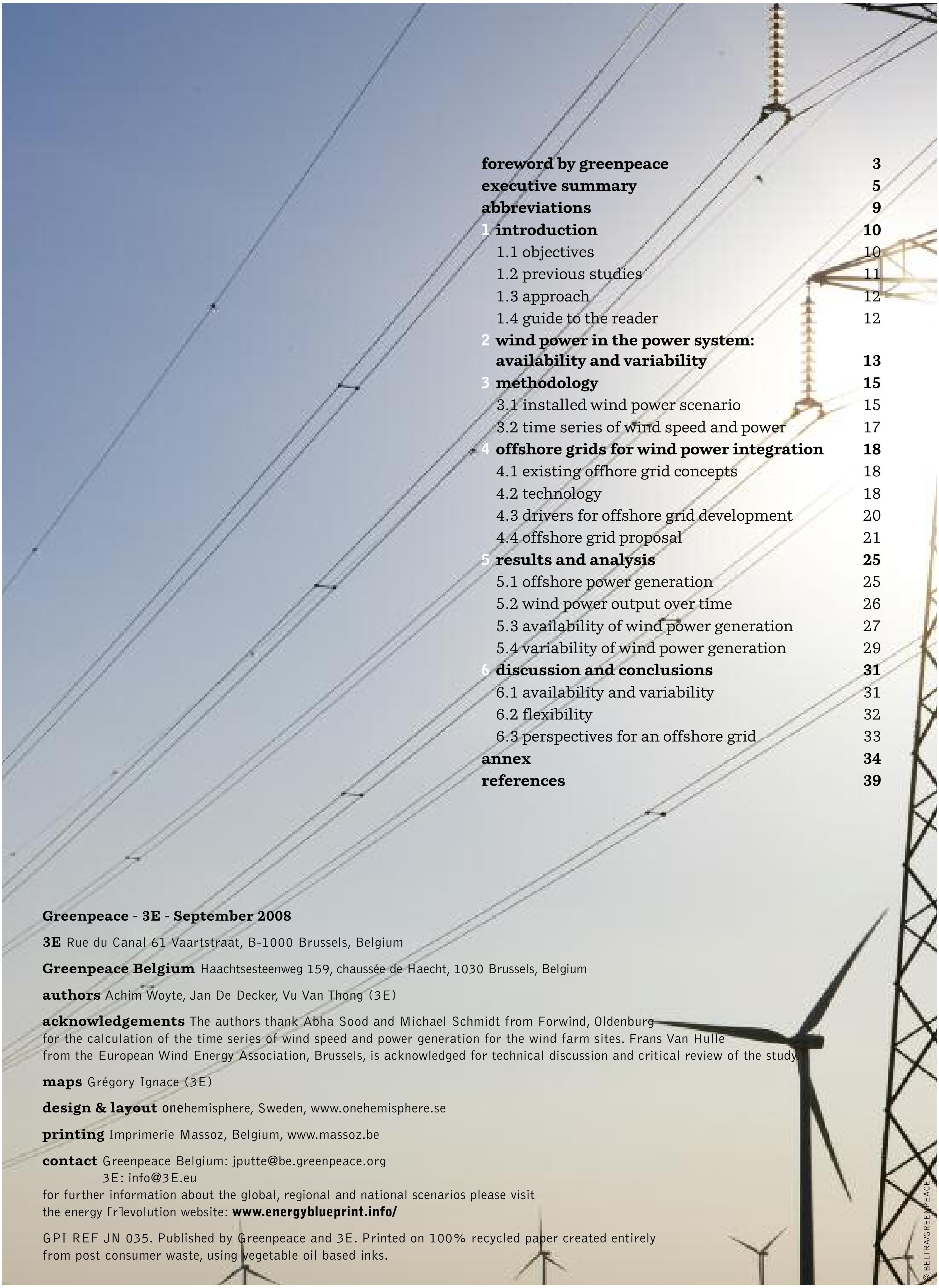
a north sea electricity grid
[r]evolution

ELECTRICITY OUTPUT OF INTERCONNECTED OFFSHORE WIND POWER
A VISION OF OFFSHORE WIND POWER INTEGRATION

© LANGROCK/ZENIT/GREENPEACE
© COURTESY OF ABB
© LANGROCK/ZENIT/GREENPEACE

report a north sea electricity grid [r]evolution



Greenpeace - 3E - September 2008

3E Rue du Canal 61 Vaartstraat, B-1000 Brussels, Belgium

Greenpeace Belgium Haachtsesteenweg 159, chaussée de Haecht, 1030 Brussels, Belgium

authors Achim Woyte, Jan De Decker, Vu Van Thong (3E)

acknowledgements The authors thank Abha Sood and Michael Schmidt from Forwind, Oldenburg for the calculation of the time series of wind speed and power generation for the wind farm sites. Frans Van Hulle from the European Wind Energy Association, Brussels, is acknowledged for technical discussion and critical review of the study.

maps Grégory Ignace (3E)

design & layout onehemisphere, Sweden, www.onehemisphere.se

printing Imprimerie Massoz, Belgium, www.massoz.be

contact Greenpeace Belgium: jputte@be.greenpeace.org
3E: info@3E.eu
for further information about the global, regional and national scenarios please visit
the energy [r]evolution website: **www.energyblueprint.info/**

GPI REF JN 035. Published by Greenpeace and 3E. Printed on 100% recycled paper created entirely from post consumer waste, using vegetable oil based inks.

cover image WINDTURBINES AT PALUDANS FLAK OFF THE COAST OF DENMARK.
image THE MARANCHON WIND TURBINE FARM IN SPAIN, OPERATED BY IBERDROLA.

image A WIND TURBINE BEING ASSEMBLED AT SEA.

foreword by greenpeace

Commissioned by Greenpeace, the 3E report A North Sea Electricity Grid [R]evolution provides an original contribution to the energy debate by showing how a massive expansion of offshore wind power by 2020-2030 will work in practice.

Although wind is a variable energy source, this is less the case over a large area like the North Sea. Variations in production at one wind park can be partly balanced by that of another park several hundreds of kilometres away. This report studies this 'balancing' effect in detail for the North Sea. It also shows how the large hydro-energy capacity in Norway can complement the remaining variations in wind power.

Calculations were performed using wind speed measurements across the North Sea. Based on actual wind speed data, the report proposes the creation of an offshore electricity grid to enable the smooth flow of electricity generated from renewable energy sources into the power systems of seven different North Sea countries: the United Kingdom, France, Germany, Belgium, the Netherlands, Denmark and Norway.

reducing variability

Advances in weather forecasting have already made the fluctuations of wind and solar energies very predictable. Fluctuations in the electricity output of energy sources like wind can be further levelled out. In an interconnected offshore grid, a lower level of electricity output at a single wind farm can usually be balanced against a simultaneous high output from another wind farm several hundred kilometres away or from another energy source. A system of this nature with many thousands of wind turbines is more reliable, and energy production more secure because the impact of maintenance or defects will be negligible.

Another contribution of the offshore electricity grid would be to combine the production of a fluctuating renewable energy source (e.g. wind) with dispatchable sources of renewable energy, such as the large hydro-energy capacity in Norway.

the real challenge: ambitious policies

Greenpeace strongly encourages political decision-makers and investors to take these key findings into consideration.

The creation of an interconnected offshore grid would give Europe an efficient and appropriate answer to climate change by relying on renewable energy sources (both variable and dispatchable) and abandoning polluting and inefficient production systems based on coal and nuclear power.

A flexible production system based on renewables better answers the demand for energy and avoids the huge loss of efficiency specific to large-scale power plants.

The 3E report assumes a total installed capacity of 68.4 GW. Locations of more than 100 offshore wind power farms have been identified based on lists of envisioned projects. The totals of installed power per country have been cross-checked with national and international targets.

Before the publication of this report, Greenpeace has been developing regional, national and global energy scenarios that define practical pathways to cut global CO2 emissions in half by 2050 (compared to 1990 levels) and to phase out nuclear power through massive investment in renewable energy and energy efficiency. The 3E report shows that wind power can offer a significant part of the solution.[1]

Greenpeace recommends that the seven North Sea countries coordinate their investments in an offshore electricity grid and facilitate its implementation. Large, outdated coal and nuclear plants have to be phased out and replaced with a more renewable, efficient and smartly-managed power system.

The exciting possibilities of a system that combines all of these elements are realistic and practical and involve only existing and cost-efficient technologies. The challenge is not a problem of technology, but rather in putting policy in place to combine these technologies in an efficient, renewable and smart system.

towards a new european energy policy

wind energy in europe: a growing success story

The world today is confronted with dangerous climate change and nuclear proliferation. Experts warn that fundamental changes must be made to energy production and use within the next ten years to avoid the worst effects of climate change.

The energy revolution is already underway, and the renewable energy industry is booming. In Europe in particular, solar and wind markets have been growing by about 20 per cent each year. In 2007, the renewable energy industry in Europe achieved a turnover of €30 billion and employed at least 350,000 people. In 2007, about 8550 MW of wind turbines were installed in the European Union (EU), generating enough electricity to meet the needs of 5 million EU households.

These new wind turbines account for 40 per cent of all newly-installed power capacity last year – an impressive growth figure, which leaves the coal and gas industries far behind, with nuclear power lagging even farther behind as the industry continues its decline.

---

footnote

[1] WWW.ENERGYBLUEPRINT.INFO

The growth of wind power is expected to continue at an even faster pace. Greenpeace and the European Wind Energy Association (EWEA) predict that based on the steady market growth over the last decade, the annual growth of wind power will more than double, with total installed capacity increasing five-fold to 300,000 MW by 2030. According to these projections, wind turbines would comprise more than one quarter (up to 28%) of all installed electricity capacity in the EU.[2]

Despite the healthy growth of the wind industry, the EU power system today is still dominated by large coal and nuclear plants. These large-scale power plants are not designed to be switched on and off according the rise and fall of electricity demand; they are inflexible when it comes to our needs.

A power system dependent on big power plants is also inefficient; about two-thirds of the energy generated is lost in heat, which is discharged into the environment. What's more, to shut down such a large plant for maintenance or refuelling requires back up. Unexpected circumstances can also lead to loss of electricity in whole cities or regions. For example, in July 2007, an earthquake in Japan knocked out all seven large reactors at the Kashiwazaki-Kariwa nuclear power plant.

a more efficient decentralised system

Generating power close to where people live is far more efficient as energy loss during the transport from the source to consumer is reduced; in small plants, heat losses can be directly recovered to heat up local houses, offices or hospitals.

In a decentralised system, buildings (from homes to industrial units) have their own wind turbine, and solar panels or co-generation units and smaller-scale power plants generate electricity closer to communities.

more intelligent management of demand

A highly efficient household consumes only one quarter of the energy of the average household. Demand can be greatly reduced with general energy-efficiency measures, such as using better appliances. Improved management of demand includes creating closer parity between electricity supply and consumption periods; electrical appliances for domestic and industrial uses, for example, can be devised to consume more when supply is higher.

and all with clean renewable sources

Fluctuating renewable energy sources can be combined with dispatchable renewable sources like biomass. Hydro plants can be switched on easily to deliver immediate power to the electricity grid. For some hydro plants, excess power (when the wind blows and sun shines) can even be used to pump water back, working like a huge water-battery.

greenpeace conclusions

European electricity companies such as EDF, E.ON, RWE or Suez are fiercely opposing the closure of their ageing nuclear power and coal plants and are pushing for new ones to be created. These inflexible, inefficient plants are incompatible with the large-scale integration of renewable energy sources. Every new, large fossil fuel or nuclear power plant installed will operate for forty years or more, locking us in to massive environmental problems and blocking the transition to an efficient, flexible and renewable electricity system.

Greenpeace and the European Renewable Energy Council (EREC) commissioned the DLR Institute (German Aerospace Centre) to develop a sustainable global energy scenario up to 2050. This Energy [R]evolution scenario is a realistic blueprint that shows that it is feasible to phase out nuclear power and fossil fuels for a sustainable and equitable energy future through renewable energy and energy efficiency.

It is clear that for Europe, and especially for the North Sea countries, offshore wind power will play a significant role in a flexible and efficient power system as part of a mixture of renewable energy sources. The 3E report shows how the reliability of the offshore wind electricity production can be improved considerably by interconnecting the wind farms in the North Sea and by envisaging its combination with dispatchable renewable sources (e.g. hydro in Norway). The report shows how, with the right decisions, the large-scale development of offshore wind would really work, once an offshore grid had been developed to enable the power to flow smoothly from the wind turbines into national power systems.

greenpeace demands

The European Commission and the seven North Sea countries should build a coordinated European approach to the planning of offshore wind development in the North Sea.

- There should be strategic and coordinated grid planning on EU and regional levels that is consistent with ambitious short- and long-term scenarios for offshore wind energy development. The guidelines for Trans-European Energy Networks should be revised to facilitate the large-scale integration of renewable energy and already-planned bilateral offshore interconnection projects (such as those between the UK and Norway, the UK and Belgium, and the UK and the Netherlands) should be made compatible with the large-scale integration of offshore wind power.
- National offshore wind policies or initiatives such as in the German Bight, the UK (3rd Round) and Belgium ("Printemps de l'Environnement") should be further developed to provide an integrated approach across the seven North Sea countries.
- European guidelines should support the identification of suitable areas for wind farm construction based on geographical, economic and technical data, including wind availability, sensitive and protected habitats and species, shipping routes, fishing activities and grid connections.
- The power system must be flexible to allow large-scale integration of fluctuating renewable energy. No new, large coal or nuclear power plants should be licensed, and existing plants must be replaced progressively with flexible, highly efficient and more decentralised plants.
- Offshore wind power, and renewable energy in general should be granted unambiguous priority access to the grid.
- Authorisation and licensing procedures for offshore wind farms across Europe should be streamlined, transparent and efficient.
- Offshore interconnections should enable the exploitation of the large storage capacity of hydro energy in Norway to complement the variability of offshore wind power and other variable renewable sources.

---

footnote

[2] EWEA, PURE POWER. 2008.

executive summary

"THIS STUDY (...) IDENTIFIES PRIORITIES FOR AN EFFICIENT INTEGRATION OF LARGE-SCALE OFFSHORE WIND POWER INTO THE EUROPEAN POWER SYSTEMS WITH SPECIAL FOCUS ON THE DEVELOPMENT OF AN OFFSHORE GRID IN THE NORTH SEA."


© LANGROCK/ZENIT/GREENPEACE

image OFFSHORE WINDFARM, MIDDELGRUNDEN, COPENHAGEN, DENMARK.

objectives & scope

The study shows how offshore wind power in the North Sea is suited to supplying the electricity demand. Perspectives are developed for the interconnection of offshore wind farms by a transnational offshore grid including an estimate of the cost for marine power transmission infrastructure.

This study builds on the acquired knowledge from a large number of studies by Greenpeace and other organisations, in which, amongst other results, development roadmaps or forecasts of installed offshore wind power capacity have been presented. In contrast with those studies, the present study is technical. It identifies priorities for an efficient integration of large-scale offshore wind power into the European power systems with special focus on the development of an offshore grid in the North Sea.

availability & variability of wind power

Although dependent on meteorological variations, the electricity generated from wind energy over the years can be estimated with high precision. Wind energy, therefore, is a reliable source for electricity generation. Since wind power has neither fuel costs nor noxious emissions wind farms should always be operated at the maximal available power level.

With increasing amounts of wind power in today's power systems, wind power affects the dispatch of conventional power plants. Two main effects, that have an impact on the overall efficiency of the power system are explored here: availability of power and its variability. The availability of wind power over the year is put in relation to other generation units and demand. Especially at wind power penetration levels of 10% and higher (corresponding to EU targets for 2020), the variability of wind power generation over several hours and days requires a more flexible dispatch of different types of power plants than is done today.

The ability to meet demand at any time must be regarded for a power system as a whole, taking into account the demand, the flexibility of available conventional power plants, and complementary renewable sources. In view of the social consensus in favour of ambitious renewable energy targets in the European Union, the power system needs to integrate generation from sustainable sources proactively.

The following means can facilitate the transition to an efficient power system based on sustainable sources:

- increased transmission capacity between power systems and synchronous zones,
- use of solar power and marine renewables being uncorrelated to wind power,
- demand-side management, e.g., by introduction of demand elasticity on the power market,
- energy storage, distributed and centralized.

wind power scenario & modelling

The wind power scenario used in this study assumes a total installed capacity of 68.4 GW (Table 1). Locations of offshore wind power generation have been identified based on lists of envisioned projects. The totals of installed power per country have been cross-checked with national and international targets. Geographically, the scenario is limited to the North Sea.

The authors consider the proposed scenario to be a best guess for the long term. Since the applied offshore wind power scenario mainly serves as a boundary condition for the technical study, no time frame has been assigned to it. Based on other recent studies however, the estimated timeframe for the development of 68GW offshore wind in the North Sea is between 2020 and 2030. Finally, the study does not account for emerging technology solutions like floating wind turbines on the open sea, wave power and tidal stream power generation. Therefore, in terms of these emerging technologies, the scenario is conservative.

Wind power generation has been calculated from hourly time series of wind speed for a 9x9 km² grid. The time series have been computed by downscaling empirical data from a period of three years with a lower resolution in time and space, with a mesoscale numerical weather prediction model.

For the conversion of wind speed into output power per wind farm, a regional power curve has been used.

table 1: capacity scenario for offshore wind power, electricity generation, capacity factor and electricity consumption per country (WIND POWER IN THE NORTH SEA ONLY)

COUNTRY	INSTALLED CAPACITY [MW]	ELECTRICITY / YEAR [TWH]	AVERAGE CAPACITY FACTOR [%]	TOTAL ELECTRICITY CONSUMPTION 2006 [TWH]
Belgium	3,846	13.1	38.9	89.9
Denmark	1,577	5.6	40.5	36.4
France	1,000	3.4	38.8	478.4
Germany	26,418	97.5	42.1	559.0
Great Britain	22,238	80.8	41.5	405.8
Netherlands	12,039	41.7	39.6	116.2
Norway	1,290	4.9	43.7	122.6
Total	**68,408**	**247.0**	**41.2**	**1,808.3**

technology for marine power transmission

Wind farms situated more than approximately 90 km from an onshore substation should be connected by high-voltage DC (HVDC) cables in order to reduce electrical losses and investment costs. Wind farms situated less than 50 km from the onshore transmission grid will in general be connected by high-voltage AC (HVAC) cables. In the intermediate range, the choice for AC or DC technology will depend on project-specific parameters.

For technical and economic reasons, high-voltage DC systems for the connection of offshore wind farms will be based on voltage source converter (VSC) technology, in contrast to the classical, so-called line-commutated, HVDC systems that have been applied until now for the electrical interconnection between power systems. The HVDC VSC technology permits connection of a wind farm directly to the end of a line. Moreover, this technology enables a multi-terminal configuration: a lay-out where several offshore wind farms could virtually be plugged into the line along the way. Therefore, HVDC VSC is the enabling technology for the development of any marine grid that is to contain offshore nodes.

offshore grids

The value of an offshore grid in the North Sea lies mainly in its role as a facilitator for power exchange and trade between regions and power systems. As such it can introduce additional flexibility to the power system. Moreover, an offshore grid allows the aggregation and dispatch of power from offshore wind farms from different regions, resulting in power generation profiles of low variability.

In the present study, an offshore grid topology is proposed (Figure 1) that is driven by two distinguished policy drivers: the need for connectivity between countries and power market regions and the demand for an economically efficient connection of offshore wind farms. While connectivity is considered the main driver today, the connection of offshore wind farms will gain importance in the future, when offshore converter stations for HVDC will be required for the connection of wind farms far from shore.

The required converter stations will be on the open North Sea and with an additional investment they can be connected to each other or to another shore. This would allow the allocation of the spare capacity of the line to the power market, while it is not used by wind power. For arbitrage between market regions, the possibility to make use of an extended wind farm grid connection is a cheaper alternative to the development of separate cables. Since the prolongation of lines from offshore wind farm converter stations is economically beneficial as long as there is opportunity for arbitrage, an offshore grid will probably emerge in such a way.

