na	30-40	100	Project GmbH, Project Ökovest
Alpha Ventus	D	Constr. starts 2009	12	5	na	28-30	43	Eon, EWE, Vattenfall
Dan Tysk	D	Constr. starts 2011	80/300	5	na	23-31	45	Vattenfall
Borkum Riffgrund West	D	Constr. starts 2010	80/458	2.5-5	na	30-35	40	Energiekontor
Borkum Riffgrund	D	Constr. starts 2008/9	77/180	3-5	na	23-29	34	Plambeck, DONG Energy, Vattenfall
Nordsee Ost	D	Constr. starts 2011	8	4-5	na	19-24	30	Essent
Offshore Bürger-Windpark Butendiek	D	Constr. starts 2010	80	3	240	16-22	35	Airtricity, Bürgerwindpark Butendiek
Delta Nordsee	D	planning ph.	48/251	4-5	na	25-33	40	Eon Energy Projects
Amrumbank West	D	planning ph.	80	3.5-5	na	21-25	35	Amrumbank West GmbH
Nördlicher Grund	D	Constr. starts 2010	80/402	3-5	na	23-40	86	Geo, Renergys
Gloal Tech 1	D	Constr. starts 2011/12	80/320	4.5	na	39-41	75	Nordsee Windpower
Hochsee Windpark Nordsee	D	Constr. starts 2010	80/508	na	na	25.7-39	75	Eos Offshore
Gode Wind	D	Constr. starts 2009/10	80/224	3-5	na	26-35	45	Plambeck, Evelop
Bard Offshore 1	D	Constr. starts 2009	80/320	3-5	na	39-41	87	Bard Engineering
Meerwind	D	Constr. starts 2010	80/270	5	na	22-32	15/80	Windland Energie-erzeugungs GmbH

At the moment a number of wind farms are being built in the UK and Germany and more are on the drawing board. Also The Netherlands, Belgium, etc are in the process of installing offshore wind power. Table 2.10 summarises the most relevant wind farms in the construction or planning phases. It can be seen that the capacity of the turbines is increasing, whereas the number of turbines in one farm, or in one phase of a larger farm, is between 50 and 80 turbines.

Apart from the wind farms mentioned above, an additional 78 potential offshore wind farm sites have been identified [26]. The term “identified” means that the area is a potential wind farm site. For some of the sites no concrete actions have been taken to develop the sites.

Table 2.11: Other potential offshore wind farm sites identified in northwestern Europe

Identified offshore wind farm sites	Number
East coast, England	16
West coast, England	8
East coast, Scotland	2
Coasts of Ireland	8
West coast, Denmark	1
Inner waters, Denmark	2
Northwest coast, Germany	9
Baltic Sea, Germany	7
Baltic Sea, Poland	3
Baltic Sea, Sweden	9
West coast, Sweden	3
Northwest coast, France	3
Mediterranean, France	2
Mediterranean, Spain	1
Northwest coast, Spain	1
Southwest coast Spain	3

Note: All wind farms within 50 metres depth

Outside Europe, two wind farms are in the planning phase in the USA; at Cape Cod, Massachusetts and Long Island, New York. However, there have been heavy NIMBY[5]-protests. Two other wind farms at Padre Island and Galverston Island in the Mexican Gulf are also in the planning phase – without this causing any NIMBY-protests. The wind farms are expected to start producing approx 2010. [23]

3. The development of offshore wind energy

As described in the previous chapters, wind energy has developed exponentially during the last decades, and there is still a large unexploited wind energy potential in many parts of the world – both onshore and offshore. As it was difficult to predict the development during the last two decades, it is also difficult to predict what the future holds in store. On the one hand, the development will be pushed forward by a number of drivers, and on the other hand it will be curbed by a number of barriers. In the following chapters the drivers and barriers and their potential effect will be introduced and discussed. The drivers and barriers are sorted in non-technological and technological issues reflecting one approach to their assessment – they will, however, interact across these definitions. Eg stable economic conditions can result in faster technological progress, technological innovation can result in lower environmental impact and therefore better public support etc.

[5] Not-In-My-Back-Yard

3.1 Non-technological barriers and drivers

The non-technological barriers and drivers that are expected to have an impact on the development of offshore wind energy are divided into energy policies, markets, economics, public opinion and the environment.

3.1.1 Political support

The political climate has a decisive impact on the development of offshore wind energy. For example the extensive development of the wind power sector in Denmark is primarily based on the ambitious political targets supported by favourable conditions for the producers. However, political support is more than just subsidies and easy access to wind energy development sites. The political drivers and barriers can be summarised as:

- political targets and actions
- administrative and legal conditions
- pricing and financial conditions
- support from universities and research institutions
- environmental approval

<u>Political targets and actions</u>

Political targets are a strong driver for the development of technology if they are backed up by favourable conditions. Globally at least 46 countries (including the EU-25) have set targets for renewable energy. Also 20 states in the USA and three provinces in Canada have set targets, although they do not have national targets. [19]

In 1997, a White Paper on Renewable Sources of Energy set a goal of doubling renewable energy in the EU from 6% in 1997 to 12% in 2010. This was followed by the EU Renewables Directive in 2001. The directive aims to increase the EU's share of electricity produced from renewable energy to 21% (from 15.2% in 2001).

In January 2008, the European Commission proposed a target of 20% renewable energy in Europe in 2020. This target was proposed as an average for the EU where some member states will carry a large burden and others a small burden, and where the certificate markets should ensure cost effectiveness in the target. Also there is no specific target for wind relative to biomass, hydropower etc. But in general this will be a large driver for more wind energy.

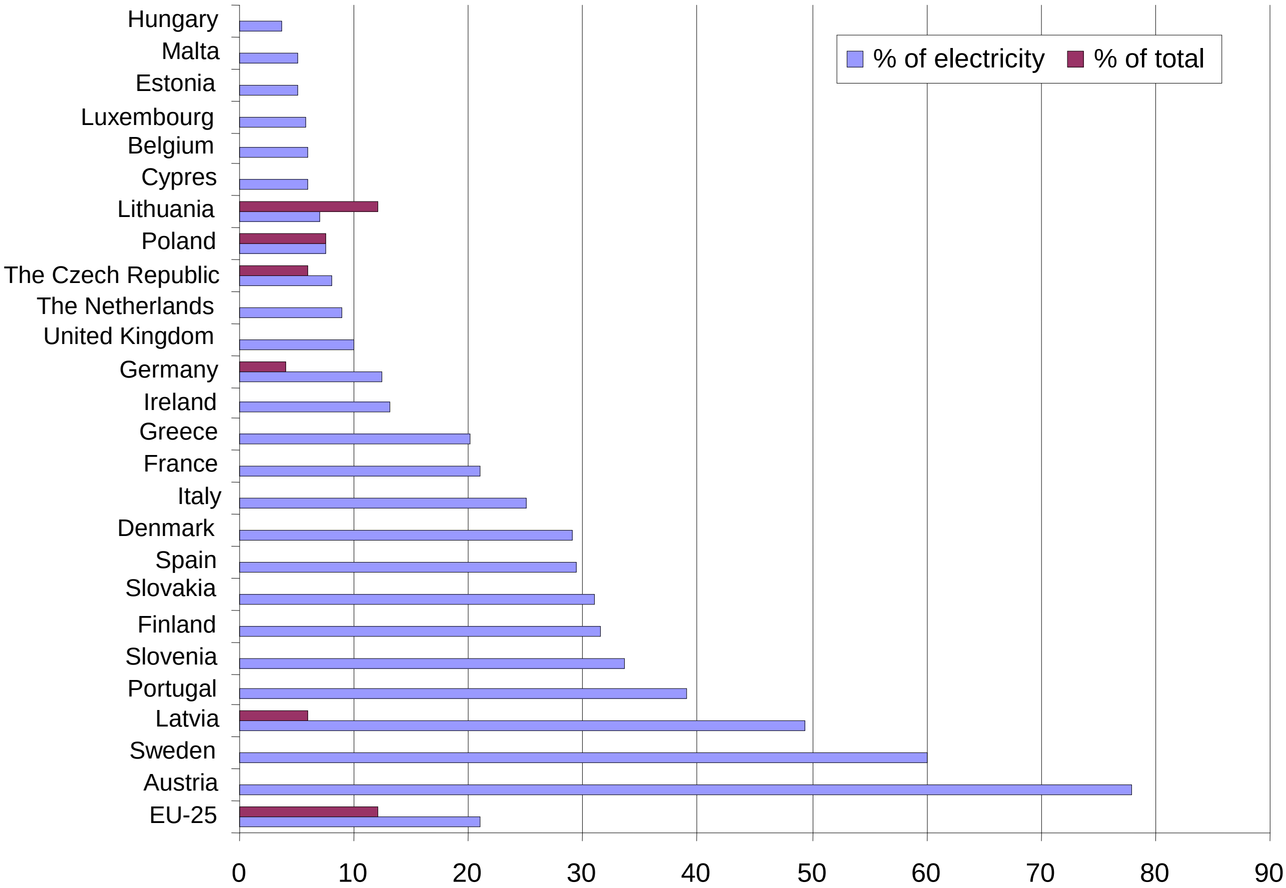


Figure 3.1: The renewable energy targets for 2010 in EU-25 [19]

In the Danish "Action Plan" for offshore wind technology, published in 1997, five trial projects with a total of 750 MW were pointed out. After these wind farms had been built, the plan was to increase the offshore wind capacity by 150 MW on average per year in order to reach 4000 MW in 2030. The wind farms were to be funded by a Public Service Obligation scheme, ie a consumer financed subsidy. Two of the five wind farms were realised through this mechanism – Horns Rev (completed in 2002) and Nysted (2003). Due to the EU liberalisation of the power sector in 1999 the scheme was changed so the remaining projects had to be put up for a public tender.

With the Renewable Energy Act, Germany has defined favourable long-running renewable energy support schemes where technologies are supported by a feed-in tariff. Electricity from offshore wind farms will receive a higher price per kWh than onshore wind farms under the feed-in tariff law, although this price will be decreasing continuously from 2008 and onwards by 2% annually. In the period 1999-2002, 22 applications for the North Sea area and 7 applications for the Baltic Sea were submitted. It has become clear that many of these applications were submitted by developers for strategic reasons and therefore the German authorities have planned to modify the scheme so that applications for the same area can be processed in parallel. [6]

In 2006, a new scheme, Partnership for Renewables (PfR), was introduced in the UK. The idea is to create a partnership between the public and the private sectors to develop onsite renewable energy projects. It is expected that through the programme, which will be run by the Carbon Trust, 500 MW of renewable energy projects, primarily 3 MW to 5 MW wind turbine projects, will be constructed or developed within the next five years. [20]

In Ireland, renewable energy was supported through a tendering mechanism until 2005 when it was replaced by a feed-in tariff scheme. Also grants through the European Commission and green tariff schemes have been used. [6]

At the moment, the wind power sector is in growth in the USA which is primarily due to the Production Tax Credit (PTC), which has been in force since 2003 and is extended to the end of 2007. [14]

Administrative and legal conditions
An important political driver identified by several sources is when all government departments have the same agenda - this makes it easier to develop new technologies. The concept of one-stop-shops where developers only have to communicate with one governmental office is also facilitating new projects. [6] At the Copenhagen Offshore Wind Conference held in October 2005, this one-stop-shop concept was pointed out as a large contributor to the success of offshore wind power in Denmark.

Among other countries the UK and Denmark have identified a number of potential offshore wind sites, and tenders have been called for site leases. With a site lease in the hand, the wind energy producer or consortium holds an option for the development of a wind farm.

Financial conditions and risk
Since wind energy is more capital-intensive in the investment phase and less competitive than fossil forms of energy, wind energy is dependent on stable conditions for investments and financial support. Without committed long-term government support – or consumer support – investors will categorise offshore wind energy as a high-risk investment resulting in the planning and realisation of fewer wind farms. With committed support the risks are minimised and investors have a more transparent investment to consider. As described above a number of countries have facilitated the investments by feed-in tariffs, tax credits, etc.

A feed-in regime sets a fixed price or a premium on top of the market price at which the producers can sell renewable energy. Usually the subsidy is financed by a small surcharge on all the utility customers who thereby share the costs of introducing renewable energy. The USA was the first country to introduce a feed-in law for renewable energy in 1978. By 2005 at least 32 countries and six states/provinces have adopted feed-in laws. [19]

As an example of the significance of price support, in Denmark the large wind farm projects stopped once the subsidies were reduced to market price plus a premium of approx 13 euro/MWh for the carbon free production. According to the agreement the premium will be reduced to zero, if the market price increases to about 48 euro/MWh [6].

Initial technical problems with offshore wind energy, such as the transformer problems at the Danish offshore wind farm Horns Rev, and gear problems at Scroby Sands have also contributed to the perception that offshore investments are high-risk investments.

The high risks involved in offshore wind farms combined with the high number of newly developed wind farms in the USA make the wind farm producers more reluctant to bid for wind turbines for new offshore wind farms which results in higher prices for the wind turbines.

The increased risk in connection with offshore wind farm projects can also mean that turbine producers will only implement thoroughly tested wind turbines in offshore plants, which can result in a slower development process of larger turbines.

6 EnergiNet.dk – the Danish Transmission System Operator

Environmental approval

In order to obtain permission to establish an offshore wind farm you have to assess the environmental impacts by making an EIA (Environmental Impact Assessment) report, which has to be made public. Often when developing new offshore wind farms, designated areas have been appointed; hence the focus will be on the results of the EIA. After the EIA procedure has been finalised, the authorities (the appropriate authority depends on the specific country) have to decide whether to approve or reject the project. This can of course be a barrier in the development of offshore wind energy, eg because the EIA often refers to a certain layout and type of wind turbine which results in inflexible project development. Another issue is the time aspect; in most cases it takes approx 1 year to prepare an EIA and ½-1 year to obtain the approval. When preparing the EIA, in most cases you must specify the details of your project including the type of turbine you will erect, which means that in some cases you will use newly developed and larger turbines, but the approval was originally given only to a smaller turbine.

