SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY

SPSD II

OPTIMAL OFFSHORE WIND ENERGY DEVELOPMENTS IN BELGIUM

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GENERAL ISSUES

AGRO-FOOD

PART 1

SUSTAINABLE PRODUCTION AND CONSUMPTION PATTERNS — ENERGY

TRANSPORT

BELGIAN SCIENCE POLICY

SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY
(SPSD II)

Part 1:
Sustainable production and consumption patterns

FINAL REPORT

Optimal Offshore Wind Energy Developments in Belgium

CP/21

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Symbols and abbreviations

AEO	Annual Energy Output
AWZ	Administratie Waterwegen en Zeewezen
BCS	Belgian Continental Shelf
CPT	Cone Penetration Test
CRP	Carbon Fibre Reinforced Plastics
DTI	Department for Trade and Industry
ECN	Energy Research Centre of the Netherlands
EIA	Environmental Impact Assessment
EWEA	European Wind Energy Association
FFT	Fast Fourier Transformation
GBS	Gravity Based Structure
GRP	Glass Fibre Reinforced Plastics
GW	Gigawatt
HV	high voltage
HV AC	High Voltage Alternating Current
HV DC	High Voltage Direct Current
MUMM	Management Unit for Mathematical Model of the North Sea
MV	medium voltage
MW	Megawatt
p.u.	Per unit
PM	Permanent Magnet
RAMS	Reliability, availability, maintainability and serviceability
SVC	Static Voltage Controllers
TTM	Tower Top Mass
TWh	Tera Watt hour
ZVI	Zones of visual influence

1 Introduction

1.1 Context

Various international and national developments in energy economy, global environment, electricity market, technology and international politics stimulate the nations into the development and utilisation of renewable energy. These developments have also been at the basis of the formulation of the European Renewable Energy Directive and the joint international 'intentions' (Kyoto Protocol) to reduce the CO_2 emissions. At the national Belgian level this has been translated into the indicative target of producing 6% of the national electricity consumption by the year 2010.

At present, wind energy technology is the fastest growing branch in the renewable energy technologies. This can be attributed to its impressive technical and economic record of accomplishment of the last decade. At present Europe is the world market leader both in wind energy technology manufacturing and in utilisation. The European Wind Energy Association has formulated a target of 75 GW installed wind power in 2010 which would represent one third of all new electricity generating capacity, one third of EU 15 total Kyoto commitment by 2010. The targeted 75 GW would deliver half of Europe's target of the Renewable Energy Directive. The actually installed wind power capacity in Europe amounts to 28 GW at the end of 2003. Belgium contributes with a modest 68 MW.

A major contribution to future wind power development is expected from offshore wind energy installations. Although still at the verge with an installed capacity not exceeding 0.5 GW, EWEA expects that the offshore wind capacity in Europe will amount to 10 GW in 2010 and 70 GW in 2020. The fact that more than 50 GW of offshore wind energy projects are under preparation[1] is supporting the probability of reaching such a target. Belgium is one of the sea border countries having direct access to a part of the North Sea with a substantial potential of wind power. Technically this can provide a substantial part of the national committed part of renewable energy in the electricity consumption.

Public studies on the potential of renewable energies in Belgium have not included yet thorough investigations on the potential of offshore wind, although the expected contribution of this technology is very important. On the other hand, a first offshore wind power plant is nearing its implementation phase, several project developers have submitted proposals for domain concessions and the international interest in this sector is high.

This shows the importance of an objective, scientific evaluation of the offshore wind energy potential without indicating direct business opportunities, and the formulation of a long term strategy on the use of the available off-shore wind resources on the Belgian continental shelf taking into account policy objectives of all involved areas.

1.2 Objectives

1.2.1 Overall objectives

- To determine the resources for off-shore wind energy production in the Belgian continental shelf by scanning the geological and geo-technical restrictions, studying the wind resources, analysing the options for grid-connection and assessing the exclusion zones in view of navigation, environmental, socio-economic or other use.
- To investigate the technological evolutions and the economic viability of long-term options by studying the offshore wind turbine technology development scenario's, the evolution in the electrical schemes for interconnection and the grid-connection and the likely development of the grid architecture, and the long term options for support structures, installation procedures and O&M procedures.
- To determine the physical, technical and economical potential for offshore wind application in the BCS based on the indicated specific resources and expected technological developments.