All lines together of the proposed offshore grid have a total single line length of 6200 km. Assuming that, in an initial phase, all transmission lines have a capacity of 1 GW, the proposed offshore grid would cost 15-20 billion Euros. The amount indicated would be needed to develop the proposed offshore grid from scratch with 1 GW capacity for each line, as it may be useful for the purpose of trade only. For increasing transmission capacities, costs increase at a slightly less than linear rate.

image AERIAL VIEW OF A WINDPARK OFF THE COAST OF DENMARK

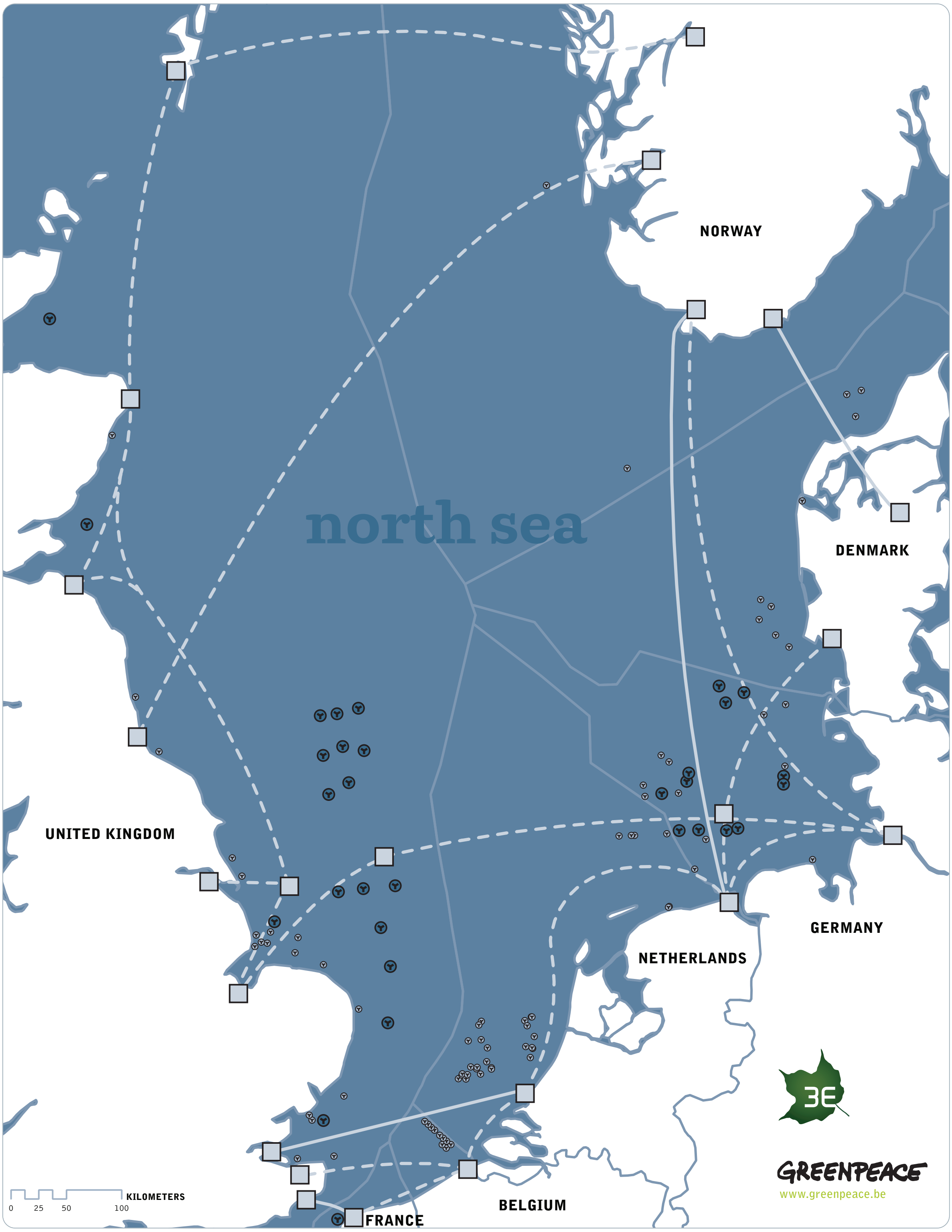

© JPSDK/DREAMSTIME

For comparison, the overall investment for the NorNed project, a classical HVDC cable connecting Norway and the Netherlands with a capacity of 700 MW, was 600 million Euros. During its first two months of operation, this interconnector has generated revenues of 50 million Euros, which is more than 800,000 Euros per day.

By extending the HVDC grid connections of offshore wind farms to other power market regions, wind power can offer transmission capacity for commercial use at much lower investment costs than for a single interconnector while providing similar benefits to the market.

---

figure 1: **offshore grid topology proposal and offshore wind power installed capacity scenario**



Wind energy is booming in the EU. In 2007 alone, no less than 8550MW of wind turbines were installed in the EU, which is 40% of all newly-installed capacity. By 2020–2030, offshore wind energy in the North Sea could grow to 68,000MW and supply 13 per cent of all current electricity production of seven North Sea countries. In order to integrate the electricity from the offshore wind farms, an offshore grid will be required. Greenpeace demands that the governments of these seven countries and the European Commission cooperate to make this happen.

INSTALLED AND PLANNED CAPACITY

[MW]

	[MW]	[TWh]
BELGIUM	3,850	13.1
DENMARK	1,580	5.6
FRANCE	1,000	3.4
GERMANY	26,420	97.5
UNITED KINGDOM	22,240	80.8
NETHERLANDS	12,040	41.7
NORWAY	1,290	4.9
TOTAL	**68,420**	**247**

LEGEND

- ╌ **GRID:** PROPOSED OR DISCUSSED IN THE PUBLIC DOMAIN
- — **GRID:** IN OPERATION OR PLANNING
- ☐ **PRINCIPLE HVDC SUBSTATIONS**
- • **WIND FARMS:** INSTALLED PLANNED CAPACITY < 1000 MW
- ● **WIND FARMS:** INSTALLED PLANNED CAPACITY > 1000 MW

* MAP IS INDICATIVE. NO ENVIRONMENTAL IMPACT ASSESSMENT OF LOCATIONS AND SITING OF WINDFARMS AND CABLES HAS BEEN DONE.

results

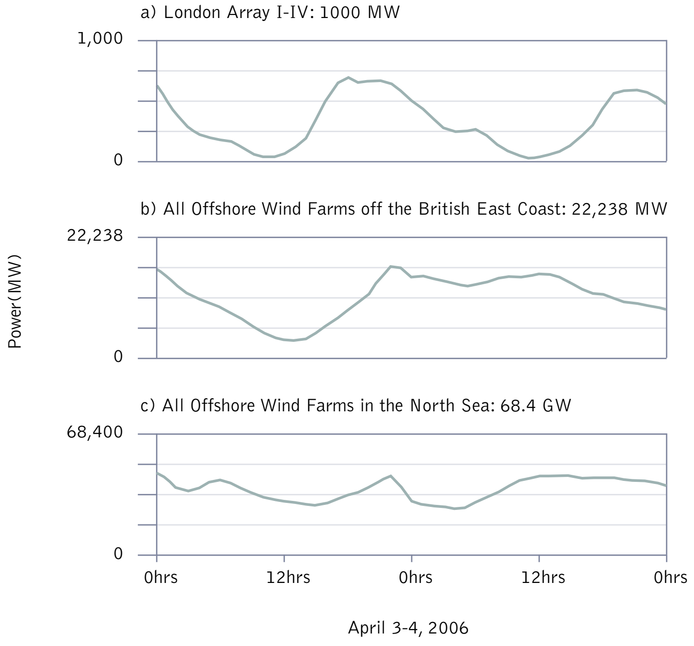
Over the year, the installed offshore wind power generation capacity of 68.4 GW would generate 247 TWh of electricity. The average capacity factor is 41.2%.

Over the year, a single offshore wind farm will experience significant periods during which the farm is running at full power. Nontheless, a single wind farm will also experience periods of very low load. When adding up power generation over the whole North Sea, the periods of very low and very high power generation are negligible. Eighty percent of the time the power output is more than 15.5% of the total installed capacity (Figure 2).

Accumulating the power generation from wind farms over larger regions can reduce the periods of full load and very low load. In conclusion, the spatial spread of wind farms over the North Sea leads to a larger fraction of time during which medium level power is generated in exchange for a reduction of periods of full load. Situations of full and no load occur during a negligible fraction of time.

With regard to unit commitment and dispatch of the power system, this means that the target should not be to operate offshore wind power in the North Sea as a classical base load plant. Wind power should rather be seen as a part of a power generation portfolio that, as a whole, has to be managed in order to supply the variable demand. For such portfolio management, flexibility is needed in supply, demand, import and export. Day-ahead and intra-day forecasting of the wind power generation is required for optimal dispatch decisions and minimization of reserve requirements.

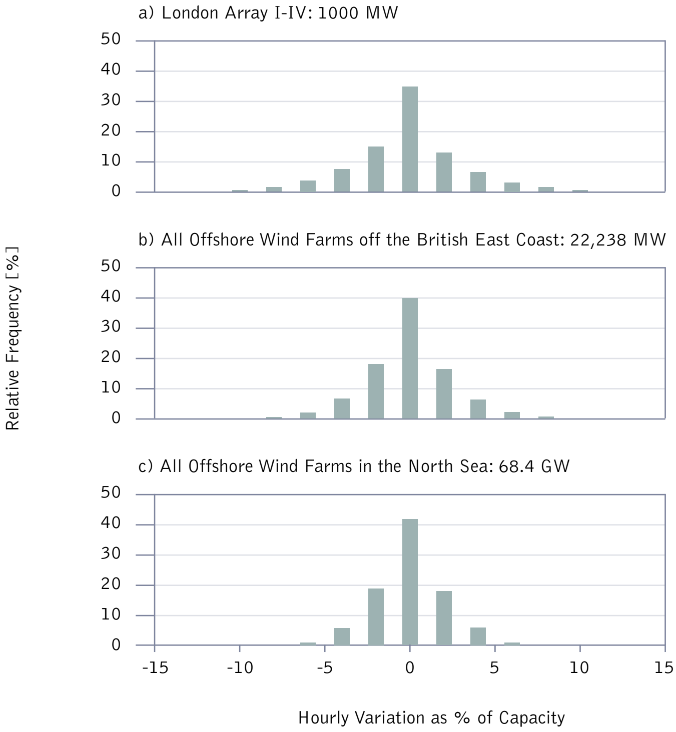
figure 2: power output of offshore wind power over two days FOR ONE WIND FARM, ALL WIND FARMS OFF THE BRITISH EAST COAST AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA



The calculations for the North Sea show that large variations of aggregated wind power generation are not very frequent (Figure 3). For a single wind farm, 35% of all hourly variations are of less than ±1% of installed capacity. For all wind farms off the British east coast together, this is the case for 40% of all hourly samples. For the accumulated generation of all wind farms together in the North Sea, 42% of all hourly variations are of less than ±1%. In all cases, more than 50% of all variations are of less than ±2% of installed capacity.

Variations larger than ±5% occur for 20% of all hourly samples for the single wind farm. For all wind farms off the British east coast together they occur only 10% of the time and for the entire North Sea only 6%. The occurrence of variations beyond ±10% appears to be negligible.

figure 3: relative frequency of hourly variations in generation FOR ONE WIND FARM, ALL WIND FARMS OFF THE BRITISH EAST COAST AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA



Flexibility is the key requirement from a power system that is largely based on generation from variable renewable sources. Flexibility can be introduced by:

- distributed generation and storage,
- controllable demand,
- centralized storage,
- reservoir hydro power,
- flexible thermal power stations.

image REPARATION WORK ON A WINDPARK OFF THE COAST OF DENMARK.


© LANGROCK/ZENIT/GP

conclusion

An offshore grid in the North Sea facilitates trade and it increases security of supply by offering increased connectivity. It allows dispatching power from offshore wind farms to different countries depending on the highest demand. By enabling the supply of aggregated generation profiles from different regions to one market, the offshore grid contributes to reducing the variability of wind power generation in the range of hours. Moreover, an offshore grid in the North Sea allows the import of electricity from hydro power from Norway to the British and the UCTE system. This can replace thermal base load plants and increase the flexibility within a portfolio. In addition, increased liquidity and trading facilities on the European power markets will allow for a more efficient portfolio management.

The value of an offshore grid in the North Sea lies in its contribution for increased security of supply, its function for the aggregation and dispatch of power from offshore wind farms, and in its role as a facilitator for power exchange and trade between regions and power systems. Integrating interconnectors with connection lines for wind farms far from shore can yield efficiency gains for the development of both wind power projects and commercial interconnectors.

abbreviations

AC	Alternative Current
BERR	British Department for Business, Enterprise & Regulatory Reform
BSH	German Federal Maritime and Hydrographical Agency (Bundesamt für Seeschifffahrt und Hydrographie)
BWEA	British Wind Energy Association
CAES	Compressed Air Energy Storage
CCGT	Combined Cycle Gas Turbine
CE2030	Belgian Expert Commission on Energy 2030 (Commissie Energie 2030)
CHP	Combined Heat and Power
COD	Concerted Action of Offshore Wind Energy Deployment
DW	Douglas Westwood
DC	Direct Current
Dena	German Energy Agency (Deutsche Energie-Agentur)
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
EACI	Executive Agency for Competitiveness and Innovation
EEZ	Exclusive Economic Zone
EPC	Equivalent Wind Power Curve
ETSO	European Transmission System Operators
EWEA	European Wind Energy Council
EWIS	European Wind Integration Study
FNL	Final Analysis
GWEC	Global Wind Energy Council
HVDC	High Voltage Direct Current
HVAC	High Voltage Alternative Current
IGBT	Insulated Gate Bi-Polar Transistor
LCC	Line Commutated Converter
MW, GW	megawatt, gigawatt (unit of power)
MWh, GWh	megawatt-hour, gigawatt-hour (unit of energy)
NCEP	United States' National Center for Environmental Prediction
NWP	Numerical Weather Prediction
OCGT	Open Cycle Gas Turbine
PAS	Pumped hydro Accumulation Storage
TEN-E	Trans-European Energy Networks
TSO	Transmission System Operator
UCTE	Union for the Coordination of Transmission of Electricity
VSC	Voltage Source Converter
WRF	Weather Research and Forecasting Model

introduction

"FOR DECISION MAKERS, THIS REPORT CAN SERVE FOR DEVELOPING A VISION ON OFFSHORE WIND POWER INTEGRATION THAT IS BROAD AS WELL AS TECHNICALLY WELL FOUNDED."

1

image MAN USING METAL GRINDER ON PART OF A WIND TURBINE MAST IN THE VESTAS FACTORY, CAMBELTOWN, SCOTLAND, GREAT BRITAIN. WIND TURBINES ARE NOT ONLY A SOURCE OF RENEWABLE ENERGY BUT ALSO A SOURCE OF EMPLOYMENT.

1.1 objectives

Offshore wind energy has the capacity to generate a significant share of electricity in a future European energy mix based largely on renewable sources. Along with the investments in offshore wind power for the next two decades, the interconnection of offshore wind farms via a, possibly meshed, offshore grid has repeatedly been brought up by public bodies and private companies.

The overall objectives of this study are to show how offshore wind power is suited to supplying the demand for electricity and to developing perspectives for the interconnection of offshore wind farms by an offshore grid.

For decision makers, this report can serve for developing a vision on offshore wind power integration that is broad as well as technically well founded. It answers the following questions:

- What is the power output that large-scale offshore wind energy in the North Sea can deliver over time?
- In what way do techno-economic developments in the power sector influence this output?
- How is the development of an offshore grid influenced by political priorities?
- What is the cost of interconnecting offshore wind energy generation?

The study answers these questions in general terms. Costs for offshore infrastructure are described by order of magnitude.

Complementary measures in order to improve the economic efficiency of power systems with a high share of wind power are discussed; however, no quantitative analysis was carried out. An examination of such measures with regard to the integration of electricity from renewable sources would require a separate study.

image LOADING SUBMARINE SEA CABLES.

1.2 previous studies

Regarding wind power, numerous policy studies about market development, energy generation potential and power system integration are available. Greenpeace, in cooperation with different partners, has published a series of studies on the wind power potential in the North Sea as well as on the potential market development of renewables, and wind power in particular, world-wide.

- Offshore Wind Energy in the North Sea (2000) [1]
- Sea Wind Europe (2004) [2]
- Offshore Wind - Implementing a new power house for Europe (2005) [3]
- Wind Force 12 (2005) [4]
- Global Wind Energy Outlook (2006) [5]
- Energy Revolution: a sustainable pathway to a clean energy future for Europe [6], and
- Energy [R]evolution [7].

The first three reports ([1] - [3]) focus on offshore wind power in Europe. While Sea Wind Europe mainly estimates the resource potential, Offshore Wind - Implementing a new power house for Europe in particular addresses issues of grid and power system integration. The study focuses mainly on questions of grid connection and infrastructure. It also contains a review of technologies for offshore power transmission. Aspects such as international cooperation and levelling of the wind power generation over the North Sea are not addressed.

Wind Force 12 and the Global Wind Energy Outlook are published by Greenpeace in cooperation with the European Wind Energy Association (EWEA) and the Global Wind Energy Council (GWEC), respectively. They are feasibility studies identifying the economical and political needs to realize a significant contribution of wind power to the global electricity supply in the long term.

Recently, EWEA published two updated scenarios for the European Union. The report "Delivering offshore wind power in Europe" [8], published in December 2007, provides policy recommendations in order to achieve an ambitious offshore wind power scenario of up to 40 GW installed by 2020. The report "Pure Power" [9], published in March 2008, provides updated targets up to 2030 for installed capacity onshore and offshore in the European Union. "Pure Power" targets 35 GW of installed offshore wind power in the EU27 in 2020 and 120 GW in 2030.

The "Energy Revolution" reports provide blueprints for a sustainable pathway to a clean energy future. While the 2005 report [6] focuses on the European Union, the "Energy [R]evolution" scenario from 2007 [7] provides an alternative to the IEA's World Energy Outlook. It demonstrates how to apply existing technologies to halve global CO_2 emissions by 2050 whilst allowing for an increase in energy consumption.

Other important studies covering grid-integration aspects of offshore wind power at the European level are

- Sealegal: Enabling Offshore Wind Developments (2002) [10],
- Concerted Action for Offshore Wind Energy Deployment, esp. report on Grid Issues (2005) [11],
- EWEA – Integration of Wind Energy in the European Power Supply (2005) [12],
- ETSO – European Wind Integration Study (EWIS), phase 1 (2007) [13],
- IEA Wind Task 25: Design and operation of power systems with large amounts of wind power [14],
- TradeWind (2008) [15].

"Sealegal" is a policy study covering legal and siting issues for offshore wind and providing best-practice guidelines for siting and permitting policy. As a follow up, the Concerted Action for Offshore Wind Energy Deployment (COD) inventoried a number of issues for offshore wind energy that are not solely technical. Amongst other results, in 2005 the COD published a comprehensive inventory of power system and grid issues for offshore wind in the participating countries. With regard to offshore power transmission, the COD emphasized that "common offshore substations could become initial nodes of an international offshore grid." The COD also stated that infrastructures were required for the transmission of wind power over wide distances in order to benefit from the existing spatial decorrelation of wind speed.

Also in 2005, EWEA published its comprehensive report on the Integration of Wind Energy in the European Power Supply. The report can be seen as an inventory of power system integration issues for wind energy and the state-of-the-art the wind power industry had achieved at that time in order to tackle them.

The European Wind Integration Study (EWIS), phase 1, was published in January 2007. EWIS is an initiative established by the association of European Transmission System Operators (ETSO). The scope of work in EWIS covers technical, operational, market and regulatory aspects related to the integration of wind power in Europe on a large scale. Currently, a second phase of EWIS is ongoing.

The IEA Wind[1] Task 25 aims to "provide information to facilitate the highest economically feasible wind energy penetration within electricity power systems worldwide." The IEA Wind's state-of-the-art report [16] is a summary of case studies addressing concerns about the impact of wind power's variability and uncertainty on power system reliability and costs. Moreover, it contains a clear classification of power system integration issues related to wind power.

TradeWind is an ongoing research project for policy support, funded by the European Commission's Executive Agency for Competitiveness and Innovation (EACI). TradeWind aims on further developing Europe's power market for the large-scale integration of wind power by recommending interconnector upgrade and market rules for power exchange. The offshore wind power scenario applied to the North Sea in the present study has been developed in close cooperation with the TradeWind project.

---

footnote

[1] INTERNATIONAL ENERGY AGENCY (IEA) IMPLEMENTING AGREEMENT FOR CO-OPERATION IN THE RESEARCH, DEVELOPMENT, AND DEPLOYMENT OF WIND ENERGY SYSTEMS - IEA WIND

With the present study, Greenpeace wants to go beyond the existing studies. This study shows the potential for energy supply from offshore wind power and how it is suited to meeting the demand of electricity. It focuses on the availability of wind power generation over time and its variability. The results are based on a detailed analysis of the wind power generation profile on the North Sea as a function of time. In view of the outcomes of this analysis, complementary measures are explored for an economically efficient integration of offshore wind power in Northern Europe. Special attention is paid to the benefit an offshore grid in the North Sea would bring for this purpose.

1.3 approach

The study is based on time series of wind speed over the North Sea. Hourly values of wind speed over three years have been calculated for the coordinates of the wind farms anticipated in the North Sea, based on historical data.

Wind farm sites and installed capacities were assumed by 3E. The assumptions are based on national targets and scenarios, on granted domain concessions, and on information from national experts. The envisioned total installed capacity amounts to 68.4 GW, a figure in between the 2020 and 2030 EWEA offshore targets for all European seas (respectively 40GW and 120 GW).

In contrast to previous studies by Greenpeace and others, the present study is not a development roadmap towards or even a forecast of installed capacity. The applied offshore wind power scenario mainly serves as a boundary condition for the technical study. It is important to note that for this reason no time frame has been assigned to the installed capacity scenario.

For the identified wind farm sites, wind power output is calculated by means of a regional power curve for wind turbine types as they may be anticipated for 2030, i.e., cut-out happening smoothly at wind speeds above 30 m/s only.

A conceptual offshore grid design is introduced based on offshore interconnectors in operation or planning and those having been proposed or discussed in the public domain. In order to assess the general principles rather than entering into planning and siting issues, the offshore grid has been reduced to its essential nodes and branches.

Technically, the analysis is based on the statistics of the available power for each node and its variation. In practical terms, this means that the availability of power and the variability of the wind power output are assessed per node and country in order to answer the following questions:

- What amount of power is usually available in which countries?
- For what fraction of time is this power available?
- How greatly does it vary over time?
- To what extent can an offshore grid facilitate power system operation with large-scale offshore wind power?
- What complementary measures should be considered?

1.4 guide to the reader

In the following section the meaning of variability and limited availability of power from offshore wind farms is explored with regard to the operation of power systems. The aspects are set in relation to the power generation mix and the responsiveness of the power system as a whole.

The methodology for the quantitative analysis is described in Section 3. There, the underlying assumptions and the applied long-term scenario for the installed offshore wind power capacity are explained. Finally, the meteorological data base and the assumed wind farm power curves are referenced.

Section 4 focuses on offshore power transmission. After a review of published concepts for offshore and overlay transmission grids, the required technology of high-voltage DC transmission with voltage source converters is introduced. An offshore grid scenario is developed based on a qualitative assessment of the possible effect of different policy drivers on the development of an offshore transmission grid. Finally, this section contains an estimate of the costs of such offshore transmission infrastructure.