3.1.2 Energy markets

Installed offshore wind energy delivers electrical power to the same physical grid as other forms of renewable and fossil energy. Since wind resources are free and the displaced fossil fuels are costly, it is usually in the producers' and the society's best interest to keep production at the maximum level and only reduce the production in case the transmission system operator (TSO) cannot balance the grid.

The power market consists of a large number of power producers constituting a supply curve, where the technologies with the lowest marginal costs (hydropower, wind power and nuclear) are at the bottom of the curve and the coal, gas and biomass fuelled technologies are further up the curve with higher marginal costs. The market price is determined every hour of the day by the actual size of the demand, which is relatively inelastic, ie consumers do not react to power prices from a short term perspective.

The average production costs of wind power are, however, still relatively high compared to fossil energy and nuclear energy and this will be the largest barrier for the future demand of wind energy. As described in IEA 2005 [6] the levelised production costs of offshore wind energy, including O&M and investments,[7] are about 45 euro/MWh. Compared to the levelised costs, including O&M, investments and fuel for coal, gas and nuclear are on average 35, 45 and 30 euro/MWh, respectively, in the countries analysed.

Offshore wind power is a relatively new form of energy compared to fossils and technological development and innovations summarised in experience curves, which are expected to lower the costs in the long run. Also fossil technologies will undergo additional progress, but the progress ratio is expected to be less steep. However, the fossil fuels for these technologies are showing increasing prices due to security of supply problems and increasing CO_2-costs, whereas the costs of "wind fuel" will remain zero.

As the European Transaction Scheme for CO_2 progresses, the CO_2 emissions related to the use of fossil fuel are being priced according to the CO_2 market and the relative competitiveness to the renewable energy form will be diminished. Since the CO_2 market started in 2005, the cost of 1 ton of carbon has peaked at 32 euro, but has since declined to an actual level of about 20 euro/t CO_2 in January 2008. With an estimated long-term price of 20 euro/t CO_2 the marginal costs of CO_2 on the power price can be estimated to be approx 14 euro/MWh for a coal-based power production and 8 euro/MWh for a gas-based power production[8]. On the marginally produced MWh the full cost of CO_2 will have effect, since the producer will be obliged to buy quotas at this amount. On average the impact on the power market prices will depend on the amount of free quotas the producer has been allocated.

While the CO_2 emission pricing is a driver for offshore wind, there are also some indirect costs of offshore wind that are not all priced according to the market, viz costs of balancing, infrastructure etc. If wind power is sold on market terms the costs of balancing will be priced accordingly. These costs arise when

[7] At a 5% discount rate

[8] Both at 45% power efficiency

other power producers are balancing the actual power production, which is usually different from the predicted power production due to the fluctuating and unpredictable properties of wind. These indirect costs that constitute a barrier in the development of offshore wind energy will depend on the specific energy system.

3.1.3 Public opinion

When an offshore wind farm is planned for an area, the local population normally protests against the placement and the design of the wind farm. Often people think that wind farms are a good idea, as long as they are not situated near them – the so-called NIMBY-effect. However, when the final decision regarding the location of the wind farm has been made, the population often accepts this decision and focuses on the positive elements of the situation instead.

A Danish survey of public attitude towards offshore wind farms one or two after their construction shows that most protests are against wind farms situated close to the shore, and thus visible from the shore. At the same time, the survey also shows that people in areas with offshore wind farms nearby in fact are more positive towards wind farms, than people in a randomly selected group of the Danish population. However, this is the people's opinion after the establishment of wind farms, when the local population has learned to live with the wind farm or has experienced that the impacts are not as considerable as they feared.

3.1.4 Environmental issues

Climate changes are key parameters driving the expansion of renewable energy. In Europe the best developed form of alternative energy is wind energy, and significant growth is predicted in the years to come.

Wind energy is a very clean type of energy, as it produces no emissions which – from an environmental point of view – make it a good alternative to conventional electricity production based on fossil fuels, such as coal, oil and gas. Wind power contributes to ensuring a reliable energy supply, reduces dependence on fuel imports and disconnects economic growth from resources. Nevertheless, wind farms exert some impact on their surrounding environment in the form of visual impressions, noise and appearance. Therefore, it is important to ensure that the development of offshore wind energy takes these aspects into consideration to avoid affecting the biodiversity and surroundings significantly.

When looking at the potential for offshore wind farms in Europe, it is crucial to consider the conservation areas, such as the NATURA 2000[9] sites designated according to the Habitat and Birds Directives.[10]

Earlier environmental studies of offshore wind farms have made the general observation that the impacts are very limited and that the wind farms pose only a very limited risk to the natural wildlife in the areas affected. However, in future the development of more wind farms could result in cumulative effects that have to be taken into consideration, eg the cumulative impact on migrating birds when they have to pass maybe five or ten wind farms on their migration routes.

Offshore wind farms can be placed in a natural habitat in the sea where they could have an effect on the local environment. The environmental impacts on habitats and wildlife can be a barrier in connection with the dissemination of offshore wind energy in specific areas and to a certain extent also to the height of the turbines, because of the birds. Apart from this, the environmental issues are not expected to become a

9 The EU has set up an objective to stop the deterioration of the biodiversity at the latest by 2010. The objective of the NATURA2000 programme is to promote the conservation of natural habitats and the habitats of wild fauna and flora while taking into account the economic, social and cultural requirements and specific regional and local characteristics of each Member State.

10 Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora and Council Directive 79/409/EEC on the conservation of wild birds.

barrier in the technical development of the wind turbines; on the contrary, the environment is one of the main drivers for the dissemination of wind energy.

The offshore wind farms potentially impact on the following:

- Birds
- Marine mammals
- Benthic fauna
- Fish

Birds
In relation to birds the focus of the potential impacts is the presence of the wind farm and not the design.

The presence of offshore wind farms can be a potential disturbance to birds in three different ways. 1) The wind farm can pose a collision risk to the birds. Since the birds are not used to the great structures there is a risk that they may collide with the wind turbines. 2) The wind farm can become a barrier for migrating or feeding birds. Birds might choose other migrating routes or feeding patterns since they might perceive the wind farm as an obstacle. The displacement of feeding birds could affect the bird population. 3) The wind farm could cause a physical loss of habitat since the turbines may occupy an area with food resources. On the other hand, the wind farms can create new food resources when the foundations are introduced in a sandy seabed.

Birds could become a barrier to the height of the turbines since high turbines could pose a higher risk to the collision of birds with the turbines.

Marine mammals
An offshore wind farm may impact on marine mammals because of the physical presence of the wind turbines and the construction activity, but also because of the underwater noise during the operation of the wind farm.

The physical presence of the wind farm can scare marine mammals away from the area which leads to loss of habitat for the animals. During operation the wind farm generates underwater noise that may affect the marine mammals. During the construction of an offshore wind farm the noise level is high and there is a lot of activity in the area that can scare the marine mammals away from the area. Pile driving activities generate very high noises which can be harmful to the animals, which is why it is important to make sure that the animals are a certain distance away from the pile driving by the use of scaring devises.

Benthic fauna
When establishing an offshore wind farm a new hard bottom structure in the form of foundation and scour protection is introduced to the seabed, and in an area with a sandy seabed it can cause a great change in the benthic fauna and an increase in the biomass. In that way the wind farm may function as an artificial reef and act as a sanctuary for threatened species.

Fish
The impacts of noise and vibrations from an offshore wind farm on the fish population are believed to be minor, while the introduction of a new hard bottom substrate and the electromagnetic fields induced by the electrical cables are believed to have an impact.

The introduction of an artificial reef might cause an increase in biomass, which means improved food resources for the fish. Furthermore, the foundations and scour protection can function as a sanctuary for the fish. The electromagnetic field around the electrical cables could be a barrier to the fish, because it would prevent them from crossing the cable.

The results from four years of environmental monitoring during the construction and operation of two of the offshore wind farms in Denmark, Nysted and Horns Rev, are summarised in the table below.

Table 3.2: Main results of the environmental monitoring programme of the Horns Rev and Nysted offshore wind farms [27]

	Horns Rev Offshore Wind Farm	**Nysted Offshore Wind Farm**
Fauna and vegetation	● The artificial reef effects from the wind turbine foundations and scour protections are changing the benthic communities to hard bottom communities with increased abundance of species and biomass.	● Monocultures of common mussels have developed at the turbine structures, due to low salinity and a lack of predators.
Fish	● Introduction of new artificial habitats with positive effects on fish communities after full development of artificial reef communities. ● No linkage between the strength of the electromagnetic field and the migration of selected fish species.	
Marine mammals	● Seals were only affected by pile driving operations. No general change in the behaviour of seals at sea or on land could be linked to the construction or operation of the wind farm.	
	● The harbour porpoise population decreased slightly during construction, but increased again during operation.	● The harbour porpoise population decreased significantly during construction and only slight recovery was observed after two years of operation.
Birds	● Birds generally show avoidance responses to the wind farm. Some species are displaced from former feeding areas. ● The collision risk with the turbines is low. ● The effects on overall bird populations are negligible.	
Attitudes	● More than 80% of the respondents from the local areas were “positive” or “very positive” towards the wind farms. ● The prevailing perception is that the impact on birds and marine life is neutral. ● Almost two thirds of the respondents stated that they found the wind farm effect on the landscape either “neutral” or even “positive”. ● More than 40% stated that they preferred future wind farms to be moved out of sight. ● There’s a significant willingness to pay to have wind farms located at distances where the visual intrusion is fairly small, ie up to 18 km from the shore. At Horns Rev there is no extra willingness to pay to have wind farms moved from 18 to 50 km from the shore.	

3.2 Technological barriers and drivers

Many technological challenges have been met in the development of offshore wind farms although costs have been higher than anticipated. It is expected that the future will bring new technical issues and therefore continued R&D is important (IEA: Offshore Wind Experiences).

3.2.1 Size

Today offshore wind turbines between 2 MW and 3 MW are currently available in many parts of Europe. There are also some larger turbines some of which are commercially available, and others are still in the prototype stage and presently undergoing testing.

In future, wind turbines are expected to become larger, although the logistics of handling such large units on land have already become quite difficult. Therefore these large dimensions mean that manufacturers face physical and logistical challenges, which require technological innovations such as using light and strong materials in order to reduce the overall weight of the turbine. Reduction of weight means cutting material consumption, reducing production and transport costs and allowing easy installation. This can also lead to reduction of the foundation costs.

There is a general understanding between experts and manufacturers that the future sizes of wind turbines are considerably larger than today. A simple extrapolation of the historical pattern would result in wind turbines the size of 64 MW and 250 m long blades in 2025, although it is expected that the speed of the growth will slow down and may reach an average size of turbine of 20 MW in 2025. This is in line with the forecast made by the IEA, where 10 MW is foreseen in 2010-15 and 20 MW in 2020-30. [6] The figures for 2050 are of course even harder to predict.

Another important factor to be considered in connection with such large wind turbines will be complying with the strict grid and production forecast requirements. Therefore, grid expansion and reinforcement measures will need to allow for the future expansion of offshore wind power.

The foundation is another challenge for such huge wind turbines in extremely tough conditions at sea. Foundation design is a key element in offshore projects since it will have a direct impact on the procurement costs as well as on the construction and installation processes. Selection of a foundation design will depend on a range of criteria such as the water depth and soil or seabed conditions. As the development moves further off shore and into water depths of more than 30 metres, the monopile design used most often up to now will need to be replaced by other designs, including tripods and larger gravity structures or jacket structures (see table 2.6).

3.2.2 Materials

As wind turbines grow in capacity, the size of the tower and the blades grow accordingly. In order to prevent this issue from becoming a barrier to the development of wind turbines, it is necessary for the manufacturers to keep construction weight as low as possible. This means, new materials and new manufacturing methods are required to design and manufacture such extremely large machines.

Today, blade manufacturers have the choice between glass fibres with epoxy, carbon fibres and in some cases a combination of fibres and wood. Carbon fibres have the advantage of providing a very rigid blade structure (high E-module) combined with a relatively low weight compared to glass fibres. Glass fibres on the other hand are competitively priced and therefore the most dominant material used for the manufacturing of blades today. By 2025 it is expected that competition will lower the price of carbon fibre which will make this the predominant material for blade manufacturing.

Another common weight reduction area is the foundation. Concrete foundations are heavy and expensive to build at water depths above 10 metres. Using steel monopiles rather than concrete foundations can be the best solution for the current offshore wind turbines in shallow waters and in the future it could also be the best option for water depths of up to 20-30 metres. But when it comes to water depths of more than 30 metres, the monopile design will need to be replaced by other designs, including tripods and larger gravity structures.

One of the main problems related to using steel foundations offshore is corrosion; however, this can be electrically prevented using what is known as cathode protection, which requires only little maintenance after installation.

3.2.3 Gear

There is no expectation that manufacturers will change to gearless operation, although this would solve the many gearbox problems. A gearless machine is 1.3 times larger than a machine with a gearbox, eg the Repower 5 MW turbine nacelle weighs 337 tonnes and the Enercon gearless machine weighs 440 tonnes. This shows that the nacelle of the gearless Enercon weighs 1.3 times more than the Repower.

3.2.4 Logistics

The logistics of handling such large units on land have already become quite difficult and it will definitely become an even greater challenge as the size of wind turbines grows. Today the size of the turbines for new wind farms is often limited by the size of the roads from the factory or to the erection site.

Since the installation of offshore wind turbines will continue on site, the production of blades, nacelles etc should be sited at new factories along the waterfront in order to limit road transportation of the very large parts.