[1] Douglas and Westwood, Wind Directions July/August 2003

1.2.2 Detailed objectives

1.2.2.1 Survey of the resources

One part of the study focuses at a geological, geo-technical, sediment- and morpho-dynamical assessment of the solid substrate and seabed sediments for the Belgian continental shelf, to help assessing potential sites on their suitability with respect to the stability of the offshore structures, and also to minimise the environmental impacts on the seabed.

The second part focuses at the wind resources in the Belgian Continental Shelf, using data from a complete network of measuring stations (meteo and oceanographic data) in the Belgian North Sea and at the shores, and using up-to-date wind resource assessment software tools.

As for the grid connection, the objective is to make a detailed analysis of the required transmission capacity in order to assess the grid reinforcement involved in pushing towards larger offshore wind farms.

In addition, based on an inventory of non-technical barriers to the implementation of offshore wind power, a list of areas excluded for wind energy will be defined. The factors influencing the exclusions will be mapped and the effect on the area will be quantified.

1.2.2.2 Analysis of technological developments

The objective of this part of the study is to assess the expected technological evolutions in offshore wind energy equipment and related installation, operation and maintenance issues based on an international research overview and determine predicted technology figures for two different time stamps i.e. the years 2005 and 2015.

In the area of grid connection the objective is to estimate the impact of the different options for the Belgian electrical system, both by steady-state and dynamic modelling and starting from the possible energy conversion and transmission system options

1.2.2.3 Determining the potential

Based on the findings on resources and technological developments this part of the study attempts to calculate the distribution of the potential in the Belgian Continental Shelf (physical, technical and economical), for expected state-of-the-art technologies in 2005 and 2015. The expected outcome is a quantification of the offshore wind energy potential (physical, technical and economical) of wind energy in the Belgian continental shelf.

Finally, the objectives include the formulation of recommendations on policy measures to assist the optimal use of the offshore wind resource and the dissemination of the results of the project. The result allows the effects of physical, political and economical planning on the offshore wind energy potential to be derived.

1.3 Structure of the report

The report is structured in accordance with the sequence of the above sketched logic. In section 2, the available resources and restrictions are analysed and discussed. These include the geological and geotechnical characteristics (contribution by RCMG), the wind resources (3E), the available electrical grid evacuation capacity (KUL-ESAT) and the potentially available zones for offshore wind power (3E).

In section 3 the technological options are discussed, divided into the specific offshore wind energy technology (3E) and the dynamic electrical impact of wind power plants on the Belgian electric grid (KUL-ESAT). Section 4 (3E) analyses various aspects of the offshore wind energy potential of the BCS, technically and economically. Finally, Section 5 contains recommendations built upon the findings of the study.

The literature references are grouped per main paragraph.

2 Survey of the resources in the BCS: seabed, wind, grid and available zones

2.1 Introduction

This section concentrates on the main aspects, which determine the available offshore resource. Essentially, the resource is determined by wind conditions, by the available area for wind farming and by the available absorption capacity of the grid. Both technical and non-technical factors determine the available area for wind farming. These aspects are discussed in this section.

2.2 Geological and geotechnical study of the Belgian Continental Shelf

2.2.1 Approach, method

The geological and geotechnical study consisted of the following:

- Evaluation of the potential of the substratum of the Belgian continental shelf: A general review of the Belgian continental shelf is made based on existing knowledge.
- Recommendations on suitable sites: An evaluation is made for the entire Belgian continental shelf with respect to its suitability for offshore wind farm implantation sites. The most suitable sites are mainly based on the relevant and available geological and geotechnical criteria. In addition, less suitable sites are indicated according to the same procedure. Sediment- and morphodynamic issues are briefly discussed.

The geological and geotechnical study has been conducted in the following way:

- A European overview of currently used stability and geo-environmental criteria enabled the definition of the parameters relevant for a geological investigation. The methodology consisted in (1) contacting people involved in European offshore wind energy projects, and (2) reviewing international literature (reports, conference proceedings, papers).
- The investigation of the seabed and substratum of the Belgian continental shelf has required a compilation of a large amount of data and studies realised offshore. On land data were also necessary when offshore data were scarce or lacking. In that sense a strong effort was made in collecting all available information concerning the geology and geotechnics of the Belgian continental shelf and partly from on land. Most of these data existed in an analogue format. Therefore, an important work has been conducted for data digitisation, integration in appropriate georeferenced software and synthesis in order to compare the data in a much more dynamic and flexible way and to help in the final mapping of the suitable sites. Although, it was not the primary aim of this study, some attention is also given to sediment- and morphodynamic issues.