Quantitative results regarding the power generation of offshore wind farms are presented and analyzed in Section 5. The parameters investigated are expected annual generation, variation of output power over time, and the statistical properties of the available output power and its variability over time. The results are compared for single wind farms, for the accumulated power output for different countries and for the entire North Sea.

In Section 6 the results are discussed and related to the operation of power systems as a whole. The influence of variable generation on a power generation and demand portfolio is discussed. This is done for conventional thermally dominated generation portfolios as well as for a sustainable portfolio largely based on renewables and cogeneration plants. The importance of flexibility in future power systems is discussed for an efficient integration of variable power generation and demand. Finally, development perspectives for an offshore grid are discussed in view of the results from Sections 4 and 5.

wind power in the power system: availability & variability

"THE ABILITY TO MEET DEMAND AT ANY TIME MUST BE CONSIDERED FOR A POWER SYSTEM AS A WHOLE, TAKING INTO ACCOUNT THE DEMAND, THE FLEXIBILITY OF AVAILABLE CONVENTIONAL POWER PLANTS, AND COMPLEMENTARY RENEWABLE SOURCES."

2

© LANGROCK/ ZENIT/GREENPEACE

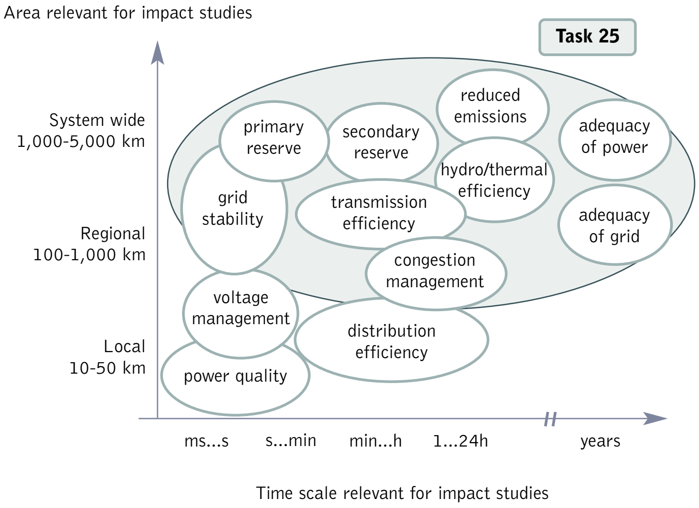
image OFFSHORE WIND PARK NYSTED HAVMØLLEPARK IN DENMARK WITH 72 WIND MILLS.

Although dependent on meteorological variations, the electricity generated from wind energy over the years can be estimated with high precision. Wind energy, therefore, is a reliable source for electricity generation. While investment costs for wind power are relatively high, the marginal cost for power generation from wind is negligible. Therefore, wind power plants are considered must-run units with variable output. Every megawatt-hour generated from wind substitutes the megawatt-hour with the highest marginal cost in the generation mix of a power system. In Europe today, this would mostly first substitute energy from combined cycle gas turbines (CCGTs) or coal-fired plant, depending on the national generation mix and the price of CO_2 emission allowances. In both cases, wind energy substitutes largely imported fossil fuel and the corresponding CO_2 emissions.

A significant amount of wind power in the power system can have different effects. The IEA Task 25 classifies these effects according to their time scale and affected area (Figure 4). In this terminology, the present study is mainly related to adequacy of power and hydro/thermal efficiency.

figure 4: **impacts of wind power on power systems, divided into different time scales and width of area**

AS COVERED BY THE IEA WIND TASK 25 (FROM [16], BY COURTESY OF H. HOLTTINEN, VTT, FINLAND)



With increasing amounts of wind power in today's power systems, wind power affects the dispatch of conventional power plants. Two main effects, which affect the overall efficiency of the power system, are explored here: the availability and the variability of power. The limited availability of wind power over the year is put in relation to other generation units and demand. The variability of wind power generation over the days requires a more flexible dispatch of different types of power plants than exists today.

Generation adequacy is a static measure for the capability of the system to supply the peak power demand when required, with sufficient margin of safety (or low risk). Today, in practice, power during periods of low wind and high demand is provided by thermal power plants and by other renewable energy sources, the latter being mainly large hydro plants. In future, other marine renewables, solar power and power generation from biomass could further complement the generation mix.

Above a certain level of wind power penetration in the system, situations arise in which wind power together with the minimum generation of the other plants exceed the power demand. In practice, this surplus generation of wind power during times of low load appears to have more serious effects on the power system than the potentially low generation during peak load [17][18]. In this case curtailment of wind power is usually sought. Curtailment of wind power can be avoided by using a larger spatial spread of wind power generation and demand and by replacing must-run base load units by more flexible generation units. Finally, energy storage may contribute to an increased overall efficiency of power supply [17][19].

With large installed capacities, the variability of must-run wind power can be significant compared to variations in overall supply and demand. The shorter the characteristic variation in supply and demand, the greater the need for fast adaptations of flexible units and flexible demand becomes. Today, variations are mainly absorbed at the supply-side, with electricity from conventional power plants. While a combined cycle gas turbine (CCGT) can be started within an hour, starting up a coal-fired plant takes six to ten hours, with decreased efficiency compared to nominal operation. Present nuclear power plants are not suited for complementing variable generation for economic and technical reasons. In response to very short variations, reservoir hydro power plants or open cycle gas turbines (OCGTs) are mostly used.

Not only wind and solar power generation, but also demand depend on the passage of weather systems. Therefore, the correlation of wind speed and solar irradiance over wide areas is low. In order to benefit from this decorrelation effect a European transmission system with sufficiently high transport capacity is required. Moreover, the power systems in Europe differ in generation mix and also in flexibility. The large capacities of reservoir hydro power in Norway and the north of Sweden in particular could complement the nuclear and fossil fuel-based generation mix in Great Britain, Ireland and many countries in continental Europe. Thus, sufficient transmission capacity between countries is essential for enabling an efficient grid integration of large-scale wind power in Europe.

In conclusion, the ability to meet demand at any time must be considered for a power system as a whole, taking into account the demand, the flexibility of available conventional power plants, and complementary renewable sources. In power systems with a low fraction of wind power generation, the effect of wind power on these parameters may be neglected. However, in view of the significant role to play by renewable energy and the ambitious targets of the EU Member States, the industry-driven scenarios of EWEA, and the recent blueprints for a sustainable energy supply by Greenpeace, this will not be the case in the foreseeable future.

The following means can facilitate the transition to an efficient power system to be based on sustainable sources:

- Increased transmission capacity between power systems and synchronous zones,
- Use of solar power and marine renewables being uncorrelated to wind power,
- Demand-side management, e.g., by introduction of demand elasticity on the power market,
- Energy storage, distributed and centralized.

methodology

> "THE WIND POWER SCENARIO USED (...) REPRESENTS A SITUATION WHICH IS LIKELY TO BE ACHIEVED, UNDER FAVOURABLE CONDITIONS, AND WHICH WILL HAVE A SIGNIFICANT IMPACT ON NECESSARY GRID DEVELOPMENTS."

3

© LANGROCK/ZENIT/GREENPEACE

image VESTAS WIND SYSTEMS A/S IN RINGKOBING, DENMARK, PRODUCING WINDTURBINE BLADES FOR OFFSHORE WIND ENERGY.

3.1 installed wind power scenario

The wind power scenario used in this study is developed in close cooperation with the European project TradeWind [15]. Geographically, the scenario is limited to the North Sea. The total installed capacity envisioned amounts to 68408 MW (Table 2). This figure lies in between the 2020 and 2030 EWEA offshore targets for all Europe being 40 GW and 120 GW, respectively. In practice the capacities in Table 1 may be exceeded in some countries while in other countries the installed capacities may be lower due to projects not being realized that are anticipated here. In this context, the authors consider the proposed scenario as a best guess for the long term. It represents a situation which is likely to be achieved, under favourable conditions, and which will have a significant impact on necessary grid developments.

It is important to note that in this study no time frame is indicated, since the objective is not to present an installed capacity forecast, but rather to serve as input for an impact analysis. The offshore wind power capacity in the North Sea as finally available in 2030 could very well be considerably higher. Furthermore, the study does not account for emerging technology solutions like floating wind turbines on the open sea, wave power and tidal stream power generation. Therefore, in terms of these emerging technologies, the scenario is conservative.

Besides country-specific data, the scenario is based on the database of Douglas Westwood (DW) [20] and on the TradeWind scenario's developed in work package 2 [21]. A bottom-up approach starting from lists of projects is combined with a top-down approach based on the national and international targets. For each country the resulting list is verified by the Greenpeace national divisions and partly by the national wind energy associations. A situation of the scenario in line with the current national and international targets is given below. The gathered data include the name of the project or location, the projected installed capacity and the geographical coordinates. A list of the projects and installed capacity per country can be found in Annex A.

table 2: capacity scenario for offshore wind per country

(NORTH SEA ONLY)

COUNTRY	INSTALLED CAPACITY [MW]
Belgium	3,846
Denmark	1,577
France	1,000
Germany	26,418
Great Britain	22,238
Netherlands	12,039
Norway	1,290
Total	**68,408**

belgium

The installed capacity in the Belgian scenario totals 3846 MW. This installed capacity includes the three projects that have currently been granted concession (around 0.8 GW), and 6 more sites of 500 MW each which are equally divided over the zone designated for offshore wind energy. It corresponds with the TradeWind 2030 high scenario [21][22], and is in line with the figures in the report Optimal offshore wind energy developments in Belgium [23] and with the upper limit in the present concession area as stated in the CE2030 report [24].

denmark

The contemplated installed capacity of offshore wind in the Danish North Sea is based on the report "50% Wind Power in Denmark in 2025" [25]. Further advice has been given by the Danish Wind Energy Association. It consists of 1577 MW, of which 377 MW are currently realized and planned projects. The locations for the remaining 1200 MW are based on the recommendations in the report from the Danish Energy Authority "Future Offshore Wind Power Sites – 2025" [26].

france

The main offshore wind power development in Northern France will not be in the North Sea but rather in the English Channel. To assess some capacity in France, the scenario assumes 1000 MW of offshore wind power near Calais and Dunkirk.

germany

The database of Douglas Westwood for Germany lists offshore projects with a total capacity of 61.8 GW. Since this exceeds by far any official scenario, a selection is made by comparison with information available from the German Energy Agency (Dena) and the German Federal Maritime and Hydrographical Agency (BSH) [27]. The resulting list contains projects with a total capacity of 26417 MW, which is in line with the TradeWind high scenario for 2030.

great britain

In December 2007, the British Department for Business Enterprise & Regulatory Reform (BERR) announced a proposal to open up its seas to up to 33 GW of offshore wind power by 2020. In addition to the currently realized and planned projects of Round 1 and Round 2 (about 10 GW of which 7.24 GW in the North Sea), there will be a Round 3 phase with projects totalling up to 23 GW. Leaving out of discussion how and when this will be possible, the presented scenario assumes for the North Sea 22238 MW of offshore wind capacity. Besides the known Round 1 and Round 2 projects this includes 15 locations of 1000 MW each for 2/3 of the projected Round 3 capacity. Based on graphs of water depth and wind speed on the British continental shelf [28][29], most of these locations are placed on the Dogger Bank. Opinion of the British Wind Energy Association (BWEA) has been taken into account in the approximate locating of the (not yet identified nor decided) Round 3 projects.

the netherlands

The scenario for the Netherlands is based on the DW database, on the list of current initiatives available from the Ministry of Public Works and Water Management (Rijkwaterstaat) [30] and on a study of the Dutch Ministry of Economic Affairs [31]. The official target in the Netherlands is to develop 6 GW of offshore wind by 2020. Given the very high potential and the fact that in the present study no time frame is indicated, the scenario assumes an installed capacity of 12039 MW. The selection of projects has been made based on wind farm clusters [31] and with further advice from experts in the Netherlands. Care has been taken to avoid geographical overlap of different initiatives.

norway

The Norwegian scenario is based on input from TradeWind, provided by SINTEF Energy Research. In the North Sea, SINTEF Energy Research distinguishes two potential projects with an estimated total potential of 1290 MW. Since this scenario considers only the North Sea, the potential in the large wind resources further north along the Norwegian Atlantic coast is not taken into account.

image CONSTRUCTION OF OFFSHORE WIND TURBINES.

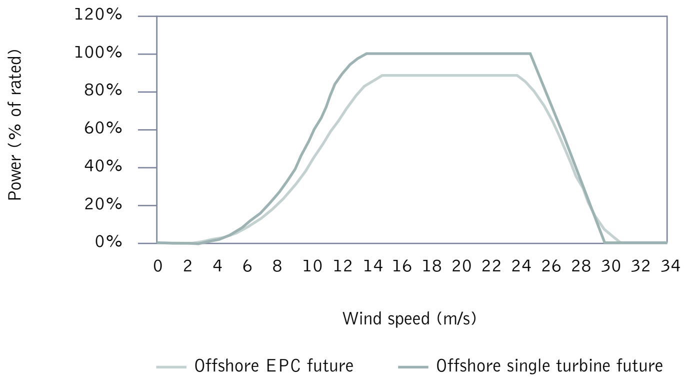
© DAVISON/GREENPEACE

3.2 time series or wind speed and power

For the wind farm locations defined in section 3.1, hourly time series of historical wind speed and power have been calculated for a period of three years (2004-2006). The wind speed time series are based on 6-hourly global analysis data (Final Analysis, FNL) from the United States' National Center for Environmental Prediction (NCEP). The calculations are done with the Weather Research and Forecasting Model (WRF [32]), which is a mesoscale numerical weather prediction model with the ability to simulate the atmospheric conditions over a wide range of horizontal resolutions from 100 km to 1 km. These simulations are used to downscale dynamically the FNL data from six-hourly resolution on a grid[2] of 1° by 1° to hourly data on a 9x9 km² grid. The model has been validated with wind speed measurements at different hub heights from the German offshore platform FINO-1 [33][34]. In the present study the wind speed time series are calculated for a hub height of 90m.

The next step comprises the conversion of wind speed to wind power. This depends on the wind turbine characteristics represented by the power curve. A power curve is always given for a single wind turbine. In order to model large wind farms distributed over a region, an aggregated power curve is needed. In the present study an equivalent wind power curve (EPC) is used that was developed by the company Garrad Hassan for the TradeWind project [35]. In this power curve, array losses in large offshore wind farms are taken into account as they are caused by wake effects. The equivalent power curve also accounts for 3% of electrical losses. In addition, an availability of 92% is assumed. Finally, the applied equivalent power curves anticipate possible future improvements in wind turbine efficiency and increased hub hights. Figure 5 shows a comparison of a possible future single wind turbine power curve with the equivalent power curve used. Due to the losses that are taken into consideration, a wind farm in the model can generate at best 89% of its installed capacity.

figure 5: power curve – conversion of wind speed into power (EPC VS. SINGLE TURBINE)



---

footnote

[2] IN GEOGRAPHICAL COORDINATES, 1° CORRESPONDS APPROXIMATELY TO 250-300 KM.

offshore grids for wind power integration

"BY EXTENDING THE HVDC GRID CONNECTIONS OF OFFSHORE WIND FARMS TO OTHER POWER MARKET REGIONS, WIND POWER CAN OFFER TRANSMISSION CAPACITY FOR COMMERCIAL USE AT MUCH LOWER INVESTMENT COSTS THAN FOR A SINGLE INTERCONNECTOR WHILE PROVIDING SIMILAR BENEFITS TO THE MARKET."

4

© COURTESY OF ABB

image SUBMARINE CABLE BEING CONNECTED TO A WINDFARM.

4.1 existing offshore grid concepts

The proposal in this study is not the first concept of an offshore grid. While Watson [36] looks at a limited grid in the Irish Sea, Airtricity [37][38], Czisch [39] and DLR [40] envision more ambitious trans-European meta grids. A vision on meshed offshore transmission infrastructure that would integrate offshore wind power and oil and gas extraction platforms has been proposed by the Norwegian TSO Statnett [41].

The Irish wind energy project developer Airtricity proposes an offshore meta grid structure to collect energy from offshore wind farms, making use of high wind resources and spatial smoothing. Czisch has taken this a step further and developed a vision of an HVDC overlay grid connecting Northern Africa, Europe and the Middle East, to transfer solar and wind energy towards Europe. In [40], DLR develops a similar scenario with a focus on the transfer of solar electricity from the sunbelt regions towards Europe. The grids of Czisch and DLR are largely land-based.

Currently, TradeWind is developing an EU-wide power flow scenario including various offshore grid configurations. Activities on transmission infrastructure within the European Commission including a review of possible offshore grid topologies are also coordinated by the European co-ordinator for the connection of offshore wind farms in Northern Europe.

4.2 technology

high-voltage AC and DC power transmission

All offshore wind farms in operation today are connected to the onshore power system with high-voltage AC (HVAC) transmission cables. Due to the high capacitance of shielded power cables, the length of such AC cables for practical use is technically limited by the required charge current of the cable. Therefore the length of undersea AC cables is limited. This problem can be overcome by using high-voltage DC (HVDC) cables, as they require no reactive power. The HVDC technology can be used to transmit electricity over long distances or to interconnect different power systems whose grid frequencies are not synchronized. In Germany, HVDC technology will be used for connecting the offshore wind farms in the German Bight to the onshore transmission grid.

classical HVDC and HVDC with voltage source converters

Two types of HVDC transmission systems exist: classical HVDC and HVDC with voltage source converters (VSC). This section briefly explains the differences between these technologies and shows how they affect wind energy development. A more into-depth analysis in relation to wind energy can be found in [3]. Classical HVDC is based on line commutated converters (LCC) using thyristors as the switching

image SUBMARINE CABLE WITH OPTICAL FIBRE.


© COURTESY OF ABB

element. The technology has been used for bulk power transmission for many decades, e.g., for the interconnector between Great Britain and France. However, classical HVDC can only transfer power between two operating power systems with a stable grid voltage. For offshore wind farms, an auxiliary start-up system would be necessary to provide the reference voltage and enable the operation of the LCC [42]. Moreover, converter stations for classical HVDC transmission are large and expensive. Therefore, this technology is not used for connecting to offshore wind farms, gas or oil extracting platforms [43].

HVDC transmission based on voltage source converters (VSCs) is a relatively new technology, since it was developed after the evolution of Insulated Gate Bipolar Transistors (IGBTs) [44]. Today two manufacturers offer these systems, ABB (HVDC light) and Siemens (HVDC plus). In spite of having high energy losses (4÷5 %), HVDC VSC has some significant advantages compared to classical HVDC [43][44], which make this technology favourable for offshore wind farms that are far from shore. HVDC VSC represents a major breakthrough for multi-terminal configurations and thus plug-and-operate offshore grids, which will have important implications for offshore wind energy. In addition, the required VSC stations are more compact than conventional converter stations. Today, HVDC VSC systems are offered for up to 1200 MW and ±320 kV [45].

Figure 6 illustrates a simple HVDC connection for a wind farm to the onshore grid, while Figure 7 gives an indication of how the equipment on an offshore VSC station could look like.

figure 6: connection of an offshore wind farm to the mainland grid via an HVDC transmission line

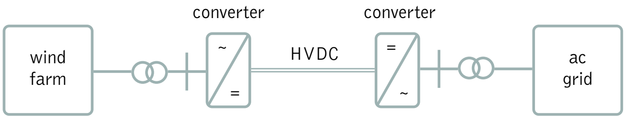
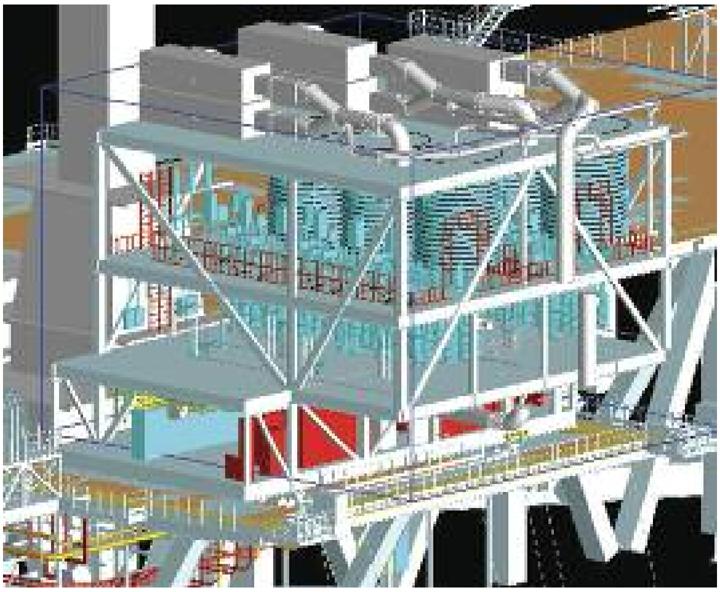


figure 7: artificial view of the HVDC light equipment on the troll offshore platform (BY COURTESY OF ABB)

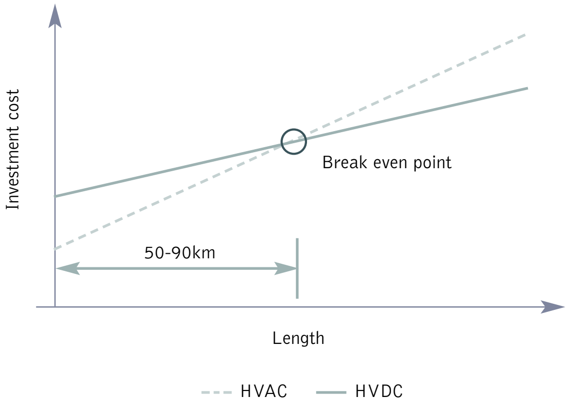


cost consideration

The cost of an HVDC transmission system depends on many factors like power capacity to be transmitted, voltage levels, technical concept, construction and environmental conditions.