There is a lack of special vessels for installation of turbines and foundations to comply with the forecasted wind farms in the next five years [28]

3.2.5 Offshore wind power in the energy system

Lack of wind resources is not expected to be a limiting factor in the development of offshore wind power. However, the development of more offshore wind farms means that more wind farms need to be integrated into the grid network.

There is an ongoing debate about the integration of wind power into the grid and the capacity of the existing grid. In the EU wind power constitutes less than 3% of the electricity demand [24], but of course there are large regional and national differences.

Adequate control methods and backup capacity have already been established to deal with the variable supply of wind power at penetration levels up to approx 20% [14]. In Denmark 20% of the electricity consumption is already met by wind power. But eg in Ireland there is a need to reinforce the grid to accommodate all of the more than 2 GW offshore wind power envisaged by the developers. [13]

Experience from Spain, Denmark and Germany that have large amounts of wind power in the system, shows that the question as to whether there is an upper limit for renewable penetration into the existing grids will be an economic and regulatory rather than a technical issue. [24]

4. Road map for development of offshore wind energy

4.1 Introduction to road mapping

The barriers and drivers discussed in chapter 3 constitute the settings for the development of the offshore wind energy technology. Dependent on the relative strength of the barriers and drivers the technological development can reach different levels following a number of pathways, also referred to as a road map.

A number of institutions and authors have produced different road maps for the future production capacity, turbine size, investment, production costs etc. While some of these road maps are projections based on analyses, others should be considered as political or strategic targets and should not be considered as technology road maps as such.

As described by Gunneskov [16] and supported by other experts in the wind energy sector, the development of wind energy technologies is very much dependent on the wind energy market; ie if the developers demand larger and/or more efficient turbines than the technology of today, new materials and concepts will be pushed forward. Since the markets for renewable energy are highly stimulated by energy policy and the related incentives, it is difficult not to consider political targets in the road maps.

4.1.1 Scope of the road map

The overall purpose of the NEEDS project is to describe the costs and externalities of energy technologies in the European energy system. However, technologies are developing on the global scene, eg the cost reductions of offshore wind energy technology are based on learning curves that are not limited by geographic borders. The results of the learning curves for the global offshore wind energy market and technology development will apply to Europe as well.

4.1.2 Projections for wind energy

A number of projections for the installed capacity of wind energy in the future are presented in figure 4.1 and described in the following.

According to World Energy Outlook 2004 [18], the global electricity production from renewable energy will double from 2002 to 2030. Wind production (onshore and offshore) will increase more than ten times to reach 929 TWh, where about 350 TWh will come from offshore sites. Globally the wind production will amount to about 3% – but for Europe it will amount to about 10%. At 929 TWh the wind power production will still only exploit about 20% of the estimated potential of about 5,000 TWh. [18] The 2004 forecast is considerably higher than the 2002 forecast of 685 TWh in 2030. [17]

The World Energy Council (WEC), 2005 has defined a number of scenarios for the future development of wind energy. As an example, the WEC projects a global wind production at about 555 TWh in 2020 in a business as usual scenario and 1,440 TWh in 2020 in an ecologically driven scenario.

Very optimistic is the European Renewable Energy Council (EREC) [25] that in a “Dynamic Current Policies Scenario” and an “Advanced International Policy Scenario” projects a global production of about 1,900 TWh and 3,100 TWh in 2020, respectively. For 2030, the projections are about 4,600 and 6,300 TWh, ie close to the total potential for wind production estimated by the IEA, 2004.

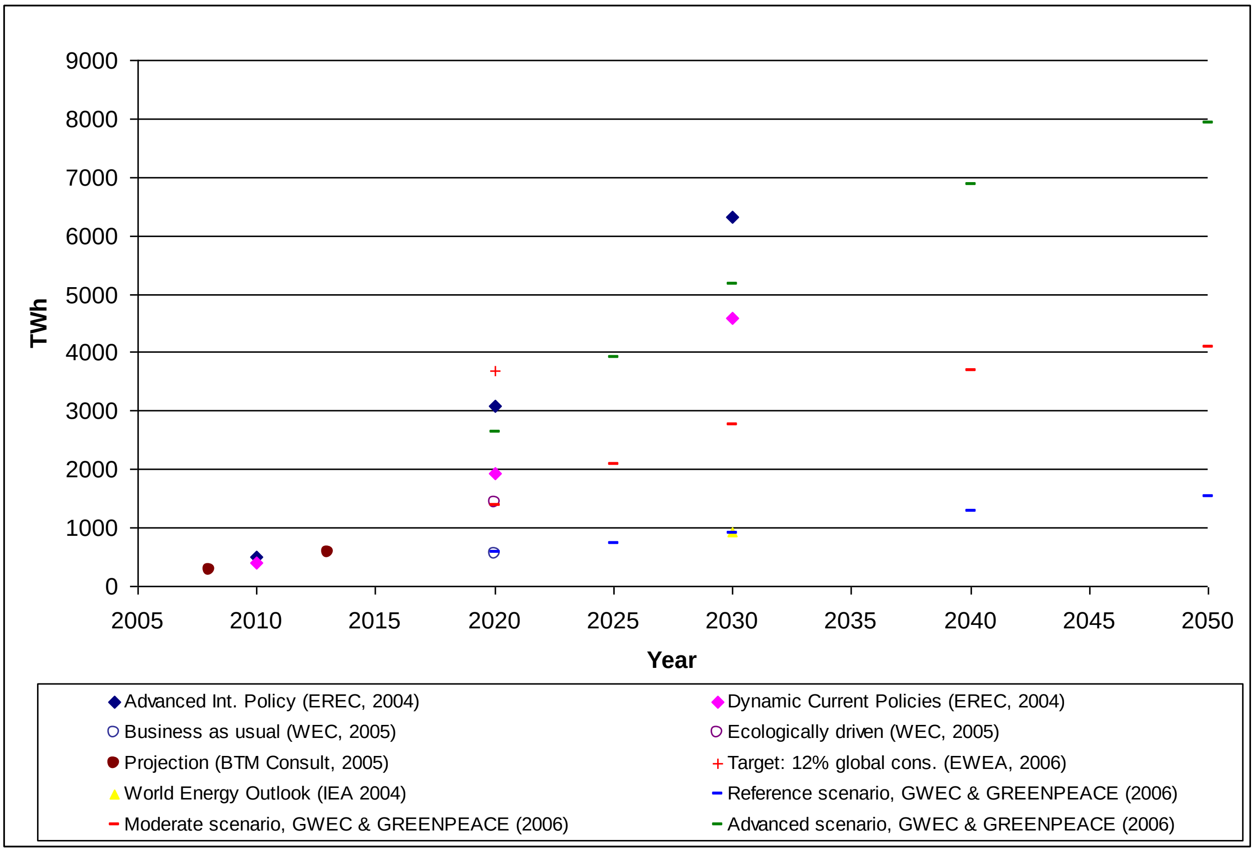
The European Wind Energy Association (EWEA), 2005 sets at target – not an estimate – for wind energy at 12% of global power consumption, which equals about 1,200 GW installed capacity or 3,700 TWh production in 2020 with an average load of 3,000 hours.

The Global Wind Energy Council (GWEC) and Greenpeace [14] have made the most recent – and long term – projection of the global wind energy development divided into three scenarios, ie reference, moderate and advanced. The *reference scenario* is based on the “business as usual” projection in World Energy Outlook 2005, IEA. The *moderate scenario* includes all policy measures that are planned or in the pipeline. All targets are met in this scenario and the goals achieved in Europe will be repeated globally. The *advanced scenario* is based on the ambitious targets described in Wind Force 10 and 12 representing the desired share of wind energy in 2020.

In the NEEDS project, three scenarios for the future development of the technologies should be presented. It is assessed that it is beyond the scope of the technical working groups in RS1a[11] to define scenarios that are consistent with the same model and coordinated between the working groups. Each working group will therefore select their own models and define three scenarios that are consistent with the following headlines:

- Very optimistic development
- Optimistic-realistic development
- Pessimistic development

Since the GWEC and Greenpeace scenarios are based on the IEA for the most pessimistic scenario and the EWEA for the most optimistic targets they are considered to be a sound choice and therefore the three scenarios will be renamed in the NEEDS-terminology: pessimistic (equal to reference scenario), optimistic-realistic (equal to moderate scenario) and very optimistic (equal to advanced scenario).



Comment: 2025-projections in GWEC & GREENPEACE (2006) are interpolated from 2020- and 2030-projections.
Sources: EREC: European Renewable Energy Council, IEA: International Energy Agency, WEC: World Energy Council, EWEA: European Wind Energy Association

Figure 4.1: Projections for global wind power production

[11] RS = Research Stream

The projections in the GWEC and Greenpeace report, 2006 for the global wind power capacity and production in the three scenarios are summarised in table 4.2. As a reference in 2005 the global installed capacity was 60 GW with less than 1 GW offshore.

Table 4.2: Scenario results for 2025 and 2050 by the GWEC and Greenpeace,2006

	Wind power capacity GW			**Production TWh**			**Share of the world's electricity supply %**		
Scenarios	**2005**	**2025***	**2050**	**2005**	**2025***	**2050**	**2005**	**2030**	**2050**
Pessimistic	59	300	577	124	730	1,517	0.8	3.5	4.0
Optimistic-realistic	59	850	1557	124	2,070	4,092	0.8	10.8	10.8
Very optimis-tic	59	1600	3010	124	3,900	7,911	0.8	20.1	20.9

Comment: * 2025-figures are extrapolated from 2020 and 2030-figures in the GWEC and Greenpeace report.

The figures show that the total wind capacity and production are expected to grow considerably in all scenarios ranging from a ten-fold increase in the period 2005-2025 in the pessimistic scenario to a 50-fold increase in the very optimistic scenario.

The specific share of offshore wind power is not specified in the GWEC and Greenpeace report, however, it is assumed in the report that the capacity factor is expected to grow from an average capacity factor of about 24% (2,100 hours/year) today to 28% in 2012 and 30% (2,600 hours/year) in 2036. This is due to the general improvements in wind technology and the increasing share of offshore wind power. Today wind farms have a capacity factor of about 45% (4,000 hours).

Assuming the share of offshore wind farms – of the total wind power capacity – increases from approx 1% today to 10% in 2025 and 20% in 2050, the installed capacity offshore in the pessimistic scenario will be 30 GW in 2025 and 120 GW in 2050.

Table 4.3: Share of offshore wind energy from 2005 to 2050

	Global offshore wind power, % of total installed wind capacity			**Global offshore wind power GW**		
Scenarios	**2005**	**2025***	**2050**	**2005**	**2025***	**2050**
Pessimistic	1.2	10	20	0.7	30	115
Optimistic-realistic	1.2	10	20	0.7	85	310
Very optimis-tic	1.2	10	20	0.7	160	600

The three scenarios in the GWEC and Greenpeace report, which are used as basis for the NEEDS scenarios, do not specify the specific shares of offshore and onshore wind energy but only the development of wind energy as a whole. The same share of offshore wind energy is therefore assumed in the three scenarios.

There are several factors that determine whether the increase in wind energy production will be offshore or onshore in different regions, eg the location of the unexploited sites and the shape of the support regimes.

Worldwide there is still a large potential for wind power both onshore and offshore, whereas in Europe the unexploited wind farm sites are primarily offshore. Therefore, it is likely that the share of offshore wind energy in Europe will be larger than the 10% as a global average. Nevertheless, it will be the global development of wind energy that will influence the development in costs and technology.

4.2 Road map for offshore wind energy

4.2.1 Key barriers and drivers – implications for the road map

Table 4.4: Key drivers and barriers and their influence on wind energy technology

Drivers/barriers	Wind energy technology	Comments
Increasing demand for energy	↑	As the costs of offshore wind energy are still higher than conventional technologies the demand for wind energy continues to depend on political support.
Dependence on highly priced imported fuel	↑	Fossil fuels are limited and prices are exposed to geopolitical instability whereas wind energy is a free and ample resource.
Availability of the wind	↑	There are plenty of uncovered offshore wind energy resources.
Safeguarding security of energy supplies	↑	Wind energy is endogenous to most countries. The challenge is to fit wind into the system.
Global climate changes	↑	The threat of climate changes is no longer an "if" but a "when" factor. Wind power is carbon neutral.
Dimensions of wind turbine	↘	Weight reduction is crucial for the future of the industry, especially the top weight.
Costs	↓	Need to reach full cost competitiveness with other power sources.
Logistics	↘	Limitation of infrastructure and lifting capacities
Operation & Maintenance (O&M)	↘	O&M of offshore turbines is difficult. Boat and helicopter are the only means of reaching offshore turbines and they depend on wave height as well as wind speed.
Foundation	↘	Reducing the top weight will help avoid severe dynamic problems for the foundation and the support structure.
Light and strong materials for blades	↓	It is crucial to reduce the weight and at the same time maintain stiffness and dampening properties. Glass/epoxy is reaching its limits and carbon fibre is too expensive. Therefore, a solution is needed.
Grid connection	↘	Current grid system lacks flexibility, accessibility and reliability for connecting wind energy. These problems will be solved by 2025 and beyond.
Integration in existing energy systems	↘	The relatively unpredictable and fluctuating character of wind energy demands more flexibility of the existing energy system. However, experience

Drivers/barriers	Wind energy technology	Comments
		shows that it is possible to integrate more than 20% wind energy into the power system.

↑ Strong pushing drivers ↓ Strong inhibiting drivers (barriers) ↘ Inhibiting drivers (barriers)

Today the strongest drivers for the development of wind energy seem to be concerns about security of supply and rising costs of fossil fuels, whereas the strongest barriers seem to be the economic risk and the lack of political support in some countries.