The study resulted in the production of synthetic tables and maps with clear and directly usable information for potential end users. The tables contain the main results from the present study; some of them include guidelines to help in the interpretation of future data. The maps show the spatial distribution of relevant criteria for stability and geo-environmental impacts. With direct relevance to wind farm implantation, the main product is a map with recommendations on the most suitable sites and also indicating less suitable sites.

The full compilation has been separately published: Le Bot, S., Van Lancker, V., Deleu, S., De Batist, M. & Henriet, JP. (2003). Tertiary and Quaternary geology of the Belgian continental shelf. Belgian Science Policy Office, SPSDII North Sea (D/2003/1191/12), 75 p. In the following paragraphs, reference is made to the figures and tables of this publication as Le Bot et al. (2003).

2.2.2 Overview of stability and geo-environmental criteria

2.2.2.1 Stability criteria related to soil conditions

Foundations

The function of foundations is to provide support to a structure that will restrict settlement and prevent failure by ground rupture. Scouring phenomena can lead to major instability of the structures, especially around the large gravity based ones. In particular, driven piles have to transfer the structural loads to the soil at some significant depth below the base of the structure. In an offshore environment, the loads acting on piles consist of: (1) vertical loads, induced by the wind turbine and the mounting equipment, and (2) horizontal loads, mainly dynamic, coming from waves, tidal currents and wind, but also dynamic bedforms. The resultant of the horizontal loads is an order of magnitude higher with respect to the vertical loads.

Foundation design is often based on an allowable bearing value (qa), defined as the maximum load that can be applied to a given geological formation without causing a settlement exceeding the tolerance for a given structure.

The ultimate load capacity of a pile consists of 2 parts: (1) one is due to friction, called shaft friction (Qf); (2) the other is due to end bearing at the base of the pile (Qb). In particular, cone penetration tests (CPT) act as a model pile test and provide a relatively reliable method for evaluating pile capacity. The cone tip resistance (qc), obtained from CPT measurements, may be used to estimate end bearing (Hunt, 1986; Budhu, 1999). The pile end bearing is governed by the cone resistance over a zone of 0.7 to 4.0 pile diameters below the pile tip, and 8 diameters above the pile tip (Hunt, 1986). The friction resistance (Qst), obtained from CPT measurements, can be used to estimate the shaft friction (Hunt, 1986; Budhu, 1999).

Submarine cables

Cables are vulnerable to damage by shipping (anchors, trawl equipment, dredging) and bed form migration (small to large dunes). For 90% of cable routes where damage to cables is likely, cable burial is the best value long-term solution to cable protection (Shaw, 2001). The risk for exposure of buried cables varies greatly with soil conditions. For a given soil type, an optimum burial depth exists: 2 m is a sufficient depth to bury the cable into medium to hard clay or rocks, but in sand, mud or soft clay, a depth between 2 and 5 m is required depending on the technical aspects for the burial (Shaw, 2001). CPT results can be used to derive soil design conditions for the top 0.1 to 1 m of the seabed although corrections may need to be applied to produce accurate results (Lunne et al., 1997, in Whitehouse et al., 2000).

2.2.2.2 Soil related parameters to be investigated:

Different aspects, mechanisms and parameters have to be investigated to prevent failure of the structures or breaking of the cables (Table 1).

Structure concerned	Aspects (Phase concerned)	Parameters needed
Foundations (in general)	general stability (exploitation phase)	Load capacity, settlement: point resistance, friction resistance, angle of internal friction, shear strength,… (info mainly from cone penetration tests)
	loading (exploitation phase)	sediment dynamics: transport rates, scouring, bedform migration (info mainly from temporal series of multibeam/side-scan sonar and sampling; hydrodynamic and sediment transport modelling)