Compared to HVAC technology, HVDC technology requires static inverters at both sending and receiving stations. They are expensive and have limited overload capacity. With short transmission distances the losses in the static inverters may be higher than in an AC transmission line. The cost of the inverters may not be offset by reductions in line construction cost and lower line losses. This leads to a break-even point for the choice between an AC and a DC cable. HVAC cable systems are favourable for transmission distance up to 50 - 90 km (Figure 8).

figure 8: break-even point of AC and HVDC VSC systems happens at some distance



To estimate quickly the investment cost of an HVDC system, some appropriate equations are found in the literature.

The cost of an HVDC VSC system mainly consists of the investment costs and installation costs of two components: the inverter station and the cable pair[3]. The costs can be estimated as [44]:

- The investment cost and installation costs of a converter station: The price of a converter station for HVDC VSC technology (including valves, transformers, filters etc) is about 0.11 M€/MW.
- The investment cost of the cable pair: Table 3 shows the specific cost (cost per km) of three types of cable pairs with a rated capacity of respectively 220, 350 and 500 MW at a rated voltage of 150 kV.

table 3: cost per cable pair with rated capacity

Cable Rated power (MW)	220	350	500
Cost per cable pair (M€/km)	0.30377	0.4453	0.6086

---

footnote

[3] THE HVDC VSC TECHNOLOGY IS A BIPOLAR TRANSMISSION TECHNOLOGY. THIS MEANS, IT MAKES USE OF A PAIR OF CONDUCTORS, IN OPPOSITE POLARITY. HENCE, FOR A SINGLE TRANSMISSION LINE, A PAIR OF CABLES IS NEEDED.

These values are calculated using the following formula of the specific investment cost of the cable per km proposed by Lundberg (also for 150 kV cables) [44][46]:

$C = 1.0887\ P + 64.26 \qquad (1000\ €/\text{km}),(2)$

where P is the rated power of the system in MW.

Until summer 2008, no HVDC VSC line with more than 500 MW has been completed. Therefore, actual prices for capacities of up to 1000 MW are not available.

- The installation costs of the cable pair: The cost for installing each cable is set to 100,000 €/km. The assumption is made that only one cable can be installed at a time thus for the cable pair the installation cost is set to 200,000 €/km.

The total investment cost of an HVDC VSC system can thus be calculated as:

Total cost$_{\text{HVDC VSC}}$ = 2 stations * Converter Station Cost + Length of cable * (Cost cable pair + Installation Cost)

example: To connect 1000 MW of offshore wind power with a distance to the onshore substation of 100 km at a voltage 150 kV, two pairs of 500 MW cables are used (Table 3). The total investment cost of the transmission can be then approximated as:

Total cost = 2 stations * 1000 MW * 0.11 M€/MW + 100 km * 2 pairs * (0.6086 + 0.2) M€/km

= 381.72 M€

It is important to note that this number only provides the investment cost. To make a full economical analysis of a high-voltage interconnector, other information must be taken into consideration like operation and maintenance costs, energy losses, etc.

The final decision on whether to choose HVAC or HVDC systems depends mainly on the distance to the nearest onshore station and on the desired transfer capacity. However, for the development of an offshore grid, HVDC VSC systems are the most favourable option: they create possibilities for multi-terminal configurations, and are compact and economically competitive.

4.3 drivers for offshore grid development

policy drivers

Two policy drivers for the development of an offshore grid can be distinguished:

- *Connectivity between countries and electricity market regions* Interconnector capacity between the different countries in Europe allows for international support actions in case of unforeseen grid faults (contingencies) and black-outs. Moreover, interconnector capacity between the different market regions in Europe enables market access among regions, resulting in liquidity and a lower consumer price through adequate competition. Historically, submarine transmission lines have been installed in order to interconnect the electrical system of continental Europe with Scandinavia and the British Isles. Today, onshore grid reinforcement often is difficult or impossible due to environmental concerns or matters of right of way. Offshore transmission can provide an alternative to a lengthy permit and planning procedure required for onshore reinforcement.
- *An economically efficient connection of offshore wind farms* When offshore wind farms are installed far from shore, they need to be connected to shore by means of high-voltage DC lines. In this case, it is economically most efficient to cluster the wind farms in an area and connect them to shore via a bundle of HVDC lines. By connecting offshore converter stations to a second shore or to another converter station, additional interconnector capacity between the countries is created at much lower cost than that of a dedicated interconnector from coast to coast. The unused capacity of the interconnector is then available for trade. The combination of offshore power generation and interconnection allows dispatching power to areas of high demand and price. In addition, the overall utilization time of the wind farm grid connection is increased.

The topology of an offshore grid will result from these drivers and will therefore heavily depend on the relative importance assigned to each in political and economic decision making. When looking at the existing concepts for offshore and trans- or intercontinental overlay grids, all aspects of the above policy drivers are mentioned; however, some of them with more or less weight. Before unfolding the offshore grid topology proposal in the next section, the weight of the different drivers today and in the future is briefly discussed.

current priorities

Today, the installed capacity of most offshore wind farms is still lower than the potential economic capacity of typical HVDC interconnector cables and converter stations. Also, distances to shore are still relatively short. Offshore converter stations for wind power have not yet been built.

A number of new submarine interconnectors are in the planning or completion stage. The development of these lines is driven by the need for connectivity. Plugging in offshore wind power has in part been discussed, but rather as an add-on. Consequently, these projects use, or will use, classical HVDC technology where no wind farms can be connected along the way.

At the same time, the development of HVDC VSC systems for the grid connection of offshore wind farms is just beginning. Currently, the first HVDC connection for offshore wind energy is being developed: in 2009 the NordE.ON 1 cable will connect the wind farm Bard Offshore 1 in the German Bight to the German transmission system. The length of this connection will be 203 km of which 75 km onshore underground and 128 km at sea [45]. Most other wind farms in the German Bight will be clustered at HVDC converter stations at sea and then connected to shore via HVDC VSC as well.

future priorities

Long-term scenarios (2020 to 2030) for offshore wind power in the North Sea envision a total of 40 to 100 GW of installed generation capacity, without taking into account other marine power generation. These wind farms will have to be connected to the onshore transmission grid. Wind farms close to shore will then still be connected via high-voltage AC cables. However, all wind farms that are more than 50 to 90 km away from shore will use an HVDC connection. This will be the case for the assumed 15 GW of the British Round 3 projects situated mainly on the Dogger Bank and also for most of the 26.4 GW in the German Bight. Consequently, HVDC lines and offshore converter

image SUBMARINE CABLES BEING LAYED OUT IN THE NORTH SEA, BELGIUM.

stations with the same total capacity will be installed in the German Bight and off the east coast of Britain. If the price of HVDC VSC technology decreases, also the larger of the envisioned Belgian, Dutch and Norwegian wind farms may be connected by HVDC.

At the same time, the need for connectivity between countries will increase. It will be driven by the demand for flexibility in the national power systems, which generate opportunities for arbitrage between power market regions. There will be an economic case for the commercial exploitation of interconnectors as long as there is opportunity for arbitrage.

In this future situation, priorities will have changed. Unlike today, offshore wind power will then be the main driving force for the development of subsea cables and offshore converter stations for HVDC. The total installed capacities of offshore HVDC stations in some countries will be 10 to 30 GW, equal to the capacity needed to transport the wind power to shore. For example, the 15 GW envisioned for the Dogger Bank and also most of the 26.4 GW envisioned for the German Bight will be connected by HVDC. In practice, different offshore converter stations may be constructed close to the different clusters of wind farms. The corresponding onshore converter stations may be situated at different connection points to the onshore transmission grid. Nevertheless, the total installed capacity of converter stations for each shore and exclusive economic zone (EEZ) will equal the installed wind power capacity. Consequently, by then, the required capacities for the connection of offshore wind farms are 5 to 10 times as high as the typical capacity of an interconnector only used for trade.

The required converter stations will be on the open North Sea and, with an additional investment, they can be connected to each other or to another shore. This would allow the allocation of the spare capacity of the line to the power market, while it is not used by wind power. For trade, the possibility to make use of an extended wind farm grid connection is a cheaper alternative to the development of separate cables [38]. Since the prolongation of lines from offshore wind farm converter stations is economically beneficial as long as there is opportunity for arbitrage, an offshore grid will probably emerge in such a way.

Moreover, such interconnectors can improve the load duration, i.e., the utilization of the wind farm cabling over the year. In order to foster such a scheme, wind power would need priority dispatch on the interconnector. The interconnector would then more than 60% of the time be available for import to the EEZ country in which the substation is situated. For export it would be available 100% of the time.[4]

Hence, in the future, offshore wind power development may surpass the demand for trade as the main driver for the development of an offshore grid. Grid infrastructures for offshore wind power will then be offered to the power market. For this purpose, the wind farm grid connection would be extended from the offshore wind farm converter station to another converter station or to shore. The power market can then make use of spare capacity as a substitute for a separate interconnector for trade.

4.4 offshore grid proposal

offshore wind clusters and connection

The possible nodes of an offshore transmission grid can be determined by spatially clustering the envisioned wind farms and assigning one node to each cluster. This will result in from one up to a few offshore wind clusters per country. In physical terms these clusters are like offshore distribution grids, collecting power from the wind farms within the cluster and transforming it into high voltage for transmission[5].

If offshore wind clusters are not too far from the mainland, they are connected to shore with an AC transmission line of sufficient capacity for their rated power. They are then assumed to be connected to the nearest onshore node within the country, i.e., the end point of an offshore interconnector (see Figure 9).

Offshore wind farms on the open North Sea may be connected to shore via an HVDC converter station at sea (Figure 10)[6]. This is the case for the most ambitious projects anticipated for the long term (British Round 3 projects on the Dogger Bank and farshore in the Greater Wash, most projects in the German Bight).

figure 9: connection of offshore wind farm cluster to shore for short distances (AC)

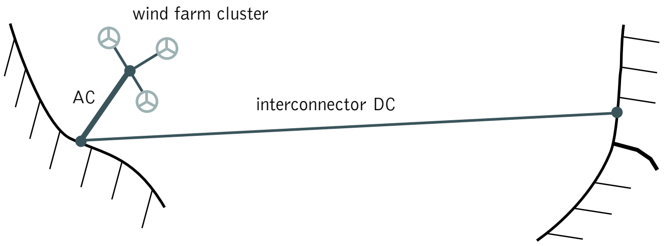
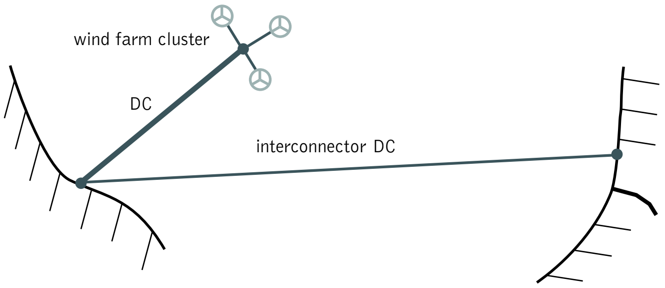


figure 10: connection of offhore wind farm cluster far from shore (DC)



---

footnotes

[4] AS DESCRIBED ABOVE, THE TRANSMISSION CAPACITY FROM THE CABLES FROM THE SUBSTATION TO THE SHORE WILL BE SIGNIFICANTLY HIGHER THAN THE CAPACITY OF THE INTERCONNECTOR FROM THE SUBSTATION TO THE OTHER COUNTRY. A WIND POWER CAPACITY FACTOR OF AROUND 40% MEANS THAT ON AVERAGE ONLY 40% OF THE CABLE CAPACITY IS USED OVER THE YEAR. MOREOVER, THE LOAD DURATION CURVES IN PARAGRAPH 5.3 SHOW THAT FULL POWER IS SELDOM REACHED, SO THAT MOST OF THE TIME THE CABLES FROM THE SUBSTATION TO THE SHORE WILL HAVE SPARE CAPACITY EQUAL TO OR LARGER THAN THE INTERCONNECTOR CAPACITY. THIS CAPACITY WILL BE AVAILABLE FOR TRADING. FROM THIS REASONING, IT FOLLOWS THAT IMPORT OF POWER WILL BE POSSIBLE MORE THAN 60% OF THE TIME, AND EXPORT WILL BE POSSIBLE AT ALL TIMES (IF THE INTERCONNECTOR IS CONNECTED DIRECTLY TO AN ONSHORE SUBSTATION IN THE OTHER INTERCONNECTED COUNTRY. IF IT IS CONNECTED TO ANOTHER OFFSHORE SUBSTATION, THIS WILL BE DIFFERENT.)

[5] THE OFFSHORE WIND CLUSTERS ARE NOT INDICATED ON THE MAP IN FIGURE 11.

[6] THE OFFSHORE WIND CLUSTER IS THEN ASSIGNED TO AN OFFSHORE TRANSMISSION GRID NODE (OFFSHORE SUBSTATION). FOR REASONS OF SIMPLICITY THE MAP IN FIGURE 11 ONLY SHOWS THREE OFFSHORE SUBSTATIONS.

offshore transmission lines

For interconnecting different countries with offshore transmission lines, different configurations are possible:

- The interconnector is drawn between two onshore substations (Figure 11). This is the configuration of all interconnectors currently in operation or in planning (eg. NorNed from Norway to the Netherlands, Skagerrak interconnectors from Norway to Denmark).
- When two countries have an offshore converter station far from shore, it may be convenient to link these stations with an interconnector (Figure 12). This way, the length of the extra interconnector cable can sometimes be limited. Moreover, the load duration of the cables transmitting the wind power from each substation to the shore can be greatly improved.
- In some cases, connecting an offshore wind farm cluster to two different countries can be economically more efficient than a single connection to the EEZ country in which the offshore wind farm cluster is located. The grid connection can then be used as an interconnector at the same time, while the investment cost remains similar (Figure 13).

The locations of the projected offshore transmission lines in the present study are based on several sources (mainly information and projects of the national TSO's, a recent study from Econnect (UK) [29], the Dutch study "Connect 6000MW" [31], the German Dena grid study [47] and the "Nordic Grid Master Plan 2008" [48][7]). A number of these projects (interconnectors) are currently either:

- in operation or planning (e.g. UK-France, NorNed, BritNed) or
- proposed or discussed in the public domain (possible, e.g. UK-Norway).

It is assumed that projects in operation or planning are available for trade; however, without the possibility of offshore plug-in for wind farms. This means that their end points on shore will form nodes of the offshore grid.

For interconnectors being in the feasibility or earlier phase, it is assumed that they will be integrated with the grid connections of offshore wind farms.

figure 11: interconnector between onshore substations

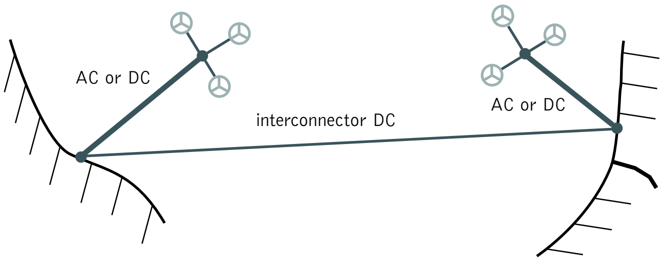


figure 12: interconnector drawn between two offshore converter stations

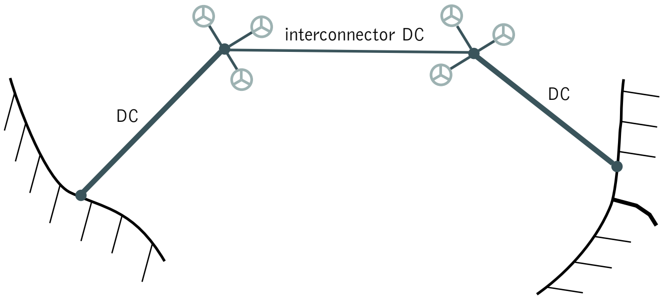
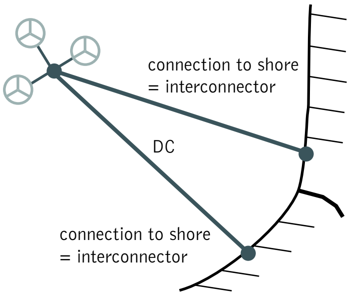


figure 13: split connection to shore with interconnector created at the same time



---

footnote

[7] PRECISE SITING AND CAPACITY ALLOCATION OF OFFSHORE CABLES IS NOT THE INTENTION OF THIS STUDY.

image SUBMARINE CABLES BEING LAYED OUT IN THE NORTH SEA, BELGIUM.


© C-POWER

other offshore power generators and loads

Other marine power generation technologies like tidal stream turbines and wave power generators will probably be installed at locations away from offshore wind power. Furthermore, the oil and gas industry considers the supply of offshore platforms with power from shore as a substitute for in-situ electricity generation with oil and gas.

These potential developments will lead to additional sites of generation and load in the North Sea and, consequently, to additional nodes of an offshore grid, being situated more towards the central and northern part of the North Sea. The final design of a future offshore grid could then differ from the proposal in Figure 14. Nevertheless, the rationale for the selection of sites as offshore nodes with a possible double use for grid connection and trade would remain the same.

For the present offshore grid proposal, these potential developments have not been taken into account any further.

resulting offshore grid proposal

The resulting topology (Figure 14) shows the completed and planned interconnectors. Also, possible transmission lines are drawn, as proposed in [29] and [48]. Furthermore, an interconnector is assumed along the coast of continental Europe from the North of France to the German Bight. This would be connected to the transmission system of the different countries along the track. Another interconnector is assumed between the Shetland Islands and Norway as suggested in [29], being available for trade and to balance wind and possible marine technologies with hydro power from Norway. All these interconnectors are direct lines between two onshore substations as shown in Figure 8.

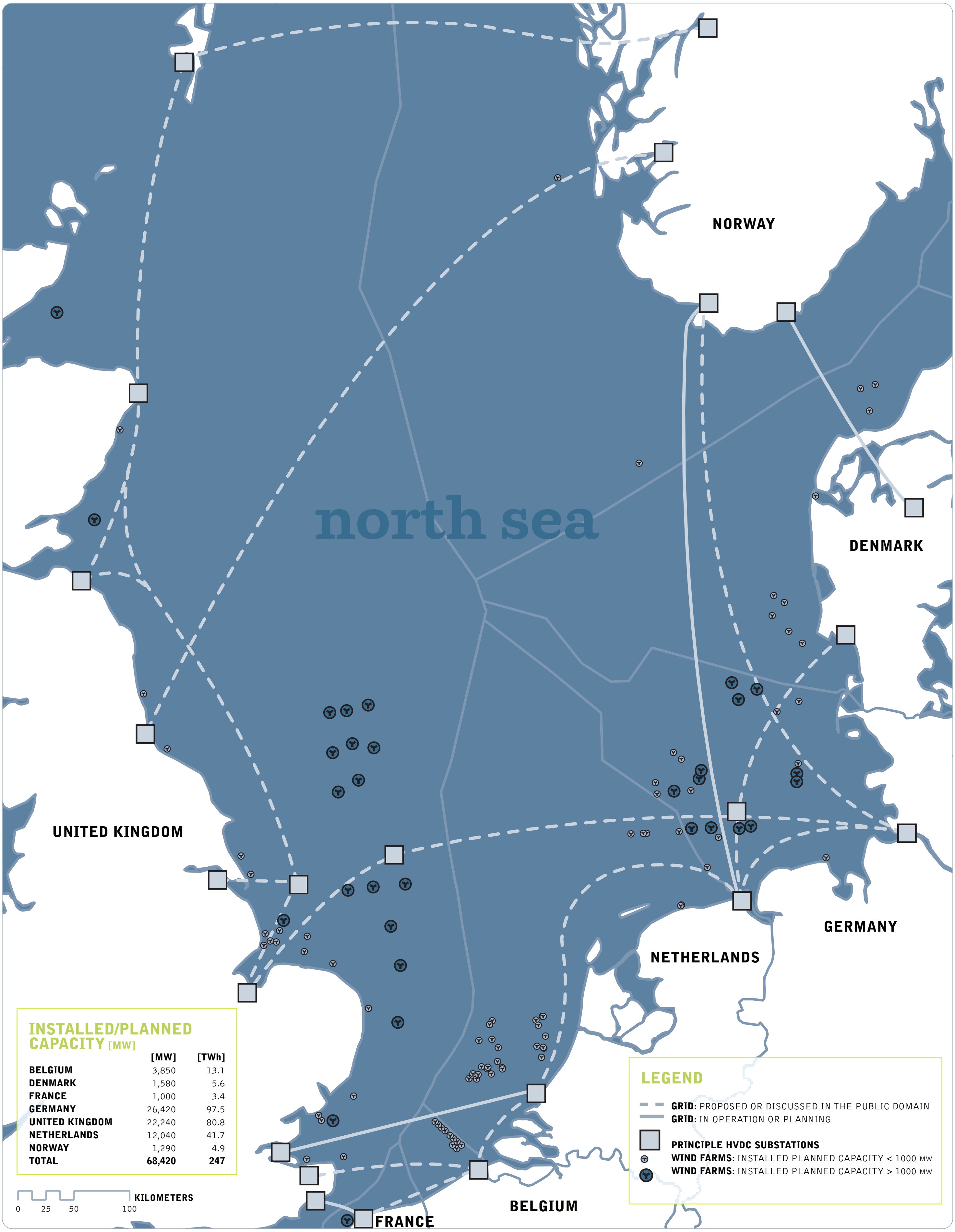
Three offshore substations are drawn: one to avoid excessive cabling in an environmental sensitive and busy shipping lane area (Humber Estuary, see [29]), one to collect the Round 3 wind energy (both based on Econnect [29]), and one for the German farshore wind farms. Moreover, an interconnector is assumed as an extension of the Round 3 transmission line to the German offshore substation. Another interconnector is drawn between the Netherlands and Denmark. This is based on [48], but with a plug-in at the German offshore substation. This connection will enable international trade and will in this way provide great improvements to the load duration of the cables. These interconnectors are configured as in Figure 12 and in Figure 13.