4.3 Expected size and technology for future offshore wind turbines

An important element of this road map is the estimation of the future development in wind energy technology. It is very difficult to extract the size of the future wind turbines from the wind energy development described in the three scenarios above. But assuming a certain size of offshore wind farms and estimating the number of future wind farms on the basis of the worldwide sites, a number for the average turbine capacity can be estimated.

Based on the existing offshore wind farms and a view of the expected farms, it is assumed that the number of turbines per wind farm will remain at approx 60 turbines in 2025.

The three scenarios result in a range of installed wind capacities from 30 GW in the pessimistic scenario to 160 GW in the very optimistic scenario in 2025, and even larger numbers for 2050, see table 4.3. The equivalent number of wind farms is globally difficult to predict, however some guidance can be found in the number of installed and planned offshore wind farms in Europe.

As table 2.9, 2.10 and 2.11 show the number of constructed, planned and identified wind farms in Europe is approx 95 at the moment, of which 20 wind farms have already been installed and another 5-10 are under construction. From a pessimistic perspective only these 25-30 offshore wind farms will be installed in Europe by 2025. Apart from the European wind farms, the construction of another 10-15 offshore wind farms could be expected in the rest of the world by 2025. Therefore, it is assumed that Europe is still the main market for offshore wind energy. From a more optimistic-realistic and very optimistic perspective even more wind farms are expected, see table 4.5.

Table 4.5: Predicted technological development of offshore wind turbines in 2025 and 2050 in the three scenarios[12]

		Pessimistic	Optimistic-realistic	Very optimistic
Installed offshore capacity worldwide (GW)	**2025**	30	85	160
	2050	115	310	600
Estimated numbers of offshore wind farms worldwide	**2025**	40	80	120
	2050	80	160	240
Wind farm capacity (GW)	**2025**	0.7	1.1	1.3
	2050	1.4	1.9	2.5
Average size of turbines (MW)	**2025**	8	12	18
	2050	15	24	32

[12] It should be mentioned that more detailed studies on the future size and logistics of wind turbines are available, eg the UpWind project with 40 participants from 11 countries with a budget of approx 23 million euro.

According to calculations based on the assumptions presented in table 4.5, the pessimistic scenario results in future turbines of about 8 MW in 2025 while the very optimistic scenario results in 18 MW. In the conservative scenario no new technologies will be implemented, ie the turbines will resemble today's technology only on a larger scale. The production and capacity figures in the pessimistic scenario are based on the IEA reference scenario, which is a "business as usual" scenario. However, this term does not apply to the size of the wind turbines since a "business as usual" development in size would result in a doubling (MW) every 4 years, as the historical development has shown. Hence the effect should be some 64 MW in 2025. The very optimistic figure in this calculation is about 32 MW in 2050. This very optimistic scenario assumes that new technologies for turbines and logistics and new materials will be used.

As basis for the life cycle inventory (LCI), the size of the turbines in the optimistic-realistic scenario is used. The details for the present and future offshore wind turbines used in the LCI are presented in table 4.6.

Table 4.6: Present and future offshore wind turbines in 2005, 2025 and 2050

	2005	**2025**	**2050**
Size	2 MW	12 MW	24 MW
Hub height	60 m	140 m	160
Rotor diameter	80 m	160 m	250
Water depth	10 – 30 m	20 –60 m	>100 m

Figure 4.7 shows the expected timeframe of the technical development of offshore wind turbines following the optimistic-realistic scenario. The horizontal lines indicate the year for a commercial turbine with the stated technological development.

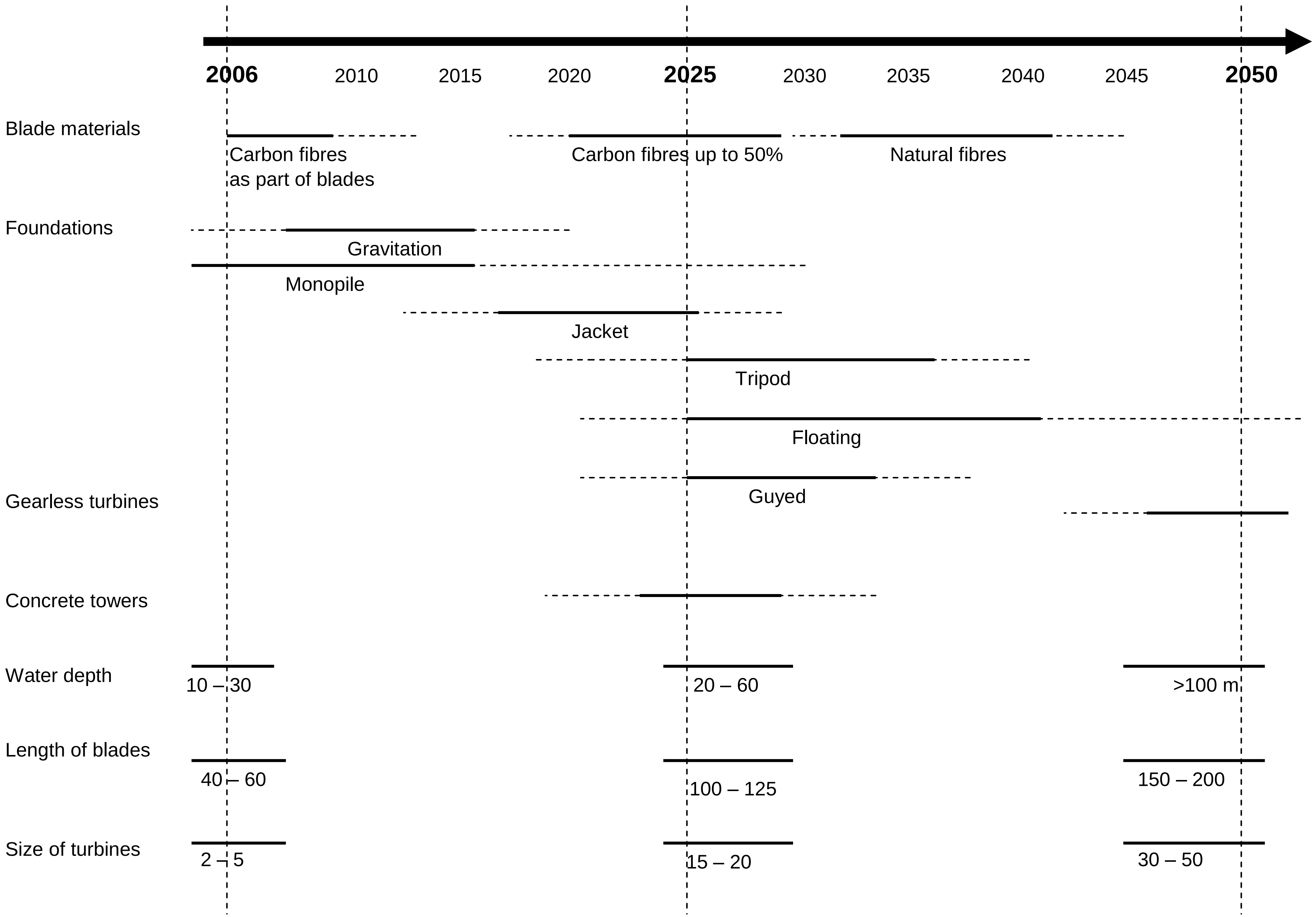


Figure 4.7: Timeframe for the technical development of offshore wind turbines following the moderate scenario

4.4 Expected cost of future offshore wind energy

4.4.1 Historic and actual costs

There are two key figures in the description of wind energy costs: the specific investment costs in euro/MW and O&M costs in euro/MWh.

The specific investment costs of *onshore* wind turbines have decreased since the 1970s due to technology improvements and experience.[13] The first *offshore* wind projects in the early 1990s should be described as demonstration projects rather than commercial wind farms and the costs should not be used as a parameter for the future development (IEA 2005). Since 2000 the specific investment costs of offshore wind have been approx 1.3 to 2 million euro/MW with a weighted average of about 1.6-1.8 million euro/MW (see table 2.9.). The following paragraph discusses the cost projection tool experience curves.

4.4.2 Application of experience curves

The theory of experience curves describes the relation between the experience and learning processes in technologies and cost development. An analysis of the historic development in investment costs shows a tendency that costs decrease by a certain percentage as the installed capacity doubles. The slope on the cost curve is described as a progress ratio (PR). Usually new technologies (at the top of the learning curve) shows a high PR of 70-80% while proven and commercial technologies show a PR of more than 95%. For new technologies the installed capacity usually doubles faster than for proven technologies.

The theory suggests that these experience curves based on observed cost improvements could play a limited role among other methodologies in technology foresight studies. The theory and results in relation to the NEEDS project are described in detail in the report by Lena Neij et al.[15]

In the NEEDS report on future cost analysis, different progress ratios for experience curves were recommended for onshore and offshore wind. A distinction is made between the progress in wind turbines and wind electricity, the latter based on levelised cost estimates for wind power production. On that basis there is an expectation that the future cost development for onshore wind will show a progress ratio of approx 90-96%, ie for every doubling of installed capacity, the costs will be reduced by 4-10%. For offshore wind power a progress ratio of 90% is recommended for *wind turbines*, while a progress ratio of 80% is recommended for *wind electricity* [8].

The installed capacity of offshore wind power is still low compared to the capacity of onshore wind power. Therefore the accumulation of capacity, which is the basis for progress and consequently cost reductions, is expected to increase within the next decade. As described earlier, there are still some barriers for the further development of large offshore wind power plants – for example in connection with the foundations, materials and gears, and it is important to overcome these barriers.

In the following figure the empirical data collected (table 2.9) has been processed as an example of an experience curve for a comparison with the NEEDS report on experience curves. It should be stressed that the data quality is questionable as the data has been compiled from different commercial sources and is difficult to verify. In particular it is difficult to see whether the total investments include the same elements of grid, grid connection, etc.

[13] Cost development – an analysis based on experience curves. Draft report 5/17/2006.

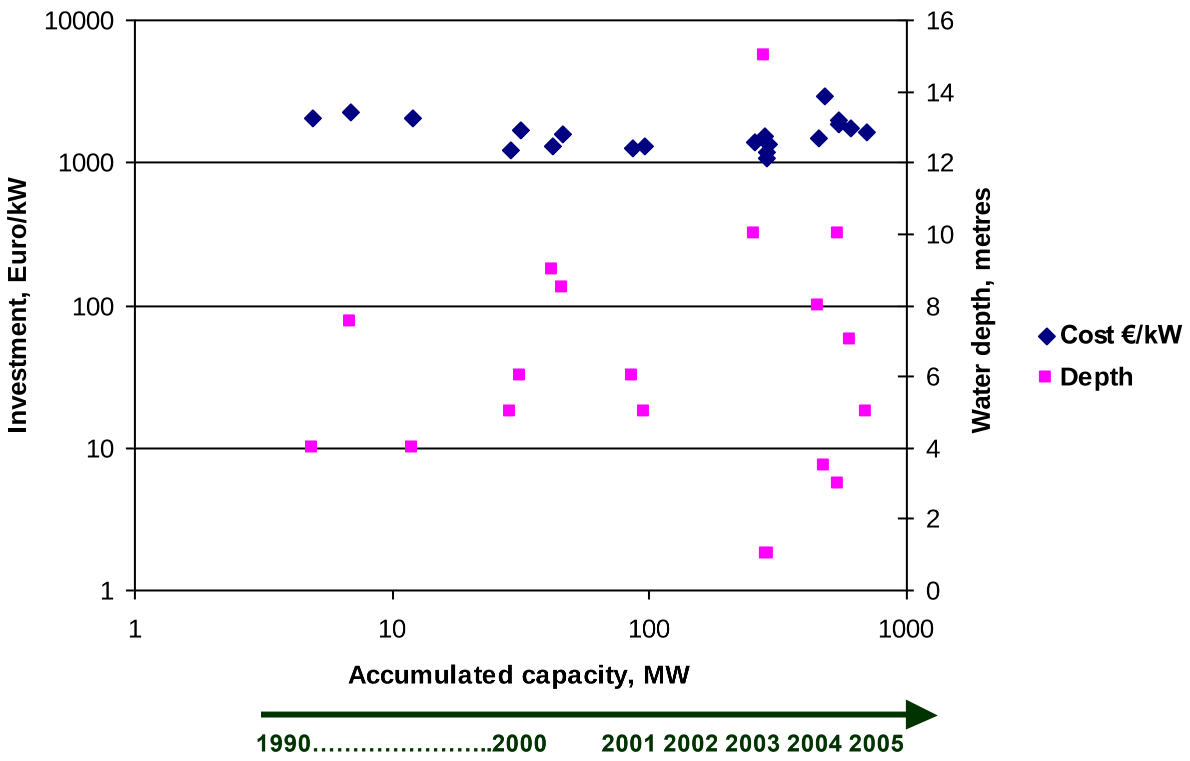


Figure 4.8: Development in specific investment costs and water depth, 1991-2005 (Source: Table 2.9)

In figure 4.8 the specific investment costs are illustrated on the left y-axis in a double logarithmic system of co-ordinates in accordance with the theory of experience curves. On the right y-axis the water depth is depicted to show the increasing depth. The x-axis shows the accumulated installed capacity of offshore wind farms, which has reached about 700 MW by 2005 in this data collection. Each dot represents a specific wind farm and the chronology is shown via the timeline in the bottom.

The figure shows that investment costs have decreased in the period from 1990 to 2001 and after this there is an increasing tendency. Looking only at the 11 years of development from 1990 to 2001 the PR can be calculated to about 88-90%, ie there has been a 10-12% decrease in investment costs for every doubling in capacity until the installed capacity reached about 250 MW. This is in accordance with the theory of experience curves. However, when looking at the whole period from 1990 to 2005 the PR is 98%, ie only a 2% decrease for every doubling.