Foundation driven in the solid substrate	drivability of pile (construction phase) settlement (exploitation phase)	solid substrate geology: nature, depth, thickness, homogeneity,… of geological layers (info mainly from a high resolution seismic survey and coring) solid substrate geotechnics: shear strength, local friction, point resistance, undrained cohesion, determination of an adequate bearing layer,…(info mainly from cone penetration tests)
Foundation put on the seabed	smoothing of the seabed (construction phase)	seabed sediments: nature and grain-size, seabed morphology: slope, bedforms, rock outcrops (info mainly from temporal series of multibeam/side-scan sonar and sampling)
Submarine cables	trench construction and infilling problems (construction phase)	seabed sediments: thickness, nature, grain-size sediment dynamics: transport rates (info mainly from sampling, multibeam/side-scan sonar; hydrodynamic and sediment transport modelling; geotechnical info from CPT's)

Table 1: Aspects, mechanisms and parameters to be investigated to ensure the stability of offshore wind turbine structures.

2.2.2.3 Impacts on sediment- and morphodynamics

Information on geo-environmental impacts from wind farms emanated essentially from different Environmental Impact Assessment reports (EIA) related to European wind farm projects.

Offshore wind energy structures (foundations, piles, cables) may have specific impacts on the physical environment, inversely marine processes may interact with the structures. The most important impacts related to geology consist of changes, which may affect: (1) sediment patterns, especially important towards habitats, and (2) sediment storage or budgets at a local (wind farm) to regional (e.g. coast) scale. Quality and quantity of possible impacts on the seabed are not well known, calling for surveys and specific project sites, as part of EIA and also as generic studies. To evaluate these impacts some parameters have to be known (Table 2).

Topics	Impacts	Parameter variation needed
seafloor characteristics	construction: sediment re-suspension exploitation: scouring	seabed morphology and nature (info from multibeam/side-scan sonar together with sampling)
sediment budget	exploitation: hydrodynamic and sedimentary changes, scouring, modification of wave pattern ?	sediment transport: erosion and accretion (info from temporal series of multibeam/side-scan sonar, sampling; hydrodynamic, sediment transport and wave modelling)

Table 2: Parameters needed to evaluate the impact of wind farms on sediment- and morphodynamics.

2.2.3 Qualification of the substratum: data synthesis

2.2.3.1 Geology

The most relevant soil characteristics for wind farm structures' stability are the nature, geometry and spatial distribution of geological units.

The soil is composed of 2 levels: (1) a solid level (oldest layers) which is "stable" at the wind farm exploitation time-scale, although internal stresses may be rapidly altered by foundations, and (2) a non-consolidated level (surficial sediments) subdued to currents and wave action.

Available data (Figure 4, Le Bot et al. 2003)

The data used to investigate the geological characteristics of the seabed and substratum essentially consist of seismic profiles (about 16,000 km, RCMG[2]) and cores (79, RGD[3] and BGD[4]). Seismic data (2D vertical) allow to determine the geometry (distribution and internal architecture) of geological layers. Cores consist in true 1D vertical data that provide information on the nature and potentially age of the geological layers (lithostratigraphy). Coupled and correlated together, these data allow to estimate the spatial distribution of seabed and substratum geological units.

Solid deposits

On the Belgian shelf, the Palaeogene deposits (minimum 110 m thick) are the only geological solid layers to evaluate regarding the stability of possible offshore wind farm structures.

The geology of the Palaeogene solid deposits of the Belgium continental shelf has been intensively studied over the past 20 years (Bastin, 1974; De Batist, 1989; De Batist et al., 1989; Henriet et al., 1989a, b; Mostaert et al., 1989; Jacobs et al., 1990; Liu et al., 1992, 1993; Jacobs & Sevens, 1993; De Batist & Henriet, 1995; Jacobs & De Batist, 1996).

- **Nature and structure of deposits**: 9 distinct units (Y1 to Y5, L1, L2, B1, P1, see Table 2, Le Bot et al. 2003) and a number of subunits have been identified within the Belgian offshore Palaeogene succession (De Batist, 1989; De Batist and Henriet, 1995). The main seismic characteristics of these units are also listed and have been compiled into a synoptic seismic and schematic type section (Figure 5, Le Bot et al. 2003). Knowledge on the nature (lithology) of solid deposits is not very detailed, although it has been improved in the framework of this project thanks to the interpretation and integration of 33 other wells (Tables 3 and 4, Le Bot et al. 2003). The Palaeogene deposits consist mainly of sandy and clayey layers, sometimes alternating within a layer. However, a high lateral variability of the Palaeogene deposits' lithology is expected in the across-shelf direction. Layers of sandstone have been observed in some onshore geological units and are probably present in the equivalent offshore units (L1, Y5, Y4, Table 2, Le Bot et al. 2003).