The offshore grid topology proposed in this study is shown in Figure 14. It shows the offshore wind power scenario and the projected transmission system. It is important to note that all of the transmission lines in Figure 14 can represent more than one cable of 500 to 1000 MW, each. Moreover, the study does not describe concrete ways of implementation like precise offshore siting, cable capacities or precise onshore connection points. For most wind farm sites and cable routes no environmental impact assessments have been carried out yet. This would be part of a step-wise development undertaken by public bodies, technology providers, developers, transmission system operators and regulators.

To form an idea of the cost of this offshore grid topology, an estimate has been calculated for the whole offshore grid based on the figures from Table 3. All lines together as shown in Figure 14 have a total single line length of 6200 km. Assuming that, in an initial phase, all transmission lines have a capacity of 1 GW, each line on the map would represent two cable pairs of 500 MW capacity, each, that is, four cables. The total cost of the system would then be of the order of magnitude of 15-20 billion Euros. This amount would be needed to develop the proposed offshore grid from scratch with 1 GW capacity for each line, as it may be useful for the purpose of trade only. For increasing transmission capacities, i.e., increasing number of cables and size of voltage source converters, costs increase at a slightly less than linear rate.

For comparison, the overall investment for the NorNed project, a classical HVDC cable connecting Norway and the Netherlands with a capacity of 700 MW, was 600 million Euros [49]. During its first two months of operation, this interconnector has generated revenues of 50 million Euros, which is more than 800,000 Euros per day [50]. By extending the HVDC grid connections of offshore wind farms to other power market regions, wind power can offer transmission capacity for commercial use at much lower investment costs than for a single interconnector while providing similar benefits to the market.

figure 14: offshore grid topology proposal and offshore wind power installed capacity scenario



INSTALLED/PLANNED CAPACITY [MW]

	[MW]	[TWh]
BELGIUM	3,850	13.1
DENMARK	1,580	5.6
FRANCE	1,000	3.4
GERMANY	26,420	97.5
UNITED KINGDOM	22,240	80.8
NETHERLANDS	12,040	41.7
NORWAY	1,290	4.9
TOTAL	**68,420**	**247**

* MAP IS INDICATIVE. NO ENVIRONMENTAL IMPACT ASSESSMENT OF LOCATIONS AND SITING OF WINDFARMS AND CABLES HAS BEEN DONE.

Wind energy is booming in the EU. In 2007 alone, no less than 8550MW of wind turbines were installed in the EU, which is 40% of all newly-installed capacity. By 2020–2030, offshore wind energy in the North Sea could grow to 68,000MW and supply 13 per cent of all current electricity production of seven North Sea countries. In order to integrate the electricity from the offshore wind farms, an offshore grid will be required. Greenpeace demands that the governments of these seven countries and the European Commission cooperate to make this happen.

results and analysis

"THE HOURLY VARIATION OF A SINGLE WIND FARM'S POWER GENERATION CAN BE SMOOTHED OUT BY COMBINING THE OUTPUT OF WIND FARMS THAT ARE DISTRIBUTED OVER THE NORTH SEA"

5


© COURTESY OF ABB

image LAYING SUBMARINE CABLE

5.1 offshore power generation

Over the year, the installed offshore wind power capacity of 68.4 GW would generate 247 TWh of electricity. The estimated annual offshore wind electricity generation per country is shown in Table 4, alongside the total electricity consumption in 2006 for comparison. The capacity factor in Table 3 represents the fraction of time during which the installed wind farms would have generated the same amount of energy when always running at full power. The total aggregated capacity factor of the offshore wind power scenario in the present study is equal to 41.2%. For comparison: the aggregated capacity factor of the present installed wind power capacity in Europe (of which the major part is onshore) is 23%.

table 4: **electricity production and associated capacity factors for offshore wind power and electricity consumption** (WIND POWER IN THE NORTH SEA ONLY, CONSUMPTION DATA FROM [51][52][53])

COUNTRY	ELECTRICITY / YEAR [TWH]	AVERAGE CAPACITY FACTOR [%]	TOTAL ELECTRICITY CONSUMPTION 2006 [TWH]
Belgium	13.1	38.9	89.9
Denmark	5.6	40.5	36.4
France	3.4	38.8	478.4
Germany	97.5	42.1	559.0
Great Britain	80.8	41.5	405.8
Netherlands	41.7	39.6	116.2
Norway	4.9	43.7	122.6
Total	**247.0**	**41.2**	**1,808.3**

In the following sections, the characteristics of the wind power generation as a function of time are explored in depth. The presentation of the results focuses on Germany, Great Britain and Belgium. For the other countries the results are in principle similar (see Annex B).

The results presented for single wind farms are based on the tri-annual wind speed time series for the coordinates of the projects envisioned and the equivalent power curve in Figure 2. They do not take into account project-specific data of the envisioned projects. Therefore, the results presented do not precisely reflect the long-term energy yield of the projects but rather provide and estimate of availability and variability of power generation at the particular sites.

5.2 wind power output over time

Figure 15a) shows an exemplary power output profile for the coordinates of one of the envisioned large offshore wind farms in the German EEZ. The profile is representative for offshore wind farms experiencing periods of very low and very high wind speeds within a few days. They reflect the passage of meteorological pressure systems with their associated fronts usually taking a few hours to several days.

When adding up all power generation in the German part of the North Sea, i.e., the German Bight, the picture remains largely the same, although, somewhat smoother than for a single wind farm (Figure 15b). In contrast, the accumulated power generation of all North Sea wind farms in the same period varies slowly between 30 and 45 GW (Figure 15c).

Compared to the German wind farms, the British wind farms are distributed over several regions off the east coast and they cover a wider geographic spread (see Figure 14). Consequently, and in contrast to the German case, the accumulated output of these wind farms is much smoother than that of a single wind farm (Figure 16).

For Belgium (Figure 17), due to the small area of the zone designated for offshore wind energy, there is still less spatial smoothing than over the German Bight. The accumulated power output profile of all wind farms in the Belgian EEZ is close to that of a single wind farm; however, over time both are complementary to offshore wind power generation in the German Bight.

The figures below are exemplary, randomly chosen from the data set for a two-day period. They show how the hourly variation of a single wind farm's power generation can be smoothed out by combining the output of wind farms that are distributed over the North Sea. However, regarding availability and variability of wind power, they do not allow for general conclusions. For this purpose, in the following section the statistical properties of the time series of power generation are analyzed.

figure 15: power output of offshore wind power over two days FOR ONE WIND FARM, ALL WIND FARMS IN THE GERMAN BIGHT AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA

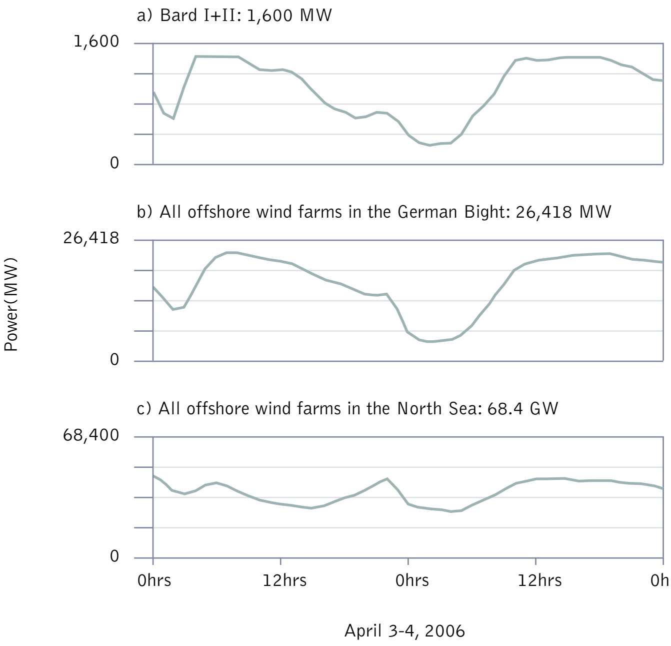


figure 16: power output of offshore wind power over two days FOR ONE WIND FARM, ALL WIND FARMS OFF THE BRITISH EAST COAST AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA

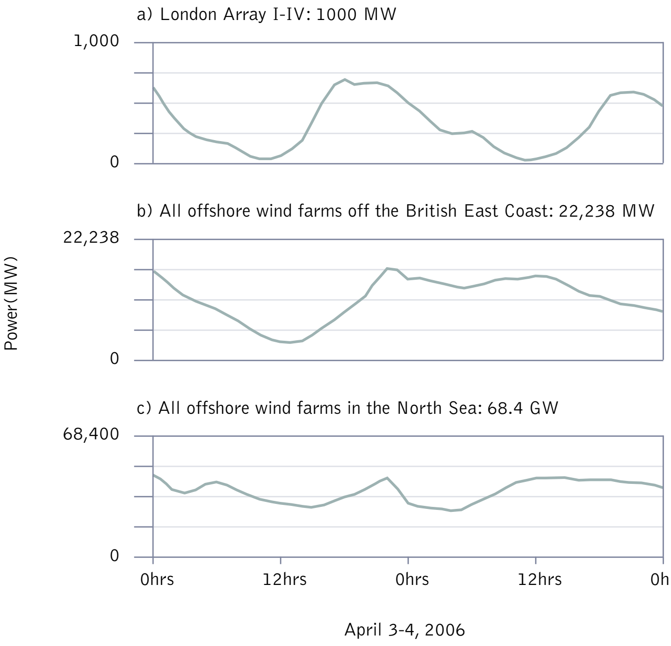
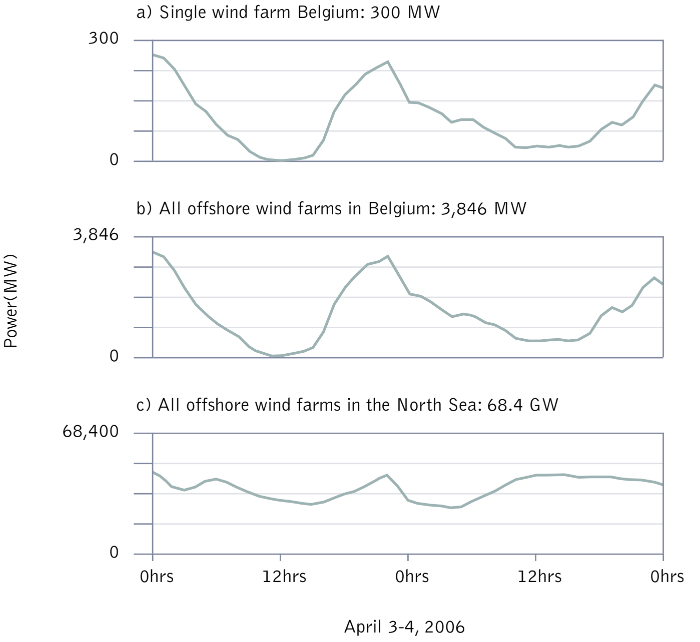


image OFFSHORE WINDFARM,
MIDDELGRUNDEN,
COPENHAGEN, DENMARK.

figure 17: power output of offshore wind power over two days FOR ONE WIND FARM, ALL WIND FARMS IN THE BELGIAN EEZ AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA



5.3 availability of wind power generation

load duration

The cumulative frequency distribution of the output power of a generator is described by its load duration curve. The load duration curve is derived from the annual time series by sorting the hourly power values in descending order. It shows during which fraction of the year's 8760 hours the power output was above a specified level.

The example for Germany (Figure 18) shows that

- the wind farm in the example runs at full power for 1120 hrs or 12.8% of the time;
- the wind farm generates more than 2% of its installed capacity over 8050 hrs or 91.9% of the time;
- the spatial distribution of wind farms over the region leads to a somewhat lower fraction of time with full power generation as compared to the single wind farm; however, the generation profiles over time of different wind farms in the German Bight would be largely similar to each other.

The load duration curve for the total installed capacity in the North Sea (Figure 18c) is shaped very differently. When adding up power generation over the whole North Sea

- full power is generated very rarely, namely, for approximately 30 hrs, which is less than half a percent of the time;
- the output is more than 2% of installed capacity or 1.37 GW over 99.7% of the time;
- for 80% of the time the power output is more than 15.5% of installed capacity.

For the wind farms in British waters (Figure 19), the load duration curves confirm the spatial smoothing effect that was already observed in the time series above. There is a clear reduction of hours with full power generation and of hours with no generation. More precisely, full power is available during approximately one percent of the time while more than 2% of installed capacity is available during 98% of the time.

Also the results for Belgium (Figure 20) confirm the effect suggested by the time series above. For a single wind farm, both full load and very low load each occur roughly 10% of the time. All wind farms in the Belgian EEZ together (Figure 20b) exhibit only little difference from the load duration of a single wind farm.

Unlike for low and high power generation, in the medium range of the duration curve, between 3000 and 6000 hrs, the shape for the entire North Sea is not fundamentally different from that of a single wind farm. In conclusion, the spatial spread of wind farms over the North Sea leads to a larger fraction of time during which medium level power is generated in exchange for a reduction of periods of full load. The fraction of time during which situations of full and no load occur is negligible.

exchange capacity from offshore interconnection

An offshore grid providing interconnector capacity between offshore wind farm clusters and onshore nodes in different countries is beneficial for the availability of offshore wind power. In a very simplified view, power from offshore wind farms can be aggregated and delivered to the country with the highest electricity price at any moment, via the offshore grid. In this view, the load duration curve for all aggregated wind farms in the North Sea (Figure 18c) reflects the ideal case of unconstrained transmission capacity.

However in practice, wind power generation is part of the generation mix within a portfolio of generation and demand. In this respect, interconnectors serve for import and export as one means of portfolio management. More precisely, they can introduce flexibility into a portfolio. The capacity available for power exchange between countries can be used to complement periods of electricity surplus or shortage within the national power system. The value of interconnector capacity is high when the interconnected power systems have a complementary generation mix and demand profile. This is largely the case with Norway compared to Great Britain and parts of continental Europe. In Norway large reservoir hydro power plants are available, with an installed hydro power capacity of 28 GW, an annual inflow of 136 TWh and a reservoir capacity equivalent to 82 TWh of electricity [54]. They can be ramped up and down very fast and complement the nuclear and coal power plants that are largely used in continental Europe and Great Britain. As a consequence of the time shift and of differences in industry and regional habits, the demand profiles of continental Europe, Great Britain and Scandinavia are also partly complementary.

The dashed horizontal lines in Figure 18b, Figure 19b and Figure 20b indicate the capacity margins that would be introduced with additional subsea cable links corresponding to the offshore grid in Figure 14. Assuming for each interconnector in Figure 14 a transmission capacity of 1 GW could very roughly reflect a first development stage of the offshore grid with, on average, one or two HVDC cable pairs for each interconnector[8]. In the long run, much higher capacities may be conceived as long as the market requires interconnector capacity for trade during a sufficiently high fraction of time (for discussion see Section 4.3 on Drivers for Offshore Grid Development).

For Germany and Belgium, 3 GW of offshore interconnector capacity is assumed. For the British east coast, 6000 MW is assumed. In Figure 18b) the capacity margin introduced by 3 GW of additional interconnector capacity is set in relation to the load duration curve of 26.4 GW of offshore wind power capacity in the German Bight. If required, this capacity is available to the market for levelling out power shortages as indicated in the figure but also for exporting surplus generation when prices are higher abroad.

Figure 19b) illustrates the same relationship for the wind farms and interconnectors at the British east coast where the assumed interconnector capacity could introduce additional flexibility for more than a quarter of the envisioned wind power capacity. In Belgium (Figure 20b), with the assumption of coastal interconnectors to the Netherlands and France, the available interconnector capacity at sea would be of the order of magnitude of the envisioned offshore wind power generation capacity.

figure 18: load duration curves of offshore wind power

FOR ONE WIND FARM, ALL WIND FARMS IN THE GERMAN BIGHT AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; DATA FOR 2004-2006

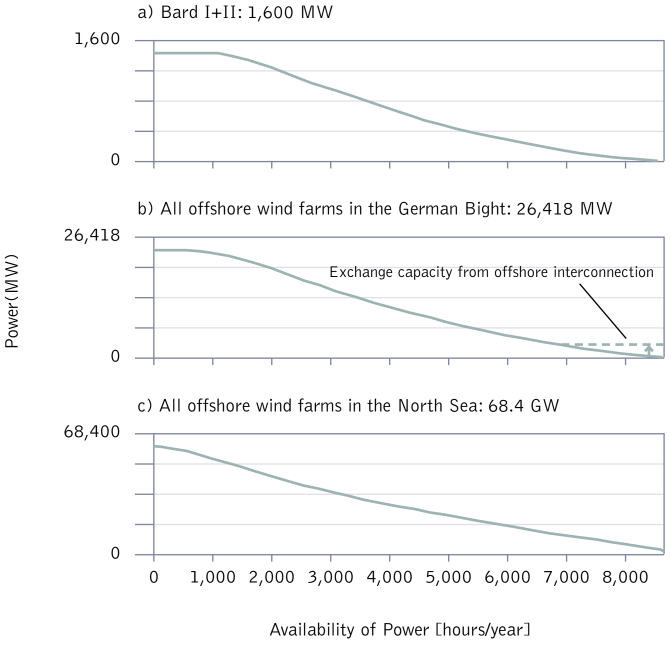


figure 19: load duration curves of offshore wind power

FOR ONE WIND FARM, ALL WIND FARMS OFF THE BRITISH EAST COAST AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; DATA FOR 2004-2006

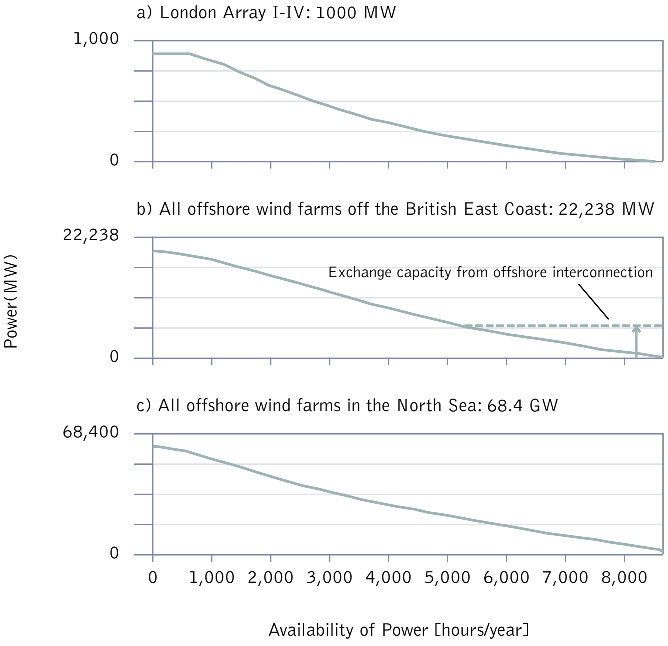
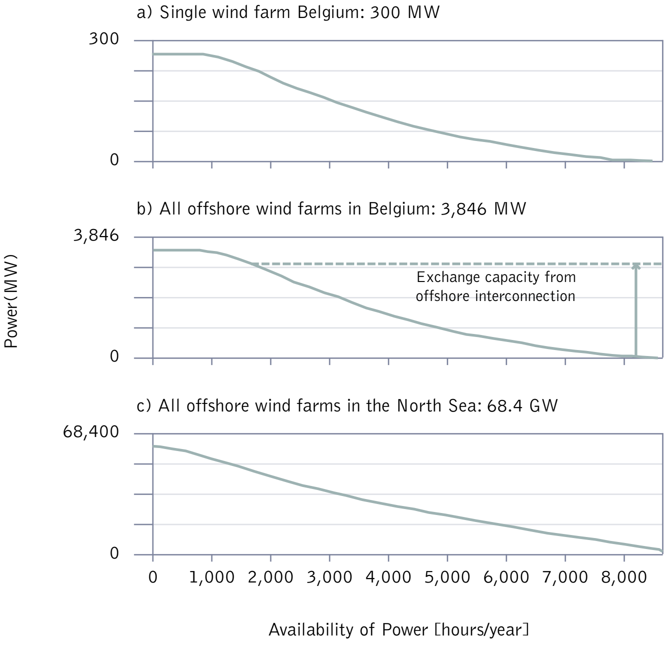


figure 20: load duration curves of offshore wind power

FOR ONE WIND FARM, ALL WIND FARMS IN THE BELGIAN EEZ AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; DATA FOR 2004-2006



footnote

8 IN PRACTICE, SOME OF THE EXISTING HVDC LINKS HAVE A HIGHER CAPACITY ALREADY, WHILE THE FIRST UPCOMING HVDC PROJECTS WITH VSC ARE BEING PLANNED FOR LESS THAN 1000 MW.

image WINDTURBINES AND ELECTRICITY CABLES.


© LANGROCK/ZENIT/GP

5.4 variability of wind power generation

Variability can be described by the power variation, that is, the difference of the generated power at two successive time steps. In order to assess the statistics of the power variations, time series of the variation between two time steps have been calculated. They can serve for the statistical analysis of wind power variations.

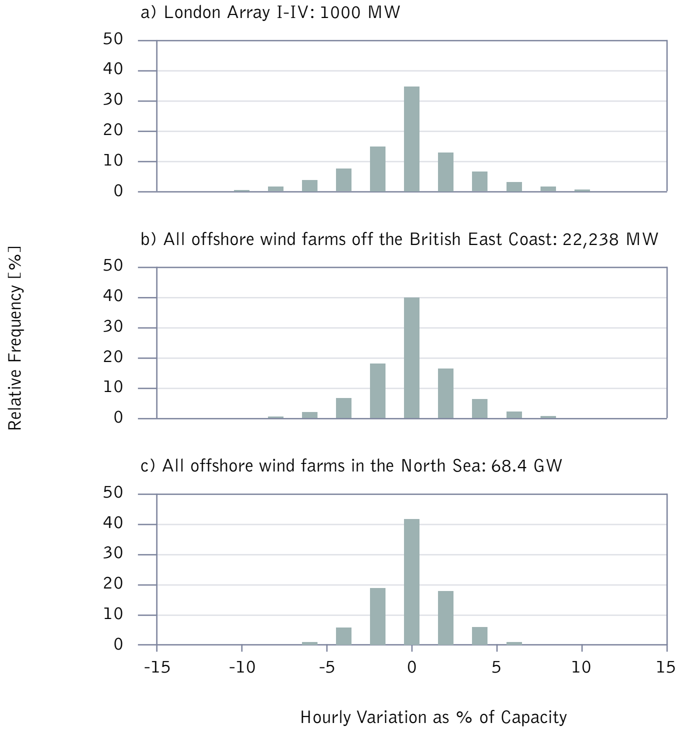
Figure 21 shows the distributions of relative frequency of hourly variations for the example of Great Britain. The figure illustrates that most power variations are small. Large variations occur rarely.