There are several reasons why the specific costs have a tendency to increase again as discussed earlier:

- Offshore wind farms meet new technical challenges and the new farms are incorporated these costs.
- Distance to shore and increasing water depth are influencing the costs of foundation, grid, etc.
- There is an undersupply of wind turbines, installation vessels, etc for the offshore market, which pushes prices up.

Looking closer at the wind farms where a cost break-down has been published it shows that turbines and foundations together typically account for about 70% of the total investments, while the costs of legal assistance, design and grid account for 30%. As it is expected that the costs of turbines and foundations are subject to a different learning curve than cost reductions related to legal, design and grid, it is suggested that different progress ratios are used for the assessment of the future costs of offshore wind.

For the foundations and turbines a PR of 90% as suggested by Neij and Borup, 2006 will be used. In the long run, ie from 2025 and beyond, a lover PR of 95% seems reasonable, as the technology becomes well-proven and markets more mature. For the remaining 30% of the investment costs, ie legal, design and grid, an even lover PR of 97.5% is suggested. The combination of these PR figures is used in table 4.9 where the future costs of offshore wind are assessed.

4.4.3 Future costs of offshore wind

Applying a progress ratio (PR) of 90% for the period 2005-2025 and a PR of 95% for the period beyond 2025, the future offshore wind farm investments can be calculated (table 4.9). As the table shows the investment costs will decrease with increasing accumulated capacity depending on the scenarios.

Table 4.9: Calculated investment costs in 2025 and 2050

	Unit	**Pessimistic**	**Optimistic realistic**	**Very optimistic**
Capacity 2005	GW	0.70	0.70	0.70
Investment 2005	Mio Euro/MW	1.8	1.8	1.8
Fixed cost of operation	Euro/kW/year	50	50	50
	Progress ratio	0.92	0.92	0.92
Capacity 2025	GW	30	85	160
Investment 2025	Mio Euro/MW	1.2	1.1	1.0
Fixed cost of operation	Euro/kW/year	30	25	23
	Progress ratio	0.96	0.96	0.96
Capacity 2050	GW	115	310	600
Investment 2050	Mio Euro/MW	1.1	1.0	0.9
Fixed cost of operation	Euro/kW/year	24	21	19

Over the first 20 years the total investment costs decrease by 35-45% whereas from 2025 to 2050 the investment costs only decrease slightly (approx another 20%) as it is assumed that the PR approaches 96%. All in all the total investment costs are assessed to be reduced by 40-50% from 2005 to 2050. In the same period the fixed cost of operation decreases even more by up to 50-60%.
The use of experience curves as a tool for projection of the future investment costs is linked with some uncertainties since it is difficult to assume that future costs automatically follow the same path as historical cost reductions. However, even if the three scenarios predict very different installed capacities, the resulting investment costs do not differ considerably.

5. Life Cycle Assessment (LCA) of current and future wind energy

5.1 Description of the technology

The electricity modelling of the current offshore wind technology includes the turbines, the internal cables, transformer station, marine transmission cable and a cable transmission station. Each of these includes materials, manufacturing, transport, erection, operation and disposal. Figure 5.1 shows the elements included in the LCA model for Horns Rev Offshore Wind Farm. The output of the current offshore wind technology is electricity delivered to the grid and the functional unit is selected for 1 kWh.

The electric power generation from Horns Rev Offshore Wind Farm is stated at 647 GWh/year, ie each of the 80 turbines produces 8,088 MWh/year, corresponding to 4,044 full load hours/year. The electricity produced from the wind farm is transmitted via an offshore transformer station and submarine cables to the land-based transmission grid. However, there is a grid loss (net loss) in the transformer and the cables stated at 10 GWh/year for the total farm, and this net loss is also taken into consideration in the electricity modelling.

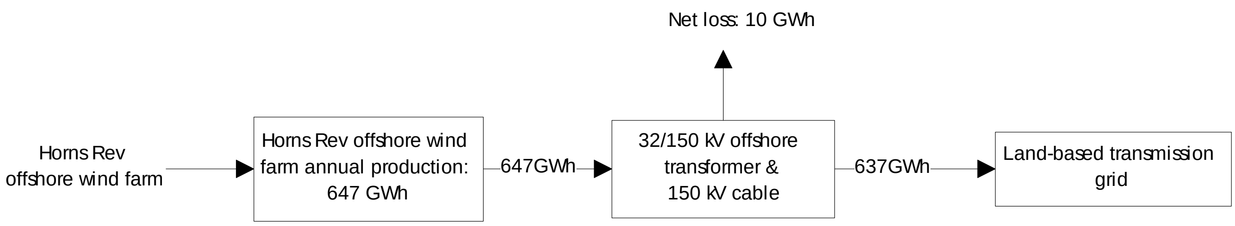


Figure 5.1: LCA system model for offshore wind farm

According to the requirements of Research Stream (RS) 2a, the LCA structure of each technology should consider the fuel supply, operation, production and disposal. But in the case of offshore wind energy technology, the fuel supply is not relevant, thus the other 3 phases, ie production, operation and disposal are considered.

Production: Production includes manufacturing of the foundation, tower, nacelle and blades as well as manufacturing of the transmission grid. Transportation of the components to the site is also included.

Operation: Change of oil, lubrication and transport to and from the turbines are included in the operation stage. Furthermore, renovation of the turbines is also included. The onshore transport is by truck, while at sea vessel and helicopter are used.

Disposal: This includes dismantling and transport to the final disposal site (recycling, incineration or deposit). At recycling, it is limited to the point where the material is ready for reuse.

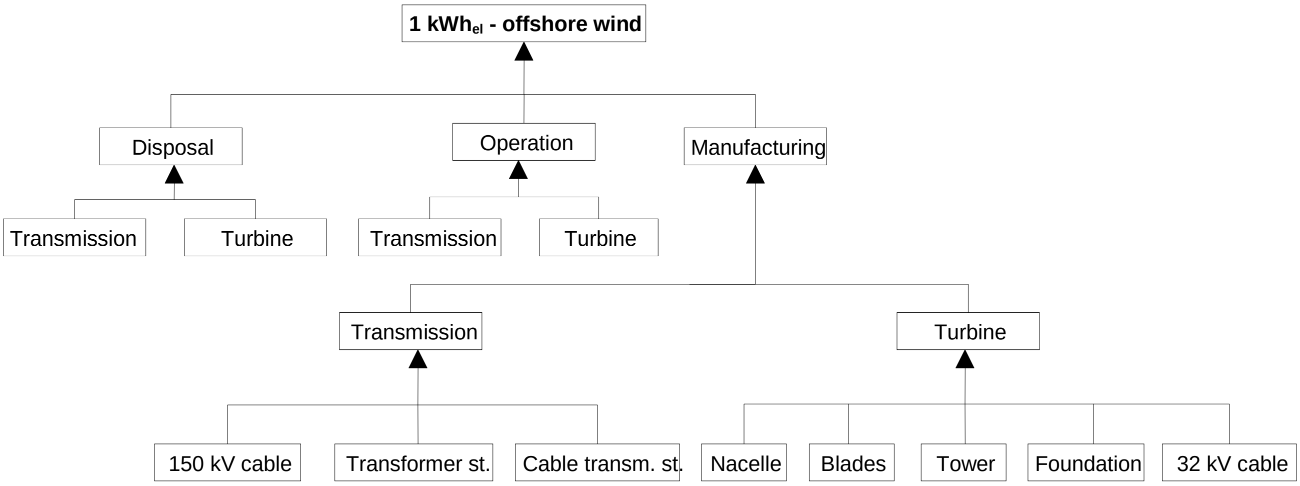


Figure 5.2: LCA model structure for offshore wind energy technology

Figure 5.2 illustrates the structure of the LCA model for the offshore wind energy farm according to the requirements of the RS2a. The technology itself has been described in chapter 2, but the relevant data is shown in table 5.3.

Table 5.3: Overview of the relevant data for the current offshore wind energy technology

Parameter	Unit	2005	
		Turbine	**Farm**
Size	MW_{el}	2	80x2=160
Hub height	m	60	
Rotor diameter	m	80	
Water depth	m	10 – 13	
Foundation type		Monopile	
Electrical efficiency	%	100	
Lifetime for turbines	a	20	
Lifetime for transmission	a	40	
Electricity production	kWh_{el}/a	8.088E+06	6.47E+08
Full load hours	h/a	4044	
Main data sources		Elsam Engineering 2004: Life Cycle Assessment of offshore and onshore sited wind farms (Elsam A/S, Energinet.dk, Vestas A/S and Nexans)	

5.2 Material flow data and sources

5.2.1 Current offshore wind technology

The current offshore wind energy technology model is based on data from Elsam Engineering 2004: "Life Cycle Assessment of offshore and onshore sited wind farms" [1]. In that project, the material flows were based on original data from the manufacturers. But in this case, due to confidentiality concerns for the original data, it has been decided to aggregate data at component level (see annex 1).

5.3 Results

5.3.1 Key emissions and land use

The complete emissions related to the current offshore wind energy technology are shown in annex 3. But the most relevant emissions are shown in table 5.4. They refer to 1 kWh electricity delivered to the grid.

Table 5.4: Key emissions and land use for the reference technology (current technology)

Parameter	Path	Unit	2005
			Current offshore wind farm
			KWh_a
Carbon dioxide, fossil	air	kg	7,64E-03
Methane, fossil	air	kg	1,69E-05
Nitrogen oxides	air	kg	2,17E-05
NMVOC	air	kg	4,04E-06
Sulphur dioxide	air	kg	2,26E-05
PM2,5	air	kg	3,58E-06
PM10	air	kg	1,05E-05
Occupation, agricultural and forestry area	resource	m^2a	2,16E-04
Occupation, built up area incl. mineral extraction and dump sites	resource	m^2a	1,40E-04

5.3.2 Contribution analysis for the main life cycle phases

The assessment showed that the environmental impact of the current offshore wind farm is concentrated mainly in the manufacturing stage and to a more modest extent in the disposal stage, but at a minimum in the operational phase (table 5.5). The use of normal and high-strength steel in the production stage is the main contributor to the high environmental impact concentration in the manufacturing and disposal stages.

Table 5.5: Key emissions and land use of the main life cycle phases for the current offshore wind technology

Parameter	Path	Unit	Current offshore wind farm			
			Total	**Manufacturing**	**Operation**	**Disposal**
Carbon dioxide, fossil	air	kg	7,64E-03	6,19E-03	2,77E-04	1,18E-03
Methane, fossil	air	kg	1,69E-05	1,59E-05	8,2=E-07	1,80E-07
Nitrogen oxides	air	kg	2,17E-05	1,93E-05	4,5E-07	1,87E-06
NMVOC	air	kg	4,04E-06	3,63E-06	1,16E-07	2,94E-07
Sulphur dioxide	air	kg	2,26E-05	2,15E-05	7,82E-07	3,05E-07
PM2,5	air	kg	3,58E-06	3,42E-06	6,75E-08	9,28E-08
PM10	air	kg	1,05E-05	1,03E-05	1,48E-07	1,30E-07
Occupation, agricultural and forestry area	re-source	m^2a	2,16E-04	2,07E-04	7,23E-06	105E-06
Occupation, built up area incl. mineral extraction and dump sites	re-source	m^2a	1,40E-04	1,32E-04	2,29E-06	5,59E-06

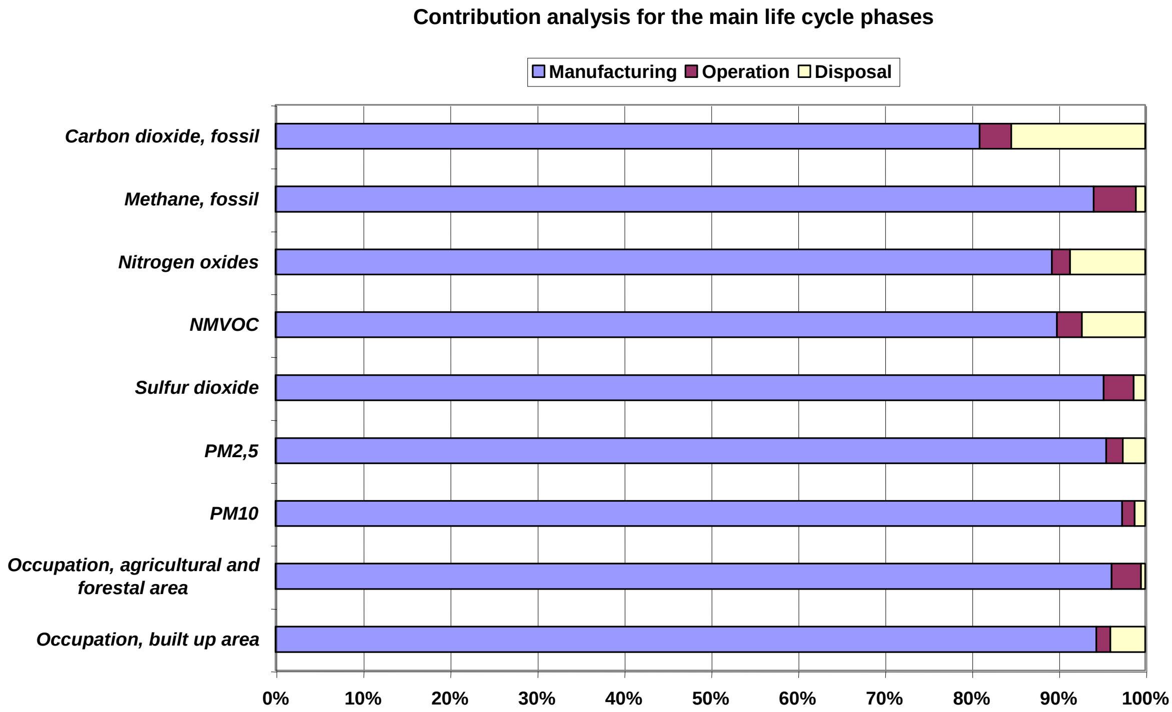


Figure 5.3: Contribution analysis of the key emissions for the main life cycle phases

6. LCA of future offshore wind technology

The future technology for offshore wind energy is expected to be based on the same type of wind turbine as we know today, ie 3-blade upwind pitch-regulated turbines with horizontal axis. The wind turbine will develop in size and effect and new materials will be implemented in the turbines, specially in the blades.