- **Distribution and geometry of deposits:** On the Belgian shelf the surface that truncates the sequence of Palaeogene strata coincides with the base of the Quaternary deposits (Mostaert et al., 1989). The Palaeogene deposits are gently dipping (0.5–1°) towards the NNE. The Palaeogene units Y1 to P1 are superposed from WSW towards ENE, the direction in which they subcrop successively (Figure 7, Le Bot et al. 2003). Thicknesses are highly variable from one unit to another, but quite constant within each unit (Figure 9-a, -b and -c, Le Bot et al. 2003). Maximum unit thicknesses are reported in Table 2, Le Bot et al. (2003). Distribution patterns vary, although some similarities can be drawn.

- **Deformations:** On the Belgian continental shelf, two different genetic types of deformations are encountered: (1) Basement induced deformations due to an external, regionally tension fields and consisting of folds, faults and collapses. They are essentially concentrated in 2 large areas (Figure 10, Le Bot et al. 2003), the Noordhinder and the Goote-Raan deformation zones and (2) sediment-dynamical or -tectonical deformations consist mainly of block-faulting, -tilting and -bending. They appear in the Y1 (Henriet et al., 1982, 1988; De Batist et al., 1989; Cameron et al., 1992) and B1 clayey units, due to a change in mechanical and rheological features of the sediment during compaction. The spatial distribution of 9 deformation types within Y1 has been mapped (Figures 11, 12-a and -b, Le Bot et al. 2003).

Non-consolidated deposits

They consist of sediments of Quaternary age. Some of them are relict, but others are currently mobile under the present hydrodynamical regime.

- **Nature and structure of deposits:** A laterally as well as vertically complex and heterogeneous facies assemblage characterises the Quaternary of the Belgian continental shelf. Their lateral extension is hitherto poorly known. Quaternary deposits can be regarded as the agglomerate of

[2] Renard Centre of Marine Geology
[3] Rijks Geologische Dienst
[4] Belgische Geologische Dienst

individual morphological subunits often with a very distinct stratigraphical build-up and lithological complexity (Bastin, 1974; Eisma et al., 1979). Sediments consist mainly of sand, intercalated with thin and numerous layers of various material (muds, silts, shells, gravels) (Tables a, b and c of Annex 4, Le Bot et al. 2003). The main deposits consist of (1) Holocene tidal sandbanks, and (2) Pleistocene scour hollow infillings (Figure 14, Le Bot et al. 2003).

- The Quaternary assembly of some of the sandbanks has been characterised (Figure 16, Le Bot et al. 2003), mainly from seismic investigations. As an example, the Middelkerke Bank (fTrentesaux et al. 1999) is vertically and laterally highly heterogeneous. It is composed of 7 distinct depositional units and 5 subunits, having very diverse sediment types, ranging from clay to gravel with a shell content of nearly 0 to more than 50 % of the total sediment (Trentesaux et al., 1999) (Figures 17 and 18, Table 7, Le Bot et al. 2003). Still research is needed to reconstruct the genesis of the sandbanks and to enhance the predictability of the occurrence of Quaternary deposits.
- Scour hollows correspond to holes of 5 to 20 m in the top surface of the solid layer (Quaternary base surface). Most of them have been filled by marine sediments of Late Pleistocene (mainly Eemian) to Weichselian age.

- **Distribution and geometry of deposits:** The Quaternary base is affected by numerous and various morphological features, such as scarps, slope breaks, cuestas, valleys and deep depressions (scour hollows, see precedent paragraph) (Liu et al. 1992, 1993) (Figures 20 and 21, Le Bot et al. 2003). The Quaternary deposits are generally thinner offshore: they range in thickness from a few metres to 50 metres (Figure 23, Le Bot et al. 2003). The larger thicknesses are reached in the Holocene tidal sandbanks (up to 30 m) and in Pleistocene scour hollows (20 to 50 m thick off Oostende and Bredene, 10 to 25 m at the NNE of the Noordhinder Bank). In some places, sandbanks and scour hollows are superposed (e.g. Oostende Bank, Figure 15, Le Bot et al. 2003).