For a single wind farm, 35% of all hourly variations are less than ±1% of installed capacity (Figure 21a). For all wind farms off the British east coast together, this is the case for 40% of all hourly samples (Figure 21b). For the accumulated generation of all wind farms together in the North Sea, 42% of all hourly variations are of less than ±1% (Figure 21c). In all cases, more than 50% of all variations are less than ±2% of installed capacity.

Variations larger than ±5% occur for 20% of all hourly samples for the single wind farm. For all wind farms off the British east coast together they occur only 10% of the time and for the entire North Sea only 6% of the time. The occurrence of variations beyond ±10% appears to be negligible.

---

figure 21: **relative frequency of hourly variations in generation** FOR ONE WIND FARM, ALL WIND FARMS OFF THE BRITISH EAST COAST AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA



In the following paragraphs, the occurrence of larger variations and variations over a longer period is analyzed in greater depth by means of cumulative frequency distribution curves. They are derived in analogy with the creation of the load duration curves for power generation, by ordering the time series of the variation between two time steps in descending order. The resulting cumulative frequency curves show the probability of a power variation to be larger than the value on the ordinate. Different distributions have been drawn for different time lags. A positive power variation represents an increase in power and a negative one a decrease.

For the example of the German Bight, variations from hour to hour are rare but for longer time lags variations occur regularly. From Figure 22a), the following can be observed:

- the maximum hourly step sizes of a single wind farm are ±44% of installed capacity;
- approximately 8.6% of all hourly power variations exceed, in any direction, 10% of the installed capacity;
- for the 3-hourly variation this is 32% and for the 9-hourly one it is 54%;
- for much longer step sizes, the power variation becomes distributed at random.

For the sum of all wind farms in the German Bight (Figure 22b), the following can be observed:

- the maximum hourly step sizes are reduced to +28% and -37% of installed capacity;
- 3.4% of all hourly power variations exceed, in any direction, 10% of the installed capacity;
- for the 3-hourly variation this is 26.6% and for the 9-hourly one it is 55.1%;

In conclusion, by accumulating the power generation for the German Bight, the overall variability is clearly reduced for hourly time steps and to some extent for 3-hourly steps. For 9-hourly time steps little smoothing effect is visible in the German Bight.

For the accumulated generation of the wind farms off the British east coast, as for the German Bight, a smoothing effect is observed (Figure 23). However, for the British wind farms, being spread over a wider area, 3-hourly variation is reduced much more than for the German Bight and 9-hourly variation is reduced as well. For the accumulated generation off the British east coast:

- the maximum hourly step sizes are reduced to +26% and -22% of installed capacity;
- 1.1% of all hourly power variations exceed, in any direction, 10% of the installed capacity;
- for the 3-hourly variation this is 18.7% and for the 9-hourly one it is 49.5%.

The accumulated generation for the Belgian EEZ exhibits a distribution of variations comparable to that from the German Bight but with larger hourly variability due to the limited area of the designated zone for offshore wind power in Belgium (Figure 24b).

In contrast, the wind power generation for the whole North Sea is very smooth. From the distributions in Figure 24c), we can observe that:

- the maximum hourly step sizes are ±19% of installed capacity;
- only 0.43% of all hourly power variations exceed in any direction 10% of the installed capacity;
- for the 3-hourly variation this is 13.5% and for the 9-hourly one it is 44.8%;
- again, for longer step sizes, the power variation becomes distributed at random.

In order to summarize the overall statistics of power variations for the three countries, P5 and P95 percentiles are given in Annex C.

In conclusion, the characteristic period for which spatial decorrelation of wind speed can lead to a smooth generation profile depends strongly on the size of the area over which wind farms are distributed. In the German Bight, variability is clearly reduced for hourly time steps and fairly well for 3-hourly steps. For the wind farms off the British east coast, variability is clearly reduced for hourly and 3-hourly time steps. Very long variations occur at random in all regions.

figure 22: cumulative frequency of variations in hourly generation FOR ONE WIND FARM, ALL WIND FARMS IN THE GERMAN BIGHT AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; LEGEND: TIME LAG

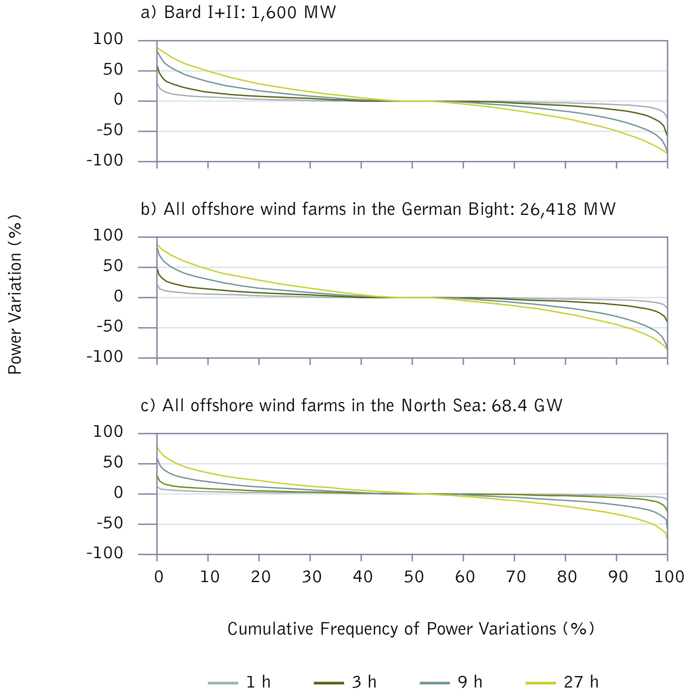


figure 23: cumulative frequency of variations in hourly generation FOR ONE WIND FARM, ALL WIND FARMS OFF THE BRITISH EAST COAST AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; LEGEND: TIME LAG

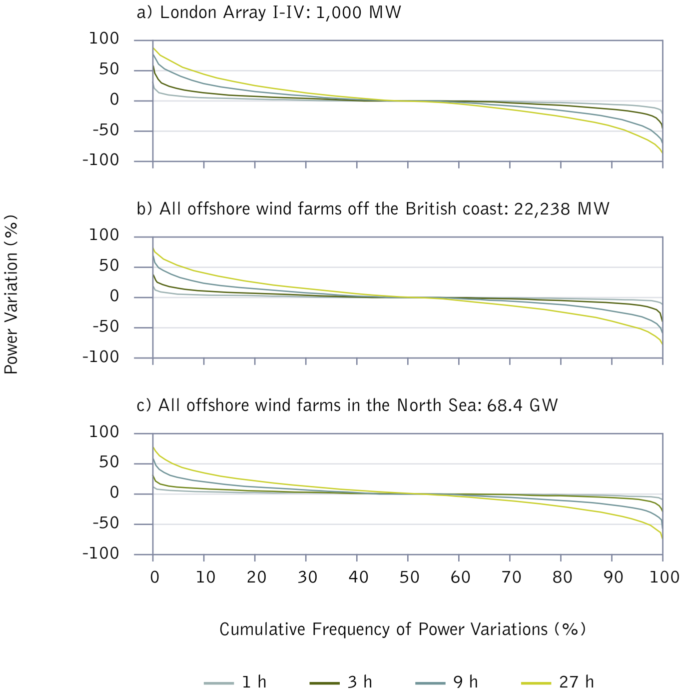
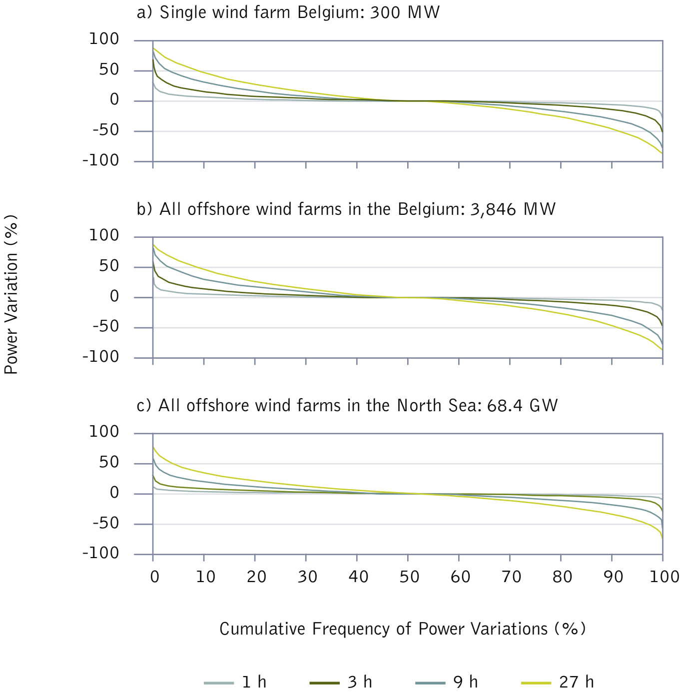


figure 24: cumulative frequency of variations in hourly generation FOR ONE WIND FARM, ALL WIND FARMS IN THE BELGIAN EEZ AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; LEGEND: TIME LAG



discussion and conclusions

"FLEXIBILITY IS THE KEY REQUIREMENT FROM A POWER SYSTEM THAT IS LARGELY BASED ON GENERATION FROM VARIABLE RENEWABLE SOURCES LIKE OFFSHORE WIND ENERGY."

image AN OFFSHORE WIND FARM OUTSIDE COPENHAGEN, DENMARK.

6.1 availability and variability

characteristics of offshore wind power generation

The availability of power from offshore wind farms can be characterized by the duration curve of wind power generation. The shape of the load duration curve depends on the local wind climate. On the one hand, for a single offshore wind farm there is typically a significant period during which it is generating at its maximum (rated) capacity (here set to 89% of installed capacity). In the cases under examination this is approximately during 10% of the time. On the other hand, a single wind farm will experience periods of very low load, in the North Sea up to another 10% of the time.

Adding up the power generation from wind farms over larger regions can reduce the periods of very low load. When the geographical area of the North Sea is considered there is always some power generated. Adding up the generation from offshore wind farms over large regions also leads to a larger amount of power generated at medium and low power levels in exchange for a reduction of periods of full and very low load.

The variability of the offshore wind power generation can be characterized by means of histograms or cumulative frequency distributions of the power variation. Hourly power variations from a single wind farm mostly do not exceed ±2% of installed capacity. The occurrence of variations beyond 10% is negligible.

With regard to unit commitment and dispatch of the power system, this means that the target should not be entirely smoothing out the variability of offshore wind power in the North Sea alone. Wind power should rather be seen as one source within a power generation portfolio that, as a whole, has to be managed in order to supply the variable demand. Today, wind power is well complemented by generation from reservoir hydro power plants and CCGT. In the future, other renewables and demand-side management may fulfil part of this task as well. Day-ahead and intra-day forecasting of the wind power generation is required for optimal dispatch decisions and minimization of reserve requirements.

portfolio management with centralized thermal power plants

The variability of wind power, and especially its characteristic time scales, determine the feasibility of complementing large amounts of wind power in a portfolio that is historically dominated by thermal generation units.

Hourly variations of wind power generation are very small even for wind farms concentrated in a small area as the Belgian designated zone for offshore wind power. Variations over a few hours are significant when wind farms are concentrated in a small area. When the wind power generation from wind farms distributed over a larger area can be aggregated, variations over a few hours are levelled out. When large areas are considered, as for example the entire North Sea, variations over longer periods are levelled out to a limited extent.

In a portfolio dominated by centralized thermal generation, the few short variations would be complemented by open cycle gas turbines (OCGT) for as far as no reservoir hydro power is available. The remaining deviations from demand would be complemented by thermal bulk generation plants, namely, CCGT for the time range of one to a few hours and also coal-fired units for the longer and less severe ones. A precise day-ahead forecast for wind power generation and demand is essential in order to optimize the commitment of these units. Due to their must-run status, nuclear power plants cannot complement deviations between supply and demand. Therefore, in power systems with a high share of nuclear generation, the penetration level at which regular overproduction of wind power would occur is reached earlier than in a power system fully based on fossil fuel.

portfolio management with renewables and distributed generation

A sustainable power system in the future will consist of different types of generation from variable renewable sources: wind power, run river hydro power, solar power, and possibly power from waves and tidal streams. Power generation from distributed, heat demand-driven, CHP plants may also be considered variable. These sources are partly uncorrelated and partly complementary to each other. In order to further complement such portfolios and match supply with demand, demand side management and flexible generation units are required. These would be thermal units based on biomass or biogas, or natural gas-fired units. Reservoir hydro power would be the prefered choice, where available.

6.2 flexibility

Flexibility is the key requirement from a power system that is largely based on generation from variable renewable sources like offshore wind energy. Flexibility can be introduced, amongst others, by:

- distributed generation and storage,
- controllable demand,
- centralized storage,
- reservoir hydro power,
- flexible thermal power stations.

distributed generation and storage

Distributed generation refers to power generation at distribution level or at the customer side of the meter. In practice distributed generation originates from photovoltaics, small wind farms and CHP heating systems. A priori, these generators do not introduce flexibility into the system but rather they increase the need for flexibility. However, with incentives for demand control in place, these technologies provide additional opportunities for integrating local generation and demand into the management of large power generation and supply portfolios. Some opportunities include:

- shifting heat demand and storing heat in order to adapt the power generation profile of CHP production [17][19],
- using the batteries of plugged-in hybrid vehicles as distributed storage devices, which could charge at periods of electricity surplus and discharge to supply electricity to the system when needed [55].

These and other ways of using distributed resources in order to introduce flexibility to the power system could be motivated along with measures for demand control.

controllable demand

Historically, electricity demand has been considered a given quantity that could not be controlled. Recently, various approaches and demonstration projects have been carried out in order to make demand controllable. The concept is based on reducing demand during periods of scarcity (high demand and limited available generation capacity, high prices) and shifting it to periods of abundance (low demand and surplus generation capacity, low prices).

The main advantage of demand control, compared to storage, is the limited investment cost. While storage requires hardware investments proportional to the required storage capacities and power levels, the investment for demand control is largely limited to software and communication equipment. In so-called smart distribution grids, demand control decisions could be taken automatically in order to maximize the benefit for the electricity consumer. Demand control actions could be initiated by a central dispatch centre depending on the condition of the power system. This practice is already applied today in many countries for industrial customers. Alternatively, demand control actions could be taken on a local level motivated by price signals. Technically, this is possible with the current technology.

centralized storage

Today, pumped hydro accumulation storage (PAS) plants exist in different countries. As an alternative, compressed air energy storage (CAES) can be applied. The technology has been tested over many years and it is commercially available at costs which are in the same order of magnitude as those of pumped-storage plants [19][56][57]. With the current penetration rates of wind power, no centralized storage is required for wind power specifically; however, again it may be applied for the economic optimization of dispatch within a portfolio [19][57].

Recently, in the Netherlands, the so-called Energy Island has been proposed. The Energy Island would be an artificial island at sea consisting of a ring of dikes that serves as a water reservoir for

image WINDTURBINE CONSTRUCTION YARD, UK.

© DAVISON/GREENPEAC

pumped hydro accumulation storage [58]. Underground pumped hydro storage has also recently been examined in the Netherlands [19]. With 10 GW of installed offshore wind power capacity, these storage options can contribute to reducing the amount of wind energy to be curtailed at situations of overproduction of wind power at low load. However; from the proposed centralized storage systems, only CAES would be economically beneficial unlike the Energy Island and underground hydro accumulation storage [19].

reservoir hydro power

Reservoir hydro power plants combine the functions of flexible generation and storage in one plant. In Europe the potential for reservoir hydro power has already been exploited to a very large extent. The largest hydro power resources are available in Norway with a reservoir capacity equivalent to 82 TWh of electricity, an annual inflow of 136 TWh and an installed capacity of 28 GW. Other significant resources for reservoir hydro power are available in Sweden, in the Alpine countries and to some extent in the Spanish Pyrenees [54].

Since hydro power is generated at no marginal costs, there is strong interest in the Baltic and North Sea region to export hydro power from Scandinavia to Great Britain and continental Europe where the power systems are dominated by fossil fuel plants. The interconnectors from these countries to Norway as they are currently envisioned and depicted in Figure 14 are mainly driven by this objective. In the future these interconnectors may be used to adapt the import and export with Norway as a function of variable generation from wind power in the southern part of the North Sea and onshore.

thermal power stations

Flexible thermal power stations facilitate the portfolio management with large amounts of wind power in the short term. Combined-cycle gas turbines and open cycle gas turbines have high partial load efficiency and short start-up times. They are characterized by low investment costs and high fuel costs, which makes them suited for complementing variable generation when required.

6.3 perspectives for an offshore grid

The main drivers for the development of an offshore grid have been listed in Section 4. The design of the offshore grid as shown in Figure 11 is influenced by the drivers connectivity between countries and electricity market regions and an economically efficient connection of offshore wind farms. Its topology results from a process dominated:

- in the past by the need of interconnectors for security of supply and long-term trade,
- today by the demand for trade and the subsequent requirement for commercial interconnectors,
- in the future by the need for grid connection of multi-gigawatt wind farm clusters far from shore.

The capacity of offshore interconnectors will always strive towards values as required for arbitrage between market regions, possibly in the range of several gigawatts. There would be a strong interest in interconnection to Norway, in order to be able to import electricity from hydro power to the UCTE system and Great Britain. Norwegian hydro power could then also serve in order to compensate for wind power variations.

Offshore wind farms will still firstly be connected to a full-sized grid connection to the country of the EEZ in which they are situated. In order to serve wind farm clusters far from shore, high-voltage DC grid connections will be required. Where opportunities for arbitrage exist, several of the required offshore HVDC converter stations may be equipped with a prolongation to another country in order to upgrade the grid connection to a commercial interconnector. The capacity of the prolongation will be determined by the expected opportunity for arbitrage between the market regions. It may be less than that of the wind farm grid connection. The first candidates for such shared infrastructures are the British wind farms at the Dogger Bank and those in the German Bight.

By upgrading grid connections to interconnectors, wind power can offer to the power market the opportunity to make use of its grid connection lines whenever capacity is available. In most cases, such continued interconnectors will be much less expensive than a shore-to-shore interconnector. Moreover, they allow increasing the overall utilization time of the wind farms' grid connection lines.

In all cases, offshore wind farms being connected to interconnectors need to enjoy priority dispatch on these interconnectors. Only the remaining available interconnector transfer capacity must be allocated to the market. If this principle is not obeyed, offshore wind farms would regularly have to curtail their output while interconnectors are used for trade.

In conclusion, an offshore grid in the North Sea facilitates trade and it increases security of supply by offering increased connectivity. It allows dispatching power from offshore wind farms to different countries depending on the highest demand. By enabling the supply of aggregated generation profiles from different regions to one market, the offshore grid contributes to reducing the variability of wind power generation in the range of hours. Moreover, an offshore grid in the North Sea allows the import of electricity from hydro power from Norway to the British and the UCTE system. This can replace thermal base load plants and increase the flexibility within a portfolio. In addition, increased liquidity and trading facilities on the European power markets will allow for a more efficient portfolio management.

The value of an offshore grid in the North Sea lies in its contribution for increased security of supply, its function for the aggregation and dispatch of power from offshore wind farms, and in its role as a facilitator for power exchange and trade between regions and power systems. Integrating interconnectors with connection lines for wind farms far from shore can yield efficiency gains for the development of both wind power projects and commercial interconnectors.

Finally, in regions where low electricity demand is concentrated at the coast, reinforcement of the onshore transmission system is as important as the development of an offshore grid in order to facilitate power transmission from the coasts to the centres of demand.

references

1 H. SÖKER, K. REHFELDT, F. SANTJER, M. STRACK, M. SCHREIBER. OFFSHORE WIND ENERGY IN THE NORTH SEA, TECHNICAL POSSIBILITIES AND ECOLOGICAL CONSIDERATIONS – A STUDY FOR GREENPEACE. DEWI, OCTOBER 2000.

2 H. SNODIN. SEA WIND EUROPE. GARRAD HASSAN AND PARTNERS FOR GREENPEACE, FEBRUARY 2004.

3 G. GERDES, A. JANSEN, K. REHFELDT. OFFSHORE WIND - IMPLEMENTING A NEW POWER HOUSE FOR EUROPE. DEUTSCHE WINDGUARD FOR GREENPEACE INTERNATIONAL, APRIL 2005.

4 WINDFORCE 12, A BLUEPRINT TO ACHIEVE 12% OF THE WORLD'S ELECTRICITY FROM WIND POWER BY 2020. GREENPEACE AND EWEA, JUNE 2005.

5 GLOBAL WIND ENERGY OUTLOOK 2006. GREENPEACE AND GWEC, SEPTEMBER 2006.

6 S. TESKE. ENERGY REVOLUTION: A SUSTAINABLE PATHWAY TO A CLEAN ENERGY FUTURE FOR EUROPE. DLR FOR GREENPEACE INTERNATIONAL, SEPTEMBER 2005.

7 S. TESKE, A. ZERVOS, O. SCHÄFER. ENERGY [R]EVOLUTION. DLR AND ECOFYS FOR GREENPEACE INTERNATIONAL AND EREC. JANUARY 2007.