6.1 Description of the technology

The electricity modelling of the future offshore wind technology includes the turbines, the internal cables, transformer station, marine transmission cable and a cable transmission station. Each of these includes materials, manufacturing, transport, erection, operation and disposal. The output of the future offshore wind technology is electricity delivered to the grid and the functional unit is selected for 1 kWh.

For the future technology the partners in the NEEDS project decided that each technology should be presented in three scenarios for 2025 and 2050, viz:

- Very optimistic development
- Optimistic-realistic development
- Pessimistic development

The power generation form these future scenarios selected for the offshore wind technology is shown in table 6.1.

The electricity produced from these future wind farms is transmitted via an offshore transformer station and submarine cables to the land-based transmission grid. However, there are grid losses (net losses) in the transformer and the cables, which are also shown in table 6.1. These net losses are also considered in the electricity modelling.

Table 6.1: Capacities of the selected scenarios of the future wind farms and their net losses

Future technology	***Size of turbine* [MW]**	***Number of turbines***	***Production/a* [GWh]**	***Net loss/a* [GWh]**
2025 – pessimistic	8	94	3158	63
2025 – optimistic realistic	12	89	4486	90
2025 – very optimistic	18	74	5594	112
2050 – pessimistic	15	96	6048	121
2050 – optimistic realistic	24	81	8165	163
2050 – very optimistic	32	78	10483	210

According to the requirements of RS2a the LCA structure of each technology should consider fuel supply, operation, production and disposal. But in the case of offshore wind energy technology the fuel supply is not relevant, thus the other three phases, viz production, operation and disposal, are considered.

The technology itself has been described in chapter 4 but the relevant data are shown in table 6.2.

Table 6.2: Overview of the relevant data for future offshore wind energy technologies

		Unit	Ref. tech.	2025			2050		
Production									
	Size	MW	2	8	12	18	15	24	32
	Full load hours	h/a	4044	4200	4200	4200	4200	4200	4200
Nacelle									
	Weight	t	64	161	246	491	491	608	764
	Material								
	Steel	%	64.4	64.4	64.4	64.4	64.4	64.4	
	Cast iron	**%**	26.9	26.9	26.9	26.9	26.9	26.9	
Rotor									
	Diameter	m	80	130	160	225	225	250	280
	Weight	t	38	106	130	258	258	319	400
	Material								
	Glass fiber/epoxy	%	70.5	70.5	70.5	50	50	0	0
	Carbon fiber	%				50	50	75	25
	Natural fibre							25	75
Tower									
	Height	m	60	110	130	140	140	150	160
	Weight	t	140	340	511	8100	8100	8679	1552
	Material								
	Steel	%		100	100	10	10	100	100
	Concrete	%	0	0	0	90	90	0	0
Foundation				Monopil	Monopil	Gravitation	Gravitation	Guyed	Floating
	Water depth	m	13						
	Weight	t	203	400	600	8000	8000	1000	1500
	Material								
	Steel	%	99	99	99	3	3	100	100
	Concrete	%	0	0		57	57		
	Stone ballast	%	0	0		40	40		

6.2 Material flow data and sources

6.2.1 Future offshore wind technologies

The future offshore wind energy technology models are based on data from the reference technology, which was described in chapter 5. The data for the different scenarios of the future technology has been obtained by up-scaling the data of the reference technology. Like the reference technology, it was also decided to aggregate data for the future technology at component level. The capacities of the selected scenarios of the future wind farms and their grid losses (net losses) are shown in table 6.1.

6.3 Results[14]

6.3.1 Key emissions and land use

The complete emissions related to the future offshore wind energy technology are shown in Annex 4; however, the most relevant emissions are shown in table 6.3. They refer to1 kWh electricity delivered to the grid.

Table 6.3: Key emissions and land use for future offshore wind technologies

Parameter	***Path***	***Unit***	***2025 pessimistic***	***2025 optimistic realistic***	***2025 very optimistic***	***2050 pessimistic***	***2050 optimistic realistic***	***2050 very optimistic***
Carbon dioxide, fossil	air	kg	2,69E-03	2,89E-03	5,60E-03	6,75E-03	3,41E-03	3,73E-03
Methane, fossil	air	kg	7,91E-06	8,69E-06	1,36E-05	1,62E-05	9,61E-06	1,05E-05
Nitrogen oxides	air	kg	9,47E-06	1,03E-05	1,97E-05	2,41E-05	1,35E-05	1,50E-05
NMVOC	air	kg	2,36E-06	2,50E-06	4,41E-06	5,39E-06	3,28E-06	3,68E-06
Sulphur dioxide	air	kg	1,24E-05	1,31E-05	2,21E-05	2,74E-05	2,27E-05	2,84E-05
PM2,5	air	kg	1,90E-06	1,99E-06	2,93E-06	3,61E-06	3,06E-06	3,56E-06
PM10	air	kg	5,57E-06	5,83E-06	7,24E-06	8,87E-06	7,85E-06	8,99E-06
Occupation, agricultural and forestry area	resource	m2a	1,06E-04	1,05E-04	2,60E-04	3,14E-04	1,50E-04	1,61E-04
Occupation, built up area incl. mineral extraction and dump sites	resource	m2a	6,07E-05	6,07E-05	1,41E-04	1,74E-04	1,15E-04	1,46E-04

6.3.2 Contribution analysis for the main life cycle phases of future technologies

The assessment showed that the environmental impact of future offshore wind technologies is concentrated mainly in the manufacturing and to a smaller extent in the disposal stage but at a minimum in the operational phase. Comparing the emissions and land use for the different scenarios selected for the project, viz pessimistic, optimistic realistic and very optimistic, the assessment showed that the highest impact comes from the 2025 very optimistic and 2050 pessimistic scenarios (figure 6.1). The use of rein-

[14] The discussion of the result is based on a previous calculation of the NEEDS results, please consult the final data v1.1 on the website of the NEEDS-project.

forced concrete for manufacturing the tower and the foundation is the main contributor to the high environmental impact concentration in these two scenarios.

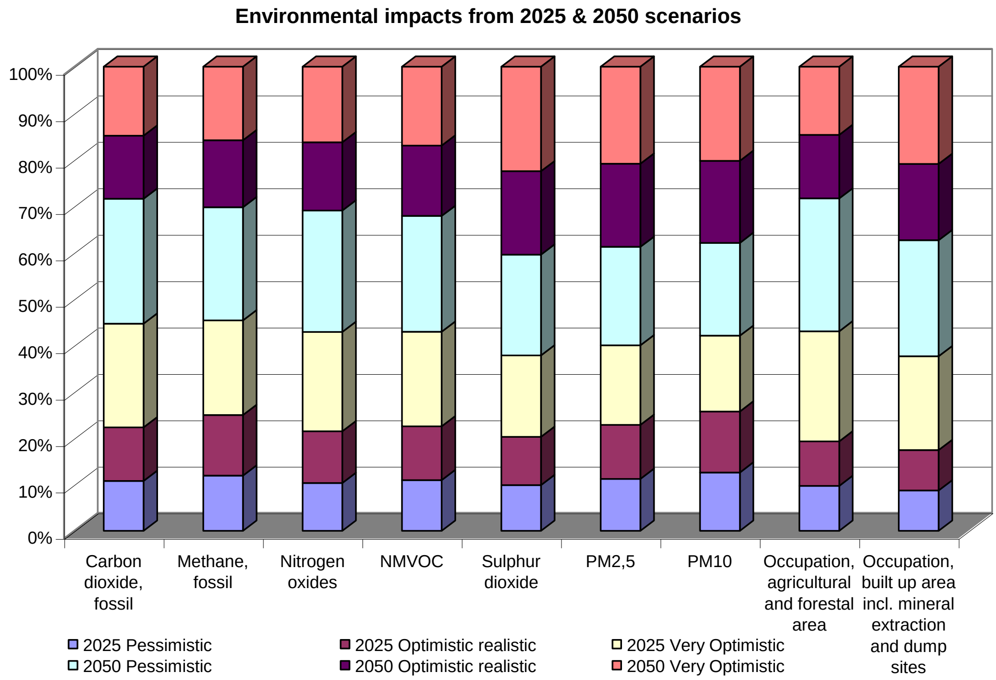


Figure 6.1: Key emissions and land use for 2025 and 2050 scenarios

7. Conclusion

Wind power is a fast growing technology with a large unexploited potential both in Europe and globally. In Europe the main "extension" of wind power will be offshore since the onshore sites – especially in western Europe – are almost fully exploited.

During the past 20 years, the wind power technology has experienced a relatively fast development process with doubling of the capacity of each individual turbine every four years; from 1985 when the turbines had a capacity of 500 kW with a rotor diameter of 15 metres up to today when the capacity of the turbines is up to 5 MW with a rotor diameter of 126 metres.

The installed capacity of wind power in Europe has increased from 1.7 GW in 1994 to 40.5 GW in 2005. In 2005, the global wind power capacity was 59 GW, 0.7 GW of which was offshore wind power.

For the future development of the installed offshore wind power capacity the following three scenarios are described:

Global offshore wind power capacity (GW)			
Year	**2005**	**2025**	**2050**
Pessimistic	0.7	30	115
Optimistic-realistic	0.7	85	310
Very optimistic	0.7	160	600

Today, the strongest driver for the development seems to be security of supply and the rising cost of fossil fuels, whereas the main barriers seem to be the financial risks and the lack of political support.

Based on today's trend of average wind farm sizes of approx 60 turbines and the number of existing and identified wind farm sites; an average turbine size has been estimated in the three scenarios.

Future offshore wind turbines		
Year	2025	2050
	MW	
Pessimistic	8	15
Optimistic-realistic	12	24
Very optimistic	18	32

In order to achieve this technological development it is essential to overcome some of the barriers mentioned in chapter 3.2, such as limitations in the materials used for manufacturing wind turbines today.

Based on experience curves the future investment costs are projected to be 1.0–1.2 million euro/MW in 2025 and 0.9–1.1 million euro/MW in 2050 for the three scenarios. Compared to the investment costs today, this is approx a 40–50% reduction.

A Life Cycle Assessment of the present and future offshore wind power technology shows that the environmental impact mostly originates from the materials used in the turbine. The study also demonstrates that the environmental impact from the offshore wind will improve until 2050 compared to that of 2005. For example CO_2 emissions will improve between 12% and 65%. Although in some cases, such as the 2025-very optimistic and 2050-pessimistic scenarios (figure 8.1), there is an emission increase due to a design change, ie the use of reinforced concrete for manufacturing the tower and the foundation is the main contributor to the high environmental impact concentration in these two scenarios.

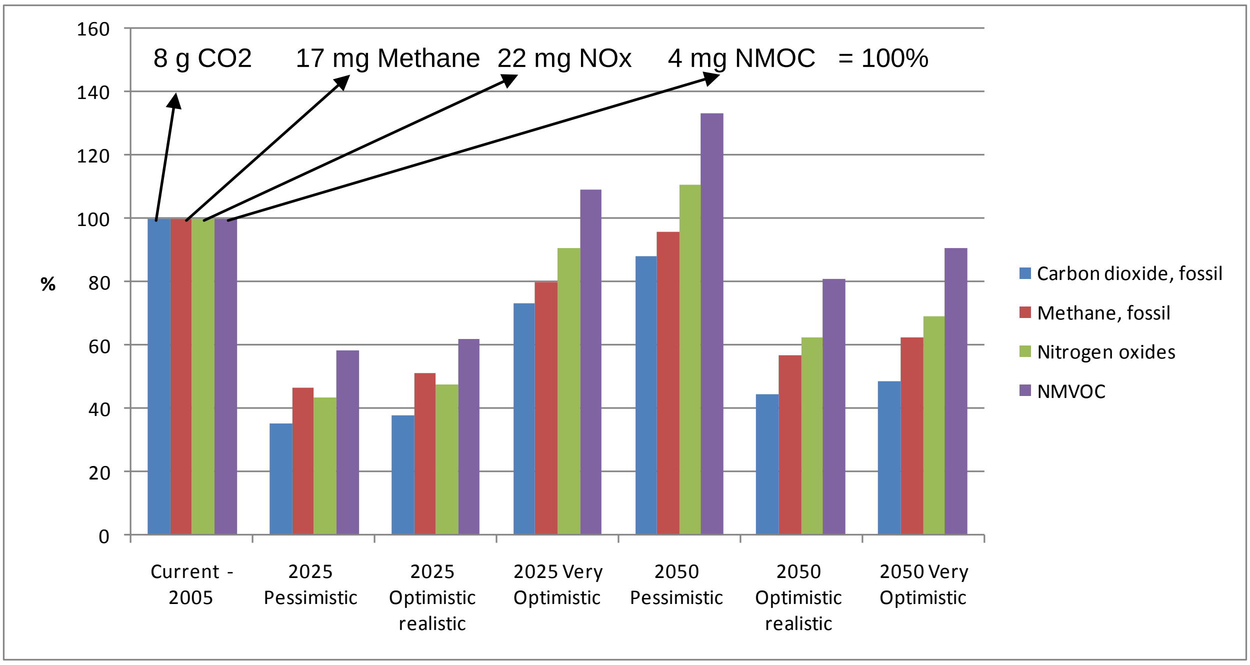


Figure 8.1: Some of the key emissions for the current, 2025 and 2050 scenarios

As can be seen this LCA study revealed that the material used in the manufacture of the various wind turbine components is very crucial for the overall environmental impact of a wind turbine.