2.2.3.2 Geotechnical properties

Available data (Figure 4, Le Bot et al. 2003)

The data used to investigate the geotechnical characteristics of the seabed and substratum consist of cone penetration tests and cores (respectively 177 and 79 evaluated). Cone penetration tests (CPT's) provide measurements of some geotechnical parameters of the geological layers, such as cone or point resistance (qc), friction resistance (Qst) and angle of internal friction (φ). Cores consist of true 1D vertical data, which allow to recognise the different geological units. By correlating the coring and CPT data, the geotechnical parameters of each geological unit can be evaluated.

Most of the available cone penetration tests have been realised on land (Department of Geotechnics from the Ministry of the Flemish Community through DOV[5]). Only 2 offshore sites were available, one on the Oostdyck sandbank (Ministerie van de Vlaamse Gemeenschap-DLI, AOSO-Afdeling Geotechniek, 1999) and the other on the Westhinder sandbank (Rijksinstituut voor Grondmechanica, 1988). Synthetic geotechnical information was also found in the reports of the new geological maps of Flanders (Jacobs et al., 1993, 1996, 1999a, 1999b, 2002).

Generalities

Typical CPT's are reported in Figure 6, Le Bot et al. (2003).

The cone resistance (qc) is largely dependent on lithology. Differences between pure sand and pure clay are clear. Clays and sands can be determined with absolute certainty when cone resistance values are respectively smaller than 2 MPa and larger than 15 MPa. However, most of the time, the values are in-between both limits and sediment nature is difficult to characterise.

The cone resistance allows to determine the presence of sandstone or calcareous layers (Tertiary), or thin layers of pebbles (Quaternary). These thin hard layers correspond to positive peak values of the cone resistance. They occur both in the Quaternary and the Tertiary deposits. The high positive peaks are however easier to recognise in the Tertiary homogeneous units, whereas it is difficult to locate them precisely in the Quaternary heterogeneous deposits. On the Belgian shelf, they are found in the

[5] Databank Ondergrond Vlaanderen

geological units composed of alternating layers of clay and sand: the Oedelem Member, Vlierzele Member, Pittem Member and Egem Member (see Table 2, Le Bot et al. 2003).

Quaternary deposits

Geotechnical properties of the Quaternary deposits are characterised by a very heterogeneous and irregular pattern, due to their complex facies assemblage. No specific characteristic trends can be drawn in the qc, Qst and φ values.

Tertiary deposits

Geotechnical properties of the Tertiary deposits (based on 111 CPTs) are more homogeneous. Contrary to the Quaternary deposits, it is possible to establish a synthetic description and quantification of the qc and Qst parameters (Tables 5 and 6, Le Bot et al. 2003).

The Tertiary clayey members have consistently lower values, which remain more or less constant over the whole unit. Members consisting of sand or a mixture of sand and clay often show no uniform pattern. No geographical evolutionary (e.g. from N to S) trends can be determined as all CPT's are confined to a small area.

2.2.3.3 Morphodynamics and sediment dynamics

Available data

Results of the Belgian Science Policy project 'BUDGET' are referred to (Lanckneus et al., 2001 ; Figures 1, 2 and 3, Le Bot et al. 2003). The report gives an overview and critical analysis of all data relevant for the study of the natural sand transport on the Belgian continental shelf.

Bedforms morphodynamics

- Sandbanks:
  Generally the sandbanks feature a major stability and this at least since 1800 (Van Cauwenberghe 1966, 1971; Table 1, Le Bot et al. 2003). Care is needed with smaller sandbanks that are more dynamic in nature and the sandy shoals under the influence of the Westerschelde estuary. Minor data are available on the stability of the Hinder Banken and the Zeeland Ridges.

- Dune structures:
  Generally, sandbanks are covered with dune structures, except for most of the Coastal Banks. These dunes are mostly in the range of 2 to 4 m and often increase in height towards the top zone of sandbanks. Figure 3, Le Bot et al. (2003) delineates areas with an indication of the dune heights divided in classes of 1-2 m, 2-4 m and more than 4 m.
  The outer ends of sandbanks and also non-linear parts of sandbanks generally show higher dunes (up to 8 m) that are also more dynamic in nature. On the Belgian shelf, migration rates of 20 m have been reported for various areas. The dunes are merely subject to oscillatory movements with a minor net migration. The swales are generally devoid of bedforms, except in the Hinder Banken area where high dunes were abundantly observed (Deleu, 2001, 2002).