8 DELIVERING OFFSHORE WIND POWER IN EUROPE. EWEA, DECEMBER 2007.

9 PURE POWER, WIND ENERGY SCENARIOS UP TO 2030. EWEA, MARCH 2008.

10 S. SHAW, M.J. CREMERS, G. PALMERS. ENABLING OFFSHORE WIND DEVELOPMENTS – SEALEGAL, BRUSSELS 2002.

11 A. WOYTE, P. GARDNER, AND H. SNODIN. CONCERTED ACTION FOR OFFSHORE WIND ENERGY DEPLOYMENT, WORK PACKAGE 8: GRID ISSUES, OFFSHORE WIND ENERGY EUROPE, COD, OCTOBER 2005. HTTP://WWW.OFFSHOREWINDENERGY.ORG/COD/, ACCESSED 14/15/2008.

12 F. VAN HULLE. LARGE SCALE INTEGRATION OF WIND ENERGY IN THE EUROPEAN POWER SUPPLY: ANALYSIS, ISSUES AND RECOMMENDATIONS. EWEA, BRUSSELS, BELGIUM, DECEMBER 2005.

13 EUROPEAN TRANSMISSION SYSTEM OPERATORS. EUROPEAN WIND INTEGRATION STUDY (EWIS) – TOWARDS A SUCCESSFUL INTEGRATION OF WIND POWER INTO EUROPEAN ELECTRICITY GRIDS. FINAL REPORT PHASE 1, JANUARY 2007.

14 IEA ANNEX 25 HOMEPAGE, DESIGN AND OPERATION OF POWER SYSTEMS WITH LARGE AMOUNTS OF WIND POWER. HTTP://WWW.IEAWIND.ORG/ANNEXXXV.HTML, ACCESSED 5/06/2008.

15 TRADEWIND – WIND POWER INTEGRATION AND EXCHANGE IN THE TRANS-EUROPEAN POWER MARKET. PROJECT WEBSITE. HTTP://WWW.TRADE-WIND.EU/, ACCESSED 5/06/2008.

16 H. HOLTTINEN ET AL. DESIGN AND OPERATION OF POWER SYSTEMS WITH LARGE AMOUNTS OF WIND POWER, STATE-OF-THE-ART REPORT. IEA WIND TASK 25, VTT WORKING PAPERS 82, FINLAND, OCTOBER 2007. HTTP://WWW.IEAWIND.ORG/ANNEXXXV.HTML, ACCESSED 5/06/2008.

17 P. NØRGAARD, H. LUND, B.V. MATHIESEN. MIX OF POWER SYSTEM FLEXIBILITY MEANS PROVIDING 50% WIND POWER PENETRATION IN THE DANISH POWER SYSTEM IN 2030. PROC. 7TH INTERNATIONAL WORKSHOP ON LARGE SCALE INTEGRATION OF WIND POWER AND ON TRANSMISSION NETWORKS FOR OFFSHORE WIND FARMS, MADRID, SPAIN, MAY 2008, PP. 162-166.

18 B.C. UMMELS, M. GIBESCU, E. PELGRUM, W. KLING, A. BRANDT. IMPACTS OF WIND POWER ON THERMAL GENERATION UNIT COMMITMENT AND DISPATCH. IEEE TRANSACTIONS ON ENERGY CONVERSION, 22(1), MARCH 2007, PP. 44-51.

19 B.C. UMMELS, E. PELGRUM, W. KLING. INTEGRATION OF LARGE-SCALE WIND POWER AND USE OF ENERGY STORAGE IN THE NETHERLANDS' ELECTRICITY SUPPLY. IET RENEWABLE POWER GENERATION, 2(1), MARCH 2008, PP. 26-33.

20 POWER TRANSNATIONAL SUPPLY CHAIN STUDY: APPENDICES, DOUGLAS WESTWOOD, 05/2006.

21 G. VAN DER TOORN, WIND POWER CAPACITY DATA COLLECTION. GARRAD HASSAN AND PARTNERS FOR TRADEWIND, D2.1, APRIL 2007. HTTP://WWW.TRADE-WIND.EU/, ACCESSED 18/04/2008.

22 F. VAN HULLE, J. DE DECKER, A. WOYTE. OFFSHORE GRID SCENARIOS: MAPPING OFFSHORE WIND POWER CAPACITY FOR TRADEWIND GRID SCENARIOS. TRADEWIND, DRAFT D6.2, MAY 2008.TO BE PUBLISHED ON HTTP://WWW.TRADE-WIND.EU/.

23 F. VAN HULLE, S. LE BOT, Y. CABOOTER, J. SOENS, V. VAN LANCKER, S. DELEU, J.P. HENRIET, G. PALMERS, L. DEWILDE J. DRIESEN, P. VAN ROY, R. BELMANS. OPTIMAL OFF-SHORE WIND ENERGY DEVELOPMENTS IN BELGIUM, SPSD II, FINAL REPORT CP/21. 3E FOR BELGIAN SCIENCE POLICY, BRUSSELS, BELGIUM, MAY 2004.

24 J. DE RUYCK, MAXIMUM POTENTIALS FOR RENEWABLE ENERGIES, SUPPORTING DOCUMENTS FOR COMMISSION ON ENERGY 2030, JUNE 2007.

25 50% WIND POWER IN DENMARK IN 2025, EA ENERGY ANALYSES, JULY 2007.

26 FUTURE OFFSHORE WIND POWER SITES – 2025, DANISH ENERGY AUTHORITY – COMMITTEE FOR FUTURE OFFSHORE WIND POWER SITES, APRIL 2007.

27 WWW.OFFSHORE-WIND.DE, DEUTSCHE ENERGIEAGENTUR (DENA). HTTP://WWW.OFFSHORE-WIND.DE/, ACCESSED 24/03/2008.

28 UK DEPARTMENT FOR BUSINESS, ENTERPRISE AND REGULATORY REFORM (BERR), HTTP://WWW.BERR.GOV.UK, ACCESSED 04/2008.

29 EAST COAST TRANSMISSION NETWORK: TECHNICAL FEASIBILITY STUDY. ECONNECT FOR THE CROWN ESTATE, JANUARY 2008.

30 RIJKSWATERSTAAT NOORDZEE, HTTP://WWW.NOORDZEELOKET.NL, ACCESSED 03/2008.

31 CONNECT 6000 MW, MINISTERIE VAN ECONOMISCHE ZAKEN, DEN HAAG, JULY 2004

32 WEATHER AND RESEARCH FORECAST MODEL (WRF). HTTP://WWW.WRF-MODEL.ORG, ACCESSED 14/03/2008.

33 A. SOOD, K. SUSELJ, D. HEINEMANN, WIND RESOURCE AND SITE ASSESSMENT IN THE GERMAN BIGHT; EXTREME WINDS AT MESO- TO MICROSCALE, PROC. EUROPEAN WIND ENERGY CONFERENCE EWEC 2007, MILAN, ITALY, MAY 2007.

34 A. SOOD, K. SUSELJ, D. HEINEMANN. HIGH RESOLUTION NWP NORTH SEA WIND FORECASTS IN THE MARINE ATMOSPHERIC BOUNDARY LAYER, PROC. EUROPEAN WIND ENERGY CONFERENCE EWEC 2007, MILAN, ITALY, MAY 2007.

35 J.R. MCLEAN, EQUIVALENT WIND POWER CURVES, GARRAD HASSAN AND PARTNERS FOR TRADEWIND, D2.4, APRIL 2007, HTTP://WWW.TRADE-WIND.EU/, ACCESSED 13/02/2008.

36 R. WATSON. AN UNDERSEA TRANSMISSION GRID TO OFFLOAD OFFSHORE WIND FARMS IN THE IRISH SEA. PROC. 3RD INTERNATIONAL WORKSHOP ON TRANSMISSION NETWORKS FOR OFFSHORE WIND FARMS, STOCKHOLM, SWEDEN, APRIL 2002.

37 AIRTRICITY, SUPERGRID, HTTP://WWW.AIRTRICITY.COM/INTERNATIONAL/WIND_FARMS/SUPERGRID/, ACCESSED 06/2008.

38 C. VEAL, C. BYRNE, S. KELLY. THE COST-BENEFIT OF INTEGRATING OFFSHORE WIND FARM CONNECTIONS AND SUBSEA INTERCONNECTORS IN THE NORTH SEA. PROC. EUROPEAN OFFSHORE WIND CONFERENCE & EXHIBITION, BERLIN, GERMANY, DECEMBER 2007.

39 G. CZISCH, SZENARIEN ZUR ZUKÜNFTIGEN STROMVERSORGUNG BEI OPTIMALER NUTZUNG VON FUSIONSKRAFTWERKEN UND REGENERATIVEN ENERGIEN, PHD. THESIS, UNIV. KASSEL 2005.

40 F. TRIEB, TRANS-CSP TRANS MEDITERRANEAN INTERCONNECTION FOR CONCENTRATING SOLAR POWER. FINAL REPORT, DLR, HTTP://WWW.DLR.DE/TT/TRANS-CSP/, ACCESSED 2/06/2008.

41 K. HAUGLUM. NORWEGIAN VISION ON THE NORTH SEA OFFSHORE GRID. PRESENTATION BY STATNETT, BRUSSELS, BELGIUM, JUNE 12, 2008.

42 T. ACKERMANN. TRANSMISSION SYSTEMS FOR OFFSHORE WIND FARMS, CHAPTER IN WIND POWER IN POWER SYSTEMS, EDITOR T. ACKERMANN, WILEY, 2005.

43 M. DE ALEGRÍA, J. L. MARTÍN, I. KORTABARRIA, J. ANDREU AND P. I. EREÑO. TRANSMISSION ALTERNATIVES FOR OFFSHORE ELECTRICAL POWER. RENEWABLE AND SUSTAINABLE ENERGY REVIEWS, AVAILABLE ONLINE 22 APRIL 2008.

44 L.P. LAZARIDIS. ECONOMIC COMPARISON OF HVAC AND HVDC SOLUTIONS FOR LARGE OFFSHORE WIND FARMS UNDER SPECIAL CONSIDERATION OF RELIABILITY. MASTER'S THESIS. ROYAL INSTITUTE OF TECHNOLOGY, STOCKHOLM, 2005.

45 ABB, HVDC AND HVDC LIGHT. HTTP://WWW.ABB.COM/HVDC, ACCESSED 13/06/2008.

46 S. LUNDBERG. CONFIGURATION STUDY OF LARGE WIND PARKS. MASTER'S THESIS. CHALMERS, UNIVERSITY OF TECHNOLOGY, GÖTEBORG, SWEDEN, 2003.

47 ENERGIEWIRTSCHAFTLICHE PLANUNG FÜR DIE NETZINTEGRATION VON WINDENERGIE IN DEUTSCHLAND AN LAND UND OFFSHORE BIS ZUM JAHR 2020. ENDBERICHT. ENERGIEWIRTSCHAFTLICHES INSTITUT AN DER UNIVERSITÄT ZU KÖLN (EWI), DEUTSCHESWINDENERGIE-INSTITUT (DEWI), E.ON NETZ GMBH, RWE TRANSPORTNETZ STROM GMBH, VATTENFALL EUROPE TRANSMISSION GMBH. STUDY COMMISSIONED BY DEUTSCHE ENERGIE-AGENTUR GMBH (DENA), KÖLN, GERMANY, 24 FEBRUARY 2005.

48 NORDIC GRID MASTER PLAN 2008, NORDEL, MARCH 2008, HTTP://WWW.NORDEL.ORG, ACCESSED 5/06/2006.

49 TENNET HOMEPAGE, PROJECTS, NORNED, PROJECT DESCRIPTION. HTTP://WWW.TENET.ORG, ACCESSED 16/07/2008.

50 NORNED AUCTION - HOMEPAGE, CAPACITY & RESULTS, EXPORT DATA. HTTP://WWW.NORNED-AUCTION.ORG/, ACCESSED 16/07/2008.

51 ENERGY CONSUMPTION IN THE UNITED KINGDOM, DEPARTMENT OF TRADE AND INDUSTRY (DTI) & NATIONAL STATISTICS, JULY 2002, TABLES UPDATED IN JULY 2007, AVAILABLE ON HTTP://WWW.BERR.GOV.UK/FILES/FILE11250.PDF, ACCESSED 03/07/2008

52 NORDEL ANNUAL STATISTICS 2006, NORDEL, AVAILABLE ON WWW.NORDEL.ORG, ACCESSED 03/07/2008

53 STATISTICAL YEARBOOK 2006, UCTE, SEPTEMBER 2007, HTTP://WWW.UCTE.ORG/PUBLICATIONS/STATSYEARBOOK, ACCESSED 03/07/2008

54 M. KORPÅS, L. WARLAND, J.O.G. TANDE, K. UHLEN, K. PURCHALA, S. WAGEMANS. GRID MODELLING AND POWER SYSTEM DATA. TRADEWIND, D3.2, DECEMBER 2007. HTTP://WWW.TRADE-WIND.EU/, ACCESSED 19/01/2008.

55 P. DENHOLM, W. SHORT. AN EVALUATION OF UTILITY SYSTEM IMPACTS AND BENEFITS OF OPTIMALLY DISPATCHED PLUG-IN HYBRID ELECTRIC VEHICLES. TECHNICAL REPORT NREL/TP-620-40293, OCTOBER 2006.

56 S. ZUNFT, C. JAKIEL, M. KOLLER, C. BULLOUGH. ADIABATIC COMPRESSED AIR STORAGE FOR THE GRID INTEGRATION OF WIND POWER. PROC. 6TH INTERNATIONAL WORKSHOP ON LARGE SCALE INTEGRATION OF WIND POWER AND ON TRANSMISSION NETWORKS FOR OFFSHORE WIND FARMS, DELFT, NETHERLANDS, OCTOBER 2006, PP. 346-351.

57 P. SIEMES, H.-J. HAUBRICH, H. VENNEGEERTS, S. OHREM. CONCEPTS FOR THE IMPROVED INTEGRATION OF WIND POWER INTO THE GERMAN INTERCONNECTED SYSTEM. IET RENEWABLE POWER GENERATION, 2(1), MARCH 2008, PP. 26-33.

58 W.W. DE BOER, F.J. VERHEIJ, D. ZWEMMER AND R. DAS. THE ENERGY ISLAND – AN INVERSE PUMP ACCUMULATION STATION. PROC. EUROPEAN WIND ENERGY CONFERENCE EWEC 2007, MILAN, ITALY, MAY 2007.

image AERIAL VIEW OF SUBMARINE CABLES BEING LAYED OUT IN THE BELGIUM NORTH SEA.

© C-POWER

annex a

table 5: wind farm sites & installed capacity data

PROJECT NAME	COUNTRY	P INSTALLED [MW]
Unnamed I	Belgium	500
Unnamed II	Belgium	500
Bligh Bank	Belgium	330
Unnamed III	Belgium	500
Bank zonder naam	Belgium	216
Unnamed IV	Belgium	500
Thornton Bank I	Belgium	120
Thornton Bank II	Belgium	180
Unnamed VI	Belgium	500
Unnamed V	Belgium	500
Rønland	Denmark	17.2
Horns Rev I	Denmark	160
Horns Rev II	Denmark	200
A - Horns Rev	Denmark	200
B - Horns Rev	Denmark	200
C - Horns Rev	Denmark	200
K - Jammerbugt	Denmark	200
L - Jammerbugt	Denmark	200
M - Jammerbugt	Denmark	200
Unnamed 1	France	1000
North Sea Windpower I+II	Germany	1226
Godewind I+II	Germany	1120
DanTysk I+II	Germany	1500
BARD Offshore 1 I+II	Germany	1600
Sandbank 24 I+II	Germany	4900
Austerngrund	Germany	400
Deutsche Bucht	Germany	400
Hochsee Windpark Nordsee I+II	Germany	2555
Nördlicher Grund I+II	Germany	2010
Nordsee Ost I+II	Germany	1250
Butendiek	Germany	240
He Dreiht	Germany	535.5
Borkum Riffgrund I+II	Germany	746
Globaltech 1 I+II	Germany	1600
Amrumbank West	Germany	400
Uthland	Germany	400
Ventotec Nord 1 I+II	Germany	600
Ventotec Nord 2 I+II	Germany	600
Borkum Riffgrund West I+II	Germany	1800
Borkum Riffgat	Germany	220
Nordergründe	Germany	125
Borkum West I+II	Germany	1040
Meerwind I+II	Germany	1150
Teeside/Redcar	Great Britain	90
Blyth Offshore	Great Britain	4
Inner Dowsing	Great Britain	97.2
Lynne	Great Britain	97.2
Cromer	Great Britain	108
Scroby Sands	Great Britain	60
Gunfleet Sands I	Great Britain	108
Gunfleet Sands II	Great Britain	64
Kentish flats	Great Britain	90
Westermost Rough	Great Britain	240
Humber Gateway	Great Britain	300
Lincs	Great Britain	250
Docking Shoal	Great Britain	500
Race ranck	Great Britain	500
Triton Knoll	Great Britain	1200
Sheringham Shoal	Great Britain	315
Dudgeon East	Great Britain	300
London Array I - IV	Great Britain	1000
Greater Gabbard I+II	Great Britain	500
Thanet	Great Britain	300
Beatrice	Great Britain	1000
Aberdeen Harbour	Great Britain	115
Round3 - 1	Great Britain	1000
Round3 - 2	Great Britain	1000
Round3 - 3	Great Britain	1000
Round3 - 4	Great Britain	1000
Round3 - 5	Great Britain	1000
Round3 - 6	Great Britain	1000
Round3 - 7	Great Britain	1000
Round3 - 8	Great Britain	1000
Round3 - 9	Great Britain	1000
Round3 - 10	Great Britain	1000
Round3 - 11	Great Britain	1000
Round3 - 12	Great Britain	1000
Round3 - 13	Great Britain	1000
Round3 - 14	Great Britain	1000
Round3 - 15	Great Britain	1000
Ijmuiden	Netherlands	246
Den Helder Noord	Netherlands	450
Helmveld	Netherlands	425
Breeveertien	Netherlands	210
Brown Ridge Oost	Netherlands	270
Den Helder I	Netherlands	650
Den Helder II	Netherlands	650
IJmuiden 1	Netherlands	500
Den Helder	Netherlands	500
Okeanos Noord	Netherlands	38
Favorius	Netherlands	129
Wijk aan Zee	Netherlands	200
Callantsoog-Noord	Netherlands	328
Q7-West	Netherlands	245
Riffgrond	Netherlands	400
Oost Friesland	Netherlands	500
Osters Bank 1	Netherlands	500
Osters Bank 3	Netherlands	500
BARD Offshore NL1	Netherlands	280
GWS Offshore NL1	Netherlands	280
Den Haag II	Netherlands	480
P15-WP	Netherlands	219
Katwijk Buiten	Netherlands	325
Eurogeul Noord	Netherlands	275
Hopper	Netherlands	400
Maas West Buiten	Netherlands	175
Den Haag Noord	Netherlands	285
Noord Hinder 1	Netherlands	560
West Rijn	Netherlands	180
Rijnveld Noord	Netherlands	60
Rijnveld West	Netherlands	144
WindNed Noord	Netherlands	156
Hoek van Holland 3	Netherlands	500
Scheveningen 3	Netherlands	500
Q10	Netherlands	151
Schaar	Netherlands	328
Utsira	Norway	300
Sørlige Nordsjøen	Norway	990
Total		**68408.1**

annex b

figure 25: power output of offshore wind power over three days FOR ONE WIND FARM, ALL WIND FARMS IN THE DANISH EEZ (NORTH SEA ONLY) AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA

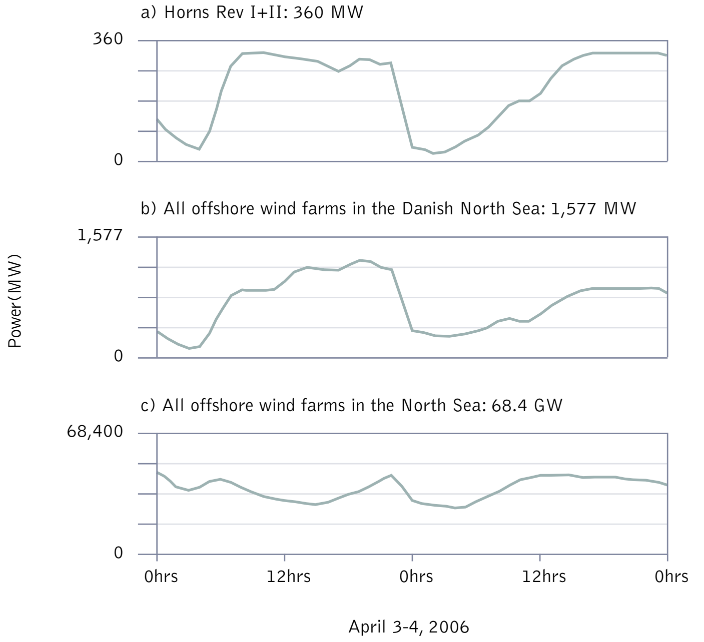


figure 27: power output of offshore wind power over three days FOR ONE WIND FARM, ALL WIND FARMS IN THE DUTCH EEZ (NORTH SEA ONLY) AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA

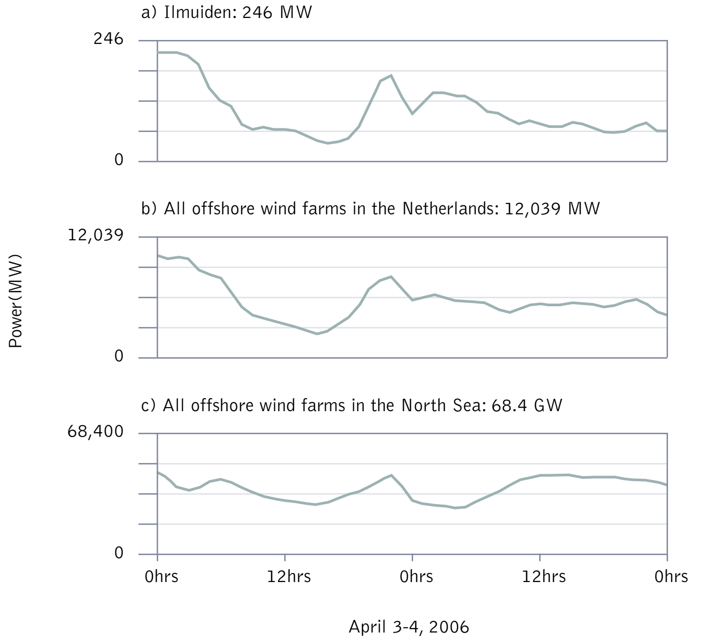


figure 26: power output of offshore wind power over three days FOR ONE WIND FARM, ALL WIND FARMS IN THE FRENCH EEZ (NORTH SEA ONLY) AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA

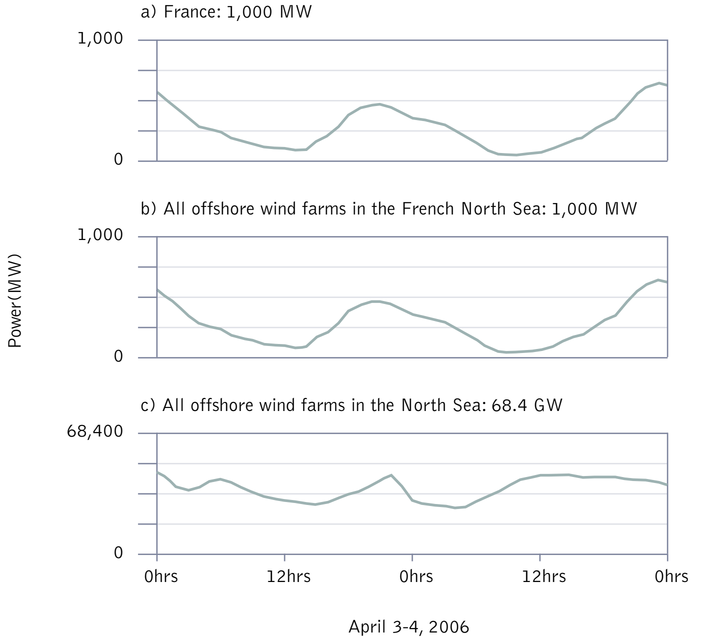


figure 28: power output of offshore wind power over three days FOR ONE WIND FARM, ALL WIND FARMS IN THE NORWEGIAN EEZ (NORTH SEA ONLY) AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA

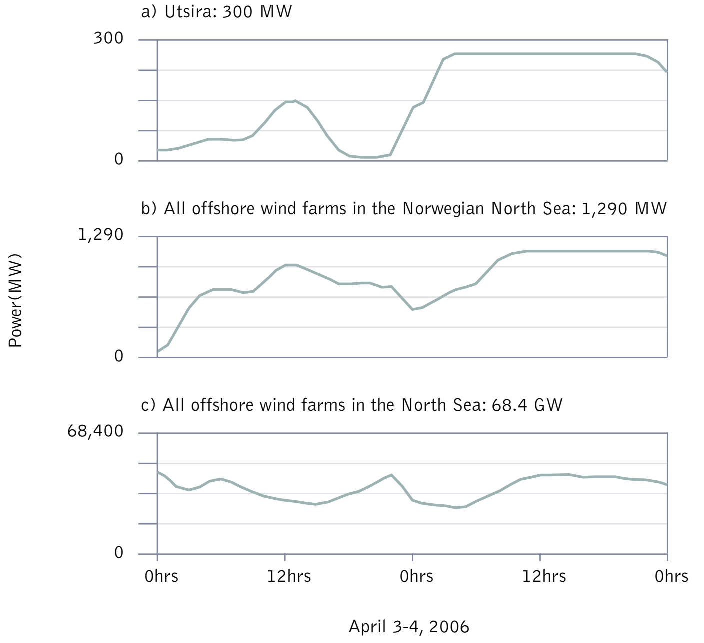


image WINDTURBINES BEING CONSTRUCTED.

annex b

figure 29: load duration of offshore wind power

FOR ONE WIND FARM, ALL WIND FARMS IN THE DANISH EEZ (NORTH SEA ONLY) AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; DATA FOR 2004-2006

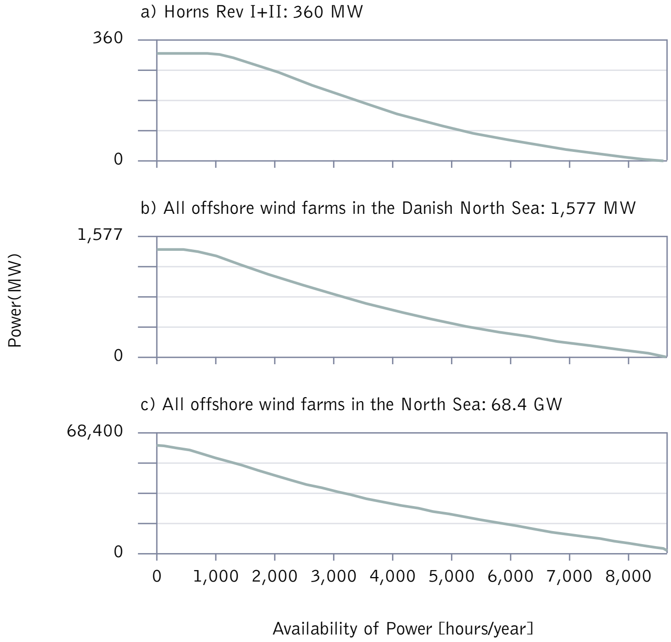


figure 30: load duration of offshore wind power

FOR ONE WIND FARM, ALL WIND FARMS IN THE FRENCH EEZ (NORTH SEA ONLY) AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH; DATA FOR 2004-2006

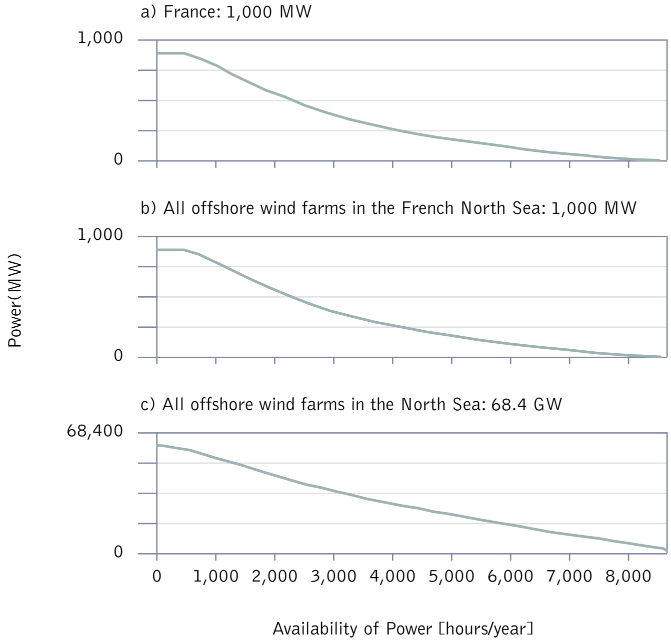


figure 31: load duration of offshore wind power

FOR ONE WIND FARM, ALL WIND FARMS IN THE DUTCH EEZ (NORTH SEA ONLY) AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; DATA FOR 2004-2006

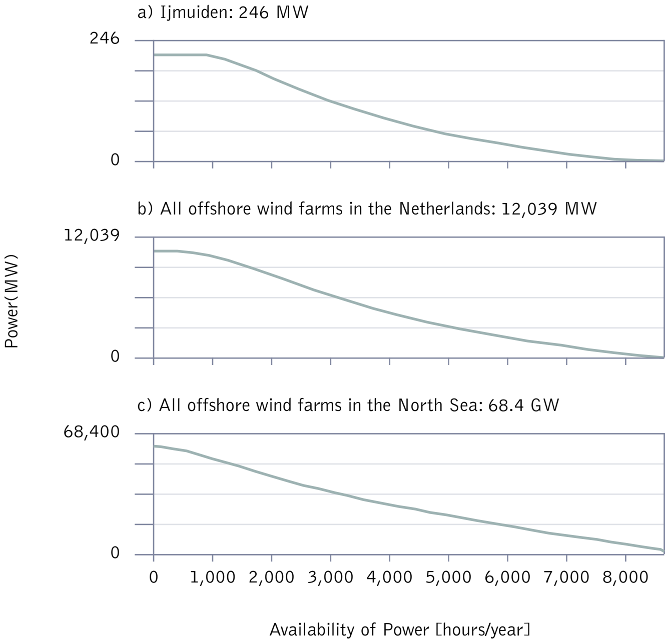
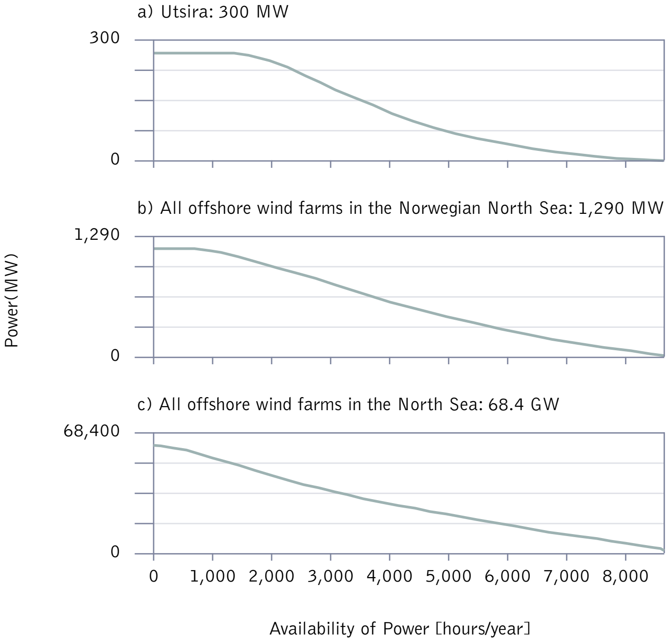


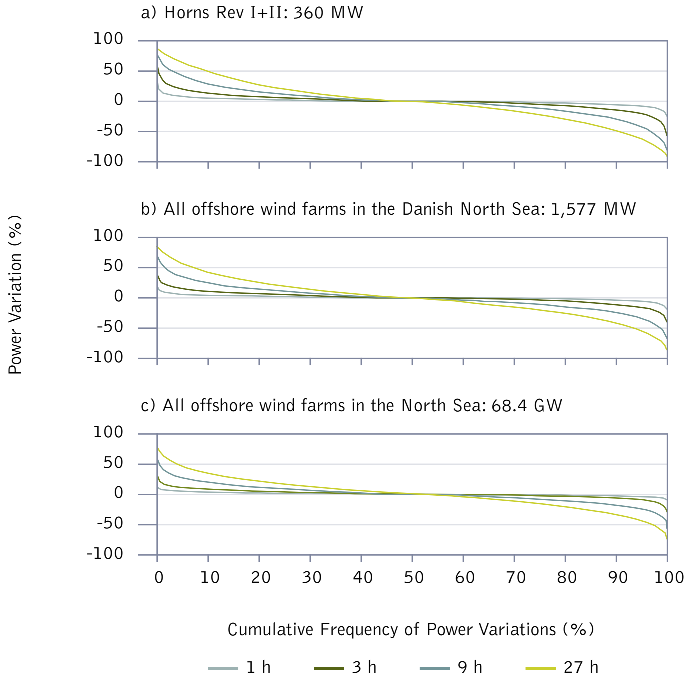
figure 32: load duration of offshore wind power

FOR ONE WIND FARM, ALL WIND FARMS IN THE NORWEGIAN EEZ (NORTH SEA ONLY) AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; DATA FOR 2004-2006



annex b

figure 33: **cumulative frequency of variations in hourly generation** FOR ONE WIND FARM, ALL WIND FARMS IN THE DANISH EEZ AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; LEGEND: TIME LAG

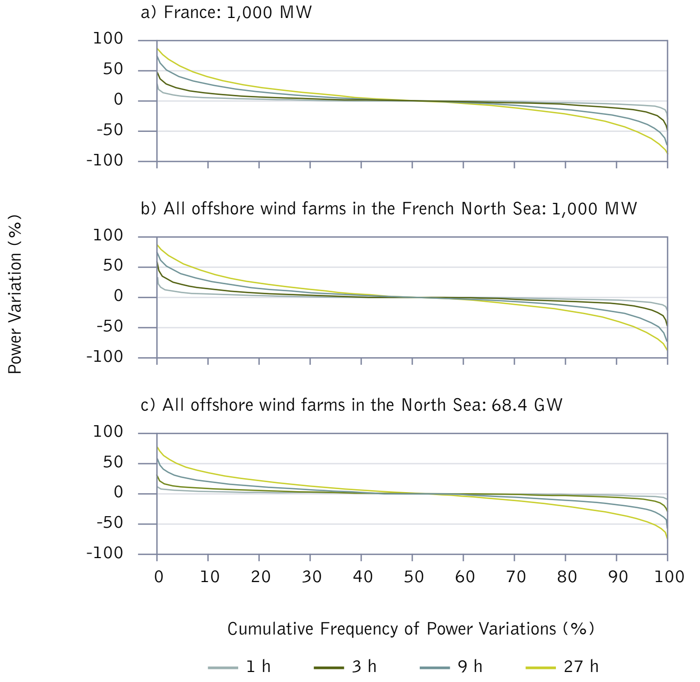


a) Horns Rev I+II: 360 MW

b) All offshore wind farms in the Danish North Sea: 1,577 MW

c) All offshore wind farms in the North Sea: 68.4 GW

figure 34: **cumulative frequency of variations in hourly generation** FOR ONE WIND FARM, ALL WIND FARMS IN THE BELGIAN EEZ AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; LEGEND: TIME LAG

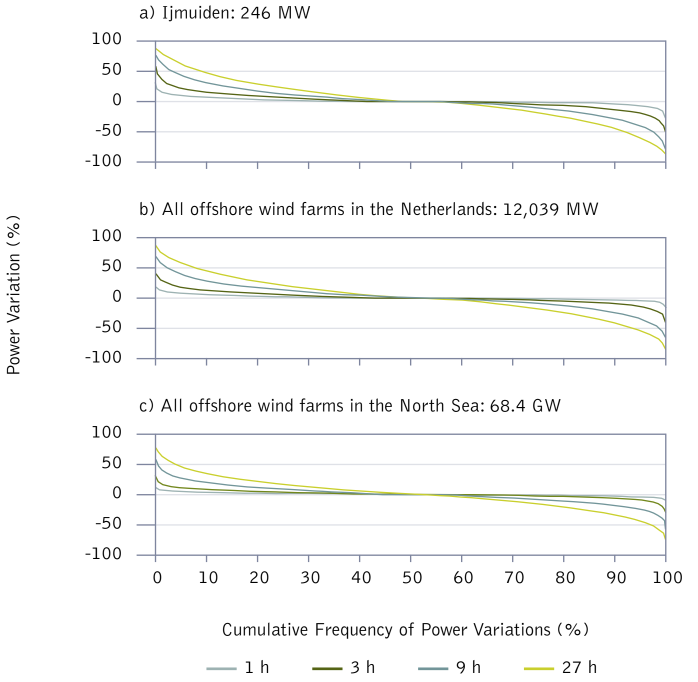


a) France: 1,000 MW

b) All offshore wind farms in the French North Sea: 1,000 MW

c) All offshore wind farms in the North Sea: 68.4 GW

figure 35: **cumulative frequency of variations in hourly generation** FOR ONE WIND FARM, ALL WIND FARMS IN THE DUTCH EEZ AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; LEGEND: TIME LAG

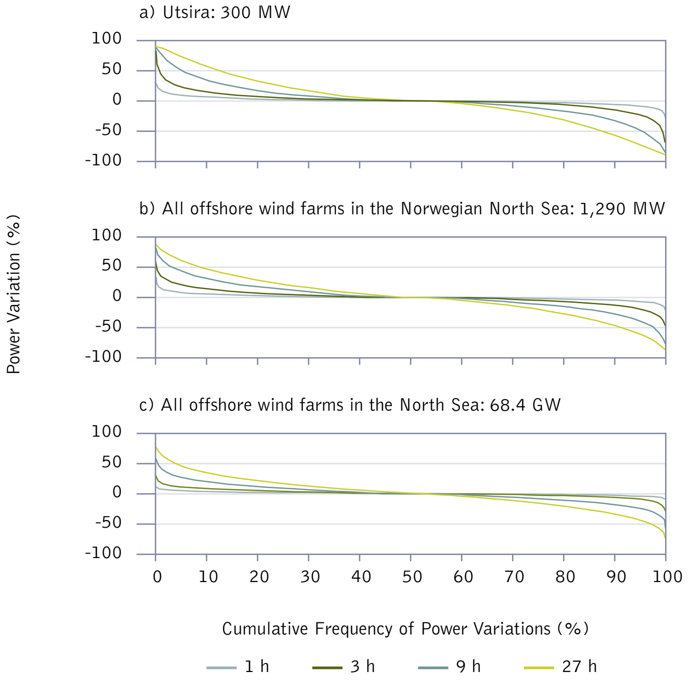


a) Ijmuiden: 246 MW

b) All offshore wind farms in the Netherlands: 12,039 MW

c) All offshore wind farms in the North Sea: 68.4 GW

figure 36: **cumulative frequency of variations in hourly generation** FOR ONE WIND FARM, ALL WIND FARMS IN THE NORWEGIAN EEZ AND ACCUMULATED FOR ALL OFFSHORE WIND FARMS IN THE NORTH SEA; LEGEND: TIME LAG



a) Utsira: 300 MW

b) All offshore wind farms in the Norwegian North Sea: 1,290 MW

c) All offshore wind farms in the North Sea: 68.4 GW

image WINDFARM OFF THE WEST COAST OF DENMARK.


© PETERSEN/DREAMSTIME

annex c

table 6: statistics of power variations in the different countries

THE TABLE SHOWS THE MAXIMUM UPWARD AND DOWNWARD STEP SIZE OF THE ACCUMULATED POWER GENERATION THAT ALTOGETHER IS EXCEEDED IN 10% OF THE CASES. THE INDICATED VALUES ARE PERCENTILES P5 AND P95.

POWER INCREASE EXCEEDED IN 5% OF THE CASES Power as % of installed capacity			P5 value	POWER DECREASE EXCEEDED IN 5% OF THE CASES			P95 value
Case A: Selected wind farms							
	BE	DE	GB		BE	DE	GB
1h	8.9%	9.5%	7.8%	1h	-8.5%	-9.1%	-7.2%
3h	22.4%	22.9%	20.2%	3h	-21.4%	-22.6%	-18.7%
9h	44.3%	46.0%	41.5%	9h	-42.7%	-44.7%	-39.7%
27h	62.3%	64.1%	59.7%	27h	-62.1%	-64.9%	-58.2%
Case B: Accumulated generation per country							
	BE	DE	GB		BE	DE	GB
1h	8.5%	6.9%	5.1%	1h	-8.2%	-6.5%	-4.9%
3h	22.2%	18.5%	14.2%	3h	-20.9%	-17.9%	-13.7%
9h	44.7%	40.3%	33.1%	9h	-42.6%	-38.9%	-31.3%
27h	62.9%	60.3%	53.2%	27h	-62.3%	-60.1%	-52.1%
Case C: Accumulated output of all wind farms in the North Sea							
	ALL WIND FARMS				ALL WIND FARMS		
1h	4.1%			1h	-4.0%		
3h	11.5%			3h	-11.1%		
9h	26.9%			9h	-26.2%		
27h	46.2%			27h	-45.5%		

image A WIND TURBINE BEING ASSEMBLED AT SEA.

© C-POWER

GREENPEACE

Greenpeace is a global organisation that uses non-violent direct action to tackle the most crucial threats to our planet's biodiversity and environment. Greenpeace is a non-profit organisation, present in 40 countries across Europe, the Americas, Asia and the Pacific. It speaks for 2.8 million supporters worldwide, and inspires many millions more to take action every day. To maintain its independence, Greenpeace does not accept donations from governments or corporations but relies on contributions from individual supporters and foundation grants.

Greenpeace has been campaigning against environmental degradation since 1971 when a small boat of volunteers and journalists sailed into Amchitka, an area west of Alaska, where the US Government was conducting underground nuclear tests. This tradition of 'bearing witness' in a non-violent manner continues today, and ships are an important part of all its campaign work.

greenpeace belgium
Haachtsesteenweg 159, chaussée de Haecht
1030 Brussels, Belgium
t +32 2 274 0200 f +32 2 274 0230
info@be.greenpeace.org
www.greenpeace.be

3E

3E is an independent expert company specialized in renewable energy and energy efficiency.

3E was established in 1999 as a spin-off company of the photovoltaics RD&D unit of IMEC - Europe's leading research centre in the fields of micro- and nanoelectronics, and nanotechnology - and broadened its horizon thanks to the association of experts from the wind energy RD&D group of the Vrije Universiteit Brussels (Belgium). 3E has continued to attract highly qualified junior and senior experts from industry, public bodies and leading RD&D groups. They represent the foundation for its dynamic development.

With a team of 50 experts and hundreds of references in over 25 countries, 3E is recognised as a leading independent authority in renewable energy, energy efficiency and energy strategy. Its clients include major technology manufacturers, project developers, energy utilities, architectural offices, construction companies and maintenance teams, as well as regional and international public authorities.

The company's drive to invest in expertise and cultivate creativity powers its aspiration: Not facing but shaping the changes.

3E
Brussels, Paris, Toulouse, Beijing
Rue du Canal 61 Vaartstraat, B-1000 Brussels, Belgium
t +32 2 217 5868 f+32 2 219 7989
info@3E.eu **www.3E.eu**