Consequently, during the design phase of an offshore wind farm it is very import to keep in mind what kind of materials will be used during the manufacturing stages and their reuse at the end of the wind farm life cycle. This means that new materials and manufacturing methods are required to design and manufacture such extremely large machines.

8. References

[1] Elsam Engineering (now DONG Energy): "*Life Cycle Assessment of offshore and onshore sited wind farms*", 2004

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Annex 1

Material and energy flows required for the production of the current offshore wind energy farm and its grid connection system

Component	Material or service	Unit	Amount
Tower			**1**
	steel, electricity, un- and low-alloyed, at plant	kg	1.50E+5
	aluminium, production mix, at plant	kg	2.00E+0
	copper, at regional storage	kg	1.12E+2
	welding, arc, steel	m	2.30E+1
	powder coating, steel	m2	1.15E+3
	polyvinylchloride, at regional storage	kg	3.80E+1
	alkyd resin, long oil, 70% in white spirit, at plant	kg	1.18E+3
	steel, low-alloyed, at plant	kg	4.00E+0
	electricity mix	kWh	3.35E+4
	transport, passenger car	pkm	1.60E+2
	transport, lorry 32t	tkm	1.20E+4
	transport, barge	tkm	6.00E+3
	heat, natural gas, at industrial furnace low-NOx >100kW	MJ	1.09E+5
Blades		**Unit**	**1**
	glass fibre, at plant	kg	5.75E+3
	epoxy resin, liquid, at plant	kg	2.09E+3
	polyvinylchloride, at regional storage	kg	2.23E+2
	aluminium, production mix, at plant	kg	4.34E+1
	synthetic rubber, at plant	kg	1.02E+0
	nylon 66, at plant	kg	6.06E-1
	steel, low-alloyed, at plant	kg	7.80E+0
	cast iron, at plant	kg	4.31E+1
	copper, at regional storage	kg	2.20E+0
	transport, lorry 32t	tkm	2.93E+2
	transport, barge	tkm	1.47E+2
	transport, passenger car	pkm	5.33E+1
Nacelle		**Unit**	**1**
	steel, low-alloyed, at plant	kg	13198
	cast iron, at plant	kg	16855
	acrylonitrile-butadiene-styrene copolymer, ABS, at plant	kg	4
	polyvinylchloride, at regional storage	kg	122
	epoxy resin, liquid, at plant	kg	633
	glass fibre, at plant	kg	1872.1
	zinc coating, pieces	m2	0.046
	heat, natural gas, at industrial furnace low-NOx >100kW	MJ	11178
	synthetic rubber, at plant	kg	412
	polyethylene, HDPE, granulate, at plant	kg	948.7
	nylon 66, at plant	kg	2.2
	polycarbonate, at plant	kg	1
	lubricating oil, at plant	kg	617
	polyethylene terephthalate, granulate, amorphous, at plant	kg	24
	electricity mix	kWh	79425
	transport, barge	tkm	2235
	transport, lorry 32t	tkm	25262

Component	Material or service	Unit	Amount
Foundation		**Unit**	**1**
	reinforcing steel, at plant	kg	202900
	aluminium, production mix, at plant	kg	1550
	powder coating, steel	m2	75
	copper, at regional storage	kg	45
	lead, at regional storage	kg	1.661
	alkyd resin, long oil, 70% in white spirit, at plant	kg	333
	heat, natural gas, at industrial furnace low-NOx >100kW	MJ	16748.6
	electricity mix	kWh	33560
	transport, barge	tkm	210000
	tap water, at user	kg	27460
Marine cable, 32 kV		**km**	**1**
	lead, at regional storage	kg	7288.7
	copper, at regional storage	kg	5778.7
	polyethylene, HDPE, granulate, at plant	kg	838.5
	steel, low-alloyed, at plant	kg	5079.3
	transport, barge	tkm	28473
	transport, lorry 32t	tkm	23006.2
Offshore transformer st.		**Unit**	**1**
	reinforcing steel, at plant	kg	819700
	steel, low-alloyed, at plant	kg	8000
	aluminium, production mix, at plant	kg	66300
	concrete, normal, at plant	m3	150000
	reinforcing steel, at plant	kg	360000
	zinc coating, pieces	m2	700
	copper, at regional storage	kg	26315
	cast iron, at plant	kg	68000
	polyethylene, HDPE, granulate, at plant	kg	330
	epoxy resin, liquid, at plant	kg	0.05
	alkyd resin, long oil, 70% in white spirit, at plant	kg	150
	transport, barge	tkm	984000
	sulphur hexafluoride, liquid, at plant	kg	200
	lubricating oil, at plant	kg	43000
	rock wool, at plant	kg	500
Marine cable, 150 kV		**km**	**1**
	copper, at regional storage	kg	18520
	electricity mix	kWh	22150
	polyethylene, HDPE, granulate, at plant	kg	10440
	zinc coating, pieces	m2	546.1
	reinforcing steel, at plant	kg	17810
	lead, at regional storage	kg	19630
	transport, lorry 32t	tkm	3683
Cable station		**Unit**	**1**
	copper, at regional storage	kg	24500
	aluminium, production mix, at plant	kg	600
	zinc coating, pieces	m2	400
	packaging, corrugated board, mixed fibre, single wall, at plant	kg	2500
	ceramic tiles, at regional storage	kg	2500
	sulphur hexafluoride, liquid, at plant	kg	57
	transport, lorry 32t	tkm	207000
	cast iron, at plant	kg	63000
	lubricating oil, at plant	kg	28500

Component	Material or service	Unit	Amount
	transport, barge	tkm	3
	steel, low-alloyed, at plant	kg	18000
Operation		**Unit**	**1**
	transport, helicopter	h	80
	steel, low-alloyed, at plant	kg	3150
	lubricating oil, at plant	kg	617
	transport, lorry 32t	tkm	6233.34
	transport, barge	tkm	1.2
	electricity mix	kWh	41847.3
	electricity mix	kWh	57362.7
	disposal, used mineral oil, 10% water, to hazardous waste incineration	kg	617

Annex 2:

Material and energy flows required for the production of the future offshore wind energy farm

Future offshore wind technology	2025-pessimistic	2025-optimistic realistic	2025-very optimistic	2050-pessimistic	2050-optimistic realistic	2050-very optimistic
Size (MW)	**8**	**12**	**18**	**15**	**24**	**32**
Hub height (m)	110	130	140	140	150	160
Rotor diameter (m)	130	160	225	225	250	280
	kg	**kg**	**kg**	**kg**	**kg**	**kg**
Rotor						
Glass fibre	6.26E+04	7.68E+04	9.45E+04	9.45E+04	0.00E+00	0,00E+00
Carbon fibre	0.00E+00	0.00E+00	4.72E+04	4.72E+04	1.20E+05	1,51E+05
Hempfibre	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.02E+04	7,56E+04
Epoxy resin	2.27E+04	2.79E+04	5.53E+04	5.53E+04	6.84E+04	8,58E+04
Polyvenyl	2.43E+03	2.98E+03	5.91E+03	5.91E+03	7.31E+03	9,17E+03
Aluminium	4.73E+02	5.80E+02	1.15E+03	1.15E+03	1.42E+03	1,79E+03
Rubber	1.11E+01	1.36E+01	2.69E+01	2.69E+01	3.33E+01	4,18E+01
Nylon	6.60E+00	8.09E+00	1.61E+01	1.61E+01	1.99E+01	2,49E+01
Steel	8.50E+01	1.04E+02	2.07E+02	2.07E+02	2.56E+02	3,21E+02
Cast iron	1.76E+04	2.16E+04	4.29E+04	4.29E+04	5.30E+04	6,65E+04
Copper	2.40E+01	2.94E+01	5.83E+01	5.83E+01	7.21E+01	9,04E+01
Total	**1.06E+05**	**1.30E+05**	**2.47E+05**	**2.47E+05**	**3.11E+05**	**3,90E+05**
Tower						
			7.97E+06	7.97E+06		
Steel, electr., un- and low-alloyed	3.34E+05	5.03E+05	7.97E+05	7.97E+05	1.22E+06	1.53E+06
Concrete	0.00E+00	0.00E+00	7.17E+06	7.17E+06	0.00E+00	0,00E+00
Aluminium	4.46E+00	6.70E+00	1.06E+02	1.06E+02	1.62E+01	2,04E+01
Copper	2.50E+02	3.75E+02	5.95E+03	5.95E+03	9.09E+02	1,14E+03
Welding, arc, steel	5.13E+01	7.71E+01	1.22E+03	1.22E+03	1.87E+02	2.34E+02
Powder coating, steel	2.56E+03	3.84E+03	6.09E+04	6.09E+04	9.31E+03	1.17E+04
Polyvenyl	8.47E+01	1.27E+02	2.02E+03	2.02E+03	3.09E+02	3,87E+02
Alkylresin	2.63E+03	3.95E+03	6.27E+04	6.27E+04	9.58E+03	1,20E+04
Steel, low, alkylde	8.92E+00	1.34E+01	2.13E+02	2.13E+02	3.25E+01	4.07E+01
Total	**3.40E+05**	**5.11E+05**	**8.10E+06**	**8.10E+06**	**1.24E+06**	**1,55E+06**
Electricity	7.47E+04	1.12E+05	1.78E+06	1.78E+06	2.72E+05	3,41E+05
Heat	2.42E+05	3.64E+05	5.77E+06	5.77E+06	8.82E+05	1,11E+06
Nacelle						
Reinforced steel	6.99E+04	1.07E+05	2.13E+05	2.13E+05	2.64E+05	3,32E+05
Aluminium	2.24E+03	3.42E+03	6.82E+03	6.82E+03	8.45E+03	1,06E+04
Steel, low-alloyed	3.38E+04	5.17E+04	1.03E+05	1.03E+05	1.28E+05	1.61E+05
Cast iron	4.32E+04	6.60E+04	1.32E+05	1.32E+05	1.63E+05	2,05E+05
ABS	1.03E+01	1.57E+01	3.13E+01	3.13E+01	3.87E+01	4,86E+01
Polyvenyl	3.13E+02	4.78E+02	9.54E+02	9.54E+02	1.18E+03	1,48E+03

Epoxy resin	1.62E+03	2.48E+03	4.95E+03	4.95E+03	6.13E+03	7,70E+03
Glass fibre	4.80E+03	7.33E+03	1.46E+04	1.46E+04	1.81E+04	2,28E+04
Zinc	1.18E-01	1.80E-01	3.60E-01	3.60E-01	4.45E-01	5,59E-01
Synthetic rubber	1.06E+03	1.61E+03	3.22E+03	3.22E+03	3.99E+03	5,01E+03
Polyethonel,HDPE	2.43E+03	3.72E+03	7.42E+03	7.42E+03	9.18E+03	1.15E+04
Nylon 66	5.64E+00	8.62E+00	1.72E+01	1.72E+01	2.13E+01	2,68E+01
Polycarbonate	2.56E+00	3.92E+00	7.82E+00	7.82E+00	9.68E+00	1,22E+01
Polyethylene terephthalate, granulate, amorphous, at plant	3.59E+01	5.48E+01	1.09E+02	1.09E+02	1.36E+02	1.70E+02
Oil for gear box	1.58E+03	2.42E+03	4.82E+03	4.82E+03	5.97E+03	7,50E+03
Total	**1.61E+05**	**2.46E+05**	**4.91E+05**	**4.91E+05**	**6.08E+05**	**7,64E+05**
Heat	2.86E+04	4.38E+04	8.74E+04	8.74E+04	1.08E+05	1,36E+05
Electricity	3.62E+04	5.53E+04	1.10E+05	1.10E+05	1.37E+05	1,72E+05
Foundation						
Steel, electr., un- and low-alloyed	3.96E+05	5.94E+05	2.38E+05	2.38E+05	9.91E+05	1.49E+06
Concrete	0.00E+00	0.00E+00	4.52E+06	4.52E+06	0.00E+00	0,00E+00
Aluminium	3.03E+03	4.54E+03	6.05E+04	6.05E+04	7.57E+03	1,14E+04
Copper	8.79E+01	1.32E+02	1.76E+03	1.76E+03	2.20E+02	3,30E+02
Lead	3.24E+00	4.87E+00	6.49E+01	6.49E+01	8.11E+00	1,22E+01
Alklyn	6.50E+02	9.75E+02	1.30E+04	1.30E+04	1.63E+03	2,44E+03
Total	**4.00E+05**	**6.00E+05**	**4.83E+06**	**4.83E+06**	**1.00E+06**	**1,50E+06**
Heat	3.27E+04	4.91E+04	3.95E+05	3.95E+05	8.18E+04	1,23E+05
Electricity	6.55E+04	9.83E+04	7.91E+05	7.91E+05	1.64E+05	2,46E+05