Seabed sediment dynamics

- Seabed sediments:
  On the 'BUDGET' synthesis map (Lanckneus et al., 2001), the variation in median grain-size is represented in the range of very-fine, fine and medium sand and at some chosen locations the relative percentage of sand, mud and gravel is indicated through sediment classes. Where very-fine to fine sediments predominate, sediment resuspension becomes increasingly important. Gravely deposits are likely to be found in the swales and especially where the Quaternary thickness is minimal.

- Sediment dynamics:
  Especially towards the geo-environmental impact, more knowledge is needed on resuspension processes and the turbidity in the water column. It should be noted that these processes have a high temporal variability and are significantly influenced by dredging activities. Reference is made to the modelling results of the Management Unit of the Mathematical Modelling of the North Sea

and Scheldt estuary (MUMM). A general result of their sand transport model is presented in Lanckneus et al. (2001). Hydrodynamic and morphodynamic modelling should be performed to study erosion and accretion rates also in view of implantation of offshore structures and especially towards scouring.

2.2.4 Suitability of the Belgian continental shelf in view of seabed characteristics

2.2.4.1 Parameters relevant for stability and geo-environmental impacts

General

As far as soil conditions are examined, the most suitable geological layers consist of: (1) the most compacted and homogeneous layers; (2) the layers having a high shear stress and a good long-term behaviour. Suitable layers should have a sufficient thickness to cope with failure mechanisms.

As far as seabed conditions are concerned, the most suitable places correspond to locations where sediment dynamics are not too high. When gravity foundations are selected, the selected site is preferably smooth and devoid of pebbles.

Particularities on the Belgian continental shelf

- Soil parameters:
  The solid layers (Tertiary) predominantly consisting of sands are better than:
  1. Quaternary sandy deposits, which are less compacted and more heterogeneous.
  2. Tertiary clay layers that present a low shear strength and a bad long-term behaviour.

  Homogeneity of geological layers is an important factor to optimise the stability of offshore wind structures. Some deposits are not suitable from this point of view:
  - Quaternary deposits, which may show a huge complexity and heterogeneity (especially the scour hollows).
  - Layers affected by regional (faults) or internal (e.g. block-faulting, -tilting) deformations. Only some clayey units show internal deformations (Y1, B1 and R2).
  - Hard layers, such as calcareous or sandstone layers in Tertiary deposits, or pebble layers in Quaternary deposits. These layers are thin and difficult to locate, but may give rise to geotechnical uncertainties and problems.

  To conclude, on the Belgian continental shelf, the most interesting sites could correspond to areas consisting of a minimal Quaternary cover, and a sufficiently thick (in case of a driven pile, depending on the length of the pile) Tertiary sandy layer. Tertiary sandy layers marked by internal deformations and containing hard layers are preferentially avoided.

- Seabed parameters:
  Belgian offshore sandbanks are stable except for their upper surface parts. The older and larger sandbanks, that are more stable, should be preferred. If wind turbines are implanted in dune areas (on sandbanks or on the flat seabed), those having a small net migration rate would be considered as most suitable.

2.2.4.2 Conclusions, site recommendations

A geo-parameter hierarchical classification is difficult to establish. Referring to considerations exposed in the previous paragraphs, it appears that a classification will vary according to the type of structure (foundations, pile, cable), the type of foundation chosen (monopile or gravity based structure) and their further technological developments. Therefore, it was merely preferred to provide a sound knowledge-base on the most relevant geo-parameters and provide maps on their spatial distribution (ref. Le Bot et al. 2003). A combination is possible of various parameters enabling to produce scenario’s according, for example, to the type of foundation selected.

Examples of maps that can be produced are presented. The areas with the most suitable subsoil characteristics are indicated in Figure 1. The map of Figure 2 indicates areas where a more careful soil investigation is recommended because of potential hazards, especially in case of monopile structures. The map has been obtained through a combination of the spatial distribution of: (1) the Tertiary stone layers (not suitable), (2) the most heterogeneous Quaternary deposits (scour hollows) (not suitable), and (3) the faults (not suitable).