Annex 3

Minimum air pollutant list of the reference wind energy technology – 2005

Parameter	Path	Unit	Dataset (Current technology)				
			Total kWh	Manufacturing	Operation	Fuel	Disposal
Resources							
Coal, brown, in ground	resource	kg	5.04E-04	4.92E-04	6.51E-06	0	4.81E-06
Coal, hard, unspecified, in ground	resource	kg	1.94E-03	1.84E-03	9.23E-05	0	7.61E-06
Gas, natural, in ground	resource	Nm^3	6.61E-04	6.33E-04	2.24E-05	0	5.62E-06
Oil, crude, in ground	resource	kg	6.00E-04	5.11E-04	3.23E-05	0	5.68E-05
Uranium, in ground	resource	kg	3.00E-08	2.91E-08	5.61E-10	0	3.41E-10
Fresh water (lake, river, ground water)	resource	m^3	7.92E-05	7.68E-05	1.23E-06	0	1.18E-06
Occupation, agricultural and forestry area	resource	m^2a	2.16E-04	2.07E-04	7.23E-06	0	1.05E-06
Occupation, built up area incl. mineral extraction and dump sites	resource	m^2a	1.40E-04	1.32E-04	2.29E-06	0	5.59E-06
Emissions to air							
Ammonia	air	kg	5.31E-07	5.17E-07	7.92E-09	0	6.34E-09
Arsenic	air	kg	1.17E-08	1.17E-08	1.39E-11	0	8.57E-12
Benzene	air	kg	3.91E-08	3.49E-08	1.05E-09	0	3.21E-09
Benzo(a)pyrene	air	kg	1.22E-10	1.20E-10	1.34E-12	0	7.22E-13
Cadmium	air	kg	4.44E-09	4.43E-09	3.81E-12	0	8.11E-12
Carbon dioxide, fossil	air	kg	7.64E-03	6.19E-03	2.77E-04	0	1.18E-03
Carbon monoxide, fossil	air	kg	5.15E-05	5.04E-05	5.84E-07	0	5.29E-07
Carbon-14	air	kBq	5.14E-05	4.98E-05	9.51E-07	0	6.15E-07
Chromium	air	kg	9.88E-09	9.15E-09	6.78E-10	0	4.44E-11
Chromium VI	air	kg	1.69E-10	1.52E-10	1.61E-11	0	8.00E-13
Dinitrogen monoxide	air	kg	1.92E-07	1.73E-07	8.22E-09	0	1.07E-08
Formaldehyde	air	kg	6.51E-09	6.16E-09	2.93E-10	0	5.62E-11
Iodine-129	air	kBq	5.04E-08	4.89E-08	9.68E-10	0	5.63E-10
Lead	air	kg	3.15E-07	3.08E-07	5.22E-09	0	2.38E-09

Parameter	Path	Unit	Dataset (Current technology)				
			Total kWh	Manufacturing	Operation	Fuel	Disposal
Methane, fossil	air	kg	1.69E-05	1.59E-05	8.20E-07	0	1.80E-07
Mercury	air	kg	3.96E-09	3.93E-09	2.11E-11	0	8.39E-12
Nickel	air	kg	2.10E-08	2.08E-08	1.38E-10	0	6.65E-11
Nitrogen oxides	air	kg	2.17E-05	1.93E-05	4.50E-07	0	1.87E-06
NMVOC	air	kg	4.04E-06	3.63E-06	1.16E-07	0	2.94E-07
PAH	air	kg	2.72E-09	2.67E-09	2.52E-11	0	1.63E-11
PM2.5	air	kg	3.58E-06	3.42E-06	6.75E-08	0	9.28E-08
PM10	air	kg	1.05E-05	1.03E-05	1.48E-07	0	1.30E-07
PCDD/F (measured as I-TEQ)	air	kg	2.26E-14	1.98E-14	1.77E-16	0	2.56E-15
Radon-222	air	kBq	9.34E-01	9.04E-01	1.82E-02	0	1.09E-02
Sulphur dioxide	air	kg	2.26E-05	2.15E-05	7.82E-07	0	3.05E-07
Emissions to water							
Ammonium, ion	water	kg	3.14E-08	2.93E-08	1.55E-09	0	4.77E-10
Arsenic, ion	water	kg	2.26E-08	2.16E-08	2.22E-10	0	6.83E-10
Cadmium, ion	water	kg	1.33E-08	1.30E-08	1.42E-10	0	1.61E-10
Carbon-14	water	kBq	1.96E-05	1.90E-05	3.77E-07	0	2.20E-07
Cesium-137	water	kBq	9.43E-06	9.14E-06	1.81E-07	0	1.06E-07
Chromium, ion	water	kg	2.40E-09	2.33E-09	3.29E-11	0	3.95E-11
Chromium VI	water	kg	5.44E-07	5.39E-07	3.28E-09	0	1.52E-09
COD	water	kg	4.10E-05	3.27E-05	7.89E-07	0	7.55E-06
Copper, ion	water	kg	3.21E-07	3.07E-07	2.97E-09	0	1.13E-08
Lead	water	kg	4.75E-07	4.42E-07	2.91E-08	0	4.13E-09
Mercury	water	kg	1.96E-09	1.93E-09	2.05E-11	0	6.55E-12
Nickel, ion	water	kg	4.28E-07	4.20E-07	7.35E-09	0	1.31E-09
Nitrate	water	kg	1.09E-06	1.06E-06	8.43E-09	0	2.47E-08
Oils, unspecified	water	kg	3.17E-06	2.79E-06	1.51E-07	0	2.28E-07
PAH	water	kg	4.09E-10	3.52E-10	3.61E-11	0	2.08E-11
Phosphate	water	kg	1.25E-06	1.23E-06	1.57E-08	0	6.98E-09
Ammonium, ion	water	kg	3.14E-08	2.93E-08	1.55E-09	0	4.77E-10

Parameter	Path	Unit	Dataset (Current technology)				
			Total kWh	Manufacturing	Operation	Fuel	Disposal
Emissions to Soil							
Arsenic	soil	kg	1.58E-11	1.47E-11	5.14E-13	0	6.29E-13
Cadmium	soil	kg	1.52E-11	1.34E-11	3.09E-13	0	1.47E-12
Chromium	soil	kg	8.89E-10	8.42E-10	1.48E-11	0	3.15E-11
Chromium VI	soil	kg	6.07E-10	5.92E-10	5.49E-12	0	8.87E-12
Lead	soil	kg	1.08E-10	9.91E-11	1.78E-12	0	7.65E-12
Mercury	soil	kg	6.62E-13	6.52E-13	7.09E-15	0	2.64E-15
Oils, unspecified	soil	kg	2.13E-06	1.75E-06	1.46E-07	0	2.34E-07

Annex 4

Minimum air pollutant list of the future offshore wind energy technologies – 2025 and 2050

Parameter	Path	Unit	*2025 Pessimistic*	*2025 Optimistic realistic*	*2025 Very Optimistic*	*2050 Pessimistic*	*2050 Optimistic realistic*	*2050 Very Optimistic*
			KWh					
Resources								
Coal, brown, in ground	resource	kg	2.64E-04	2.83E-04	3.78E-04	4.60E-04	3.80E-04	4.17E-04
Coal, hard, unspecified, in ground	resource	kg	9.62E-04	9.88E-04	1.26E-03	1.50E-03	1.04E-03	1.16E-03
Gas, natural, in ground	resource	Nm^3	3.18E-04	3.81E-04	7.19E-04	8.65E-04	4.62E-04	4.92E-04
Oil, crude, in ground	resource	kg	2.69E-04	2.80E-04	6.00E-04	7.33E-04	3.55E-04	3.93E-04
Uranium, in ground	resource	kg	1.46E-08	1.58E-08	2.34E-08	2.84E-08	2.28E-08	2.34E-08
Freshwater (lake, river, groundwater)	resource	m^3	3.03E-05	3.25E-05	5.05E-05	6.14E-05	4.29E-05	4.83E-05
Occupation, agricultural and forestry area	resource	m^2a	1.06E-04	1.05E-04	2.60E-04	3.14E-04	1.50E-04	1.61E-04
Emissions to air								
Ammonia	air	kg	2.91E-07	2.90E-07	5.51E-07	6.90E-07	5.82E-07	7.56E-07
Arsenic	air	kg	7.37E-09	8.19E-09	1.42E-08	1.81E-08	1.90E-08	2.51E-08
Cadmium	air	kg	2.80E-09	3.06E-09	5.34E-09	6.81E-09	7.20E-09	9.57E-09
Carbon dioxide, fossil	air	kg	2.69E-03	2.89E-03	5.60E-03	6.75E-03	3.41E-03	3.73E-03
Carbon monoxide, fossil	air	kg	2.67E-05	2.73E-05	2.19E-05	2.64E-05	2.88E-05	3.09E-05
Carbon-14	air	kBq	2.50E-05	2.64E-05	3.90E-05	4.74E-05	3.78E-05	3.89E-05
Chromium	air	kg	5.42E-09	5.48E-09	7.68E-09	9.43E-09	8.30E-09	9.45E-09
Chromium VI	air	kg	9.57E-11	9.66E-11	1.57E-10	1.93E-10	1.61E-10	1.87E-10
Dinitrogen monoxide	air	kg	9.67E-08	1.06E-07	3.05E-07	3.69E-07	1.38E-07	1.54E-07
Iodine-129	air	kBq	2.52E-08	2.66E-08	3.84E-08	4.66E-08	3.81E-08	3.91E-08
Lead	air	kg	4.25E-08	4.19E-08	7.24E-08	9.34E-08	1.06E-07	1.44E-07
Methane, fossil	air	kg	7.91E-06	8.69E-06	1.36E-05	1.62E-05	9.61E-06	1.05E-05
Mercury	air	kg	2.09E-09	2.14E-09	2.09E-09	2.51E-09	2.49E-09	2.50E-09
Nickel	air	kg	1.43E-08	1.42E-08	2.53E-08	3.24E-08	3.43E-08	4.63E-08

Parameter	Path	Unit	*2025 Pessimistic*	*2025 Optimistic realistic*	*2025 Very Optimistic*	*2050 Pessimistic*	*2050 Optimistic realistic*	*2050 Very Optimistic*
					KWh			
Nitrogen oxides	air	kg	9.47E-06	1.03E-05	1.97E-05	2.41E-05	1.35E-05	1.50E-05
NMVOC total	air	kg	2.36E-06	2.50E-06	4.41E-06	5.39E-06	3.28E-06	3.68E-06
PAH	air	kg	1.48E-09	1.52E-09	3.82E-09	4.57E-09	1.64E-09	1.71E-09
PM10	air	kg	5.57E-06	5.83E-06	7.24E-06	8.87E-06	7.85E-06	8.99E-06
PM2.5	air	kg	1.90E-06	1.99E-06	2.93E-06	3.61E-06	3.06E-06	3.56E-06
PCDD/F (measured as I-TEQ)	air	kg	1.02E-14	1.04E-14	1.03E-14	1.25E-14	1.26E-14	1.37E-14
Radon-222	air	kBq	4.57E-01	4.83E-01	7.14E-01	8.68E-01	6.93E-01	7.10E-01
Sulphur dioxide	air	kg	1.24E-05	1.31E-05	2.21E-05	2.74E-05	2.27E-05	2.84E-05
Emissions to Water								
Ammonium, ion	water	kg	1.25E-08	1.49E-08	2.37E-08	2.87E-08	1.86E-08	1.98E-08
Arsenic, ion	water	kg	1.18E-08	1.20E-08	2.12E-08	2.54E-08	1.33E-08	1.41E-08
Cadmium, ion	water	kg	7.01E-09	7.13E-09	7.05E-09	8.48E-09	7.61E-09	8.22E-09
Carbon-14	water	kBq	9.80E-06	1.04E-05	1.49E-05	1.82E-05	1.48E-05	1.52E-05
Cesium-137	water	kBq	4.70E-06	4.97E-06	7.18E-06	8.73E-06	7.12E-06	7.31E-06
Chromium, ion	water	kg	1.26E-09	1.26E-09	1.13E-09	1.36E-09	1.35E-09	1.44E-09
Chromium VI	water	kg	2.91E-07	2.96E-07	2.67E-07	3.21E-07	3.31E-07	3.34E-07
COD	water	kg	1.76E-05	1.88E-05	2.06E-05	2.49E-05	2.08E-05	2.21E-05
Copper, ion	water	kg	1.68E-07	1.69E-07	1.44E-07	1.73E-07	1.85E-07	1.94E-07
Lead	water	kg	2.01E-08	2.11E-08	1.05E-07	1.26E-07	2.43E-08	2.63E-08
Mercury	water	kg	1.04E-09	1.06E-09	8.41E-10	1.01E-09	1.12E-09	1.20E-09
Nickel, ion	water	kg	2.32E-07	2.33E-07	2.55E-07	3.09E-07	2.78E-07	3.03E-07
Nitrate	water	kg	6.94E-07	5.51E-07	5.24E-06	6.29E-06	6.34E-07	6.21E-07
Oils, unspecified	water	kg	1.54E-06	1.55E-06	2.41E-06	2.93E-06	1.70E-06	1.83E-06
PAH	water	kg	2.06E-10	2.07E-10	3.66E-10	4.46E-10	2.80E-10	3.07E-10
Phosphate	water	kg	6.52E-07	6.63E-07	5.49E-07	6.60E-07	6.97E-07	7.47E-07
Emissions to Soil								
Arsenic	soil	kg	6.04E-12	9.41E-12	1.47E-11	1.78E-11	1.15E-11	1.09E-11
Cadmium	soil	kg	7.45E-12	7.97E-12	3.33E-11	4.02E-11	1.01E-11	8.89E-12
Chromium	soil	kg	1.42E-10	1.42E-10	6.29E-10	7.59E-10	1.77E-10	1.64E-10

Parameter	Path	Unit	*2025 Pessimistic*	*2025 Optimistic realistic*	*2025 Very Optimistic*	*2050 Pessimistic*	*2050 Optimistic realistic*	*2050 Very Optimistic*
					KWh			
Chromium VI	soil	kg	3.86E-10	4.07E-10	7.31E-10	8.83E-10	5.16E-10	5.71E-10
Lead	soil	kg	4.25E-11	6.40E-11	1.30E-10	1.57E-10	7.92E-11	7.19E-11
Mercury	soil	kg	4.27E-13	3.32E-13	3.26E-12	3.92E-12	3.91E-13	3.77E-13
Oils, unspecified	soil	kg	9.96E-07	9.91E-07	2.06E-06	2.51E-06	1.13E-06	1.21E-06