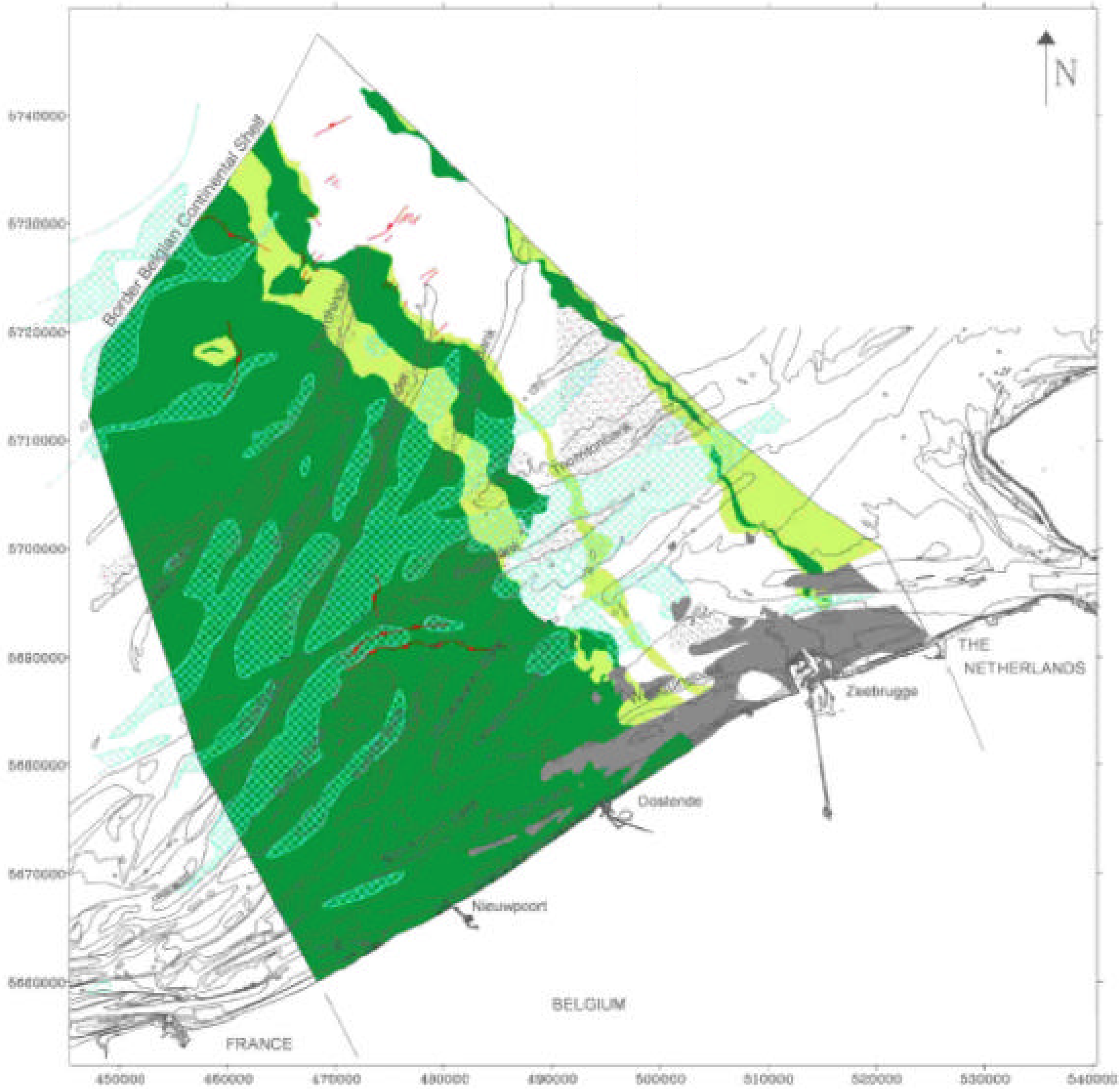

Figure 1: Map of the subsoil of the BCS indicating areas with the most suitable geotechnical properties. The map shows in green colour the structure of the soil (solid units), the dark green indicating clay and the light green indicating clayey sands which show homogeneous natural and geotechnical properties without stoney inclusions. Furthermore the map shows the seabed areas (non-consolidated unit) with thickness lower than 2.5 m (shaded blue) and dune areas (gray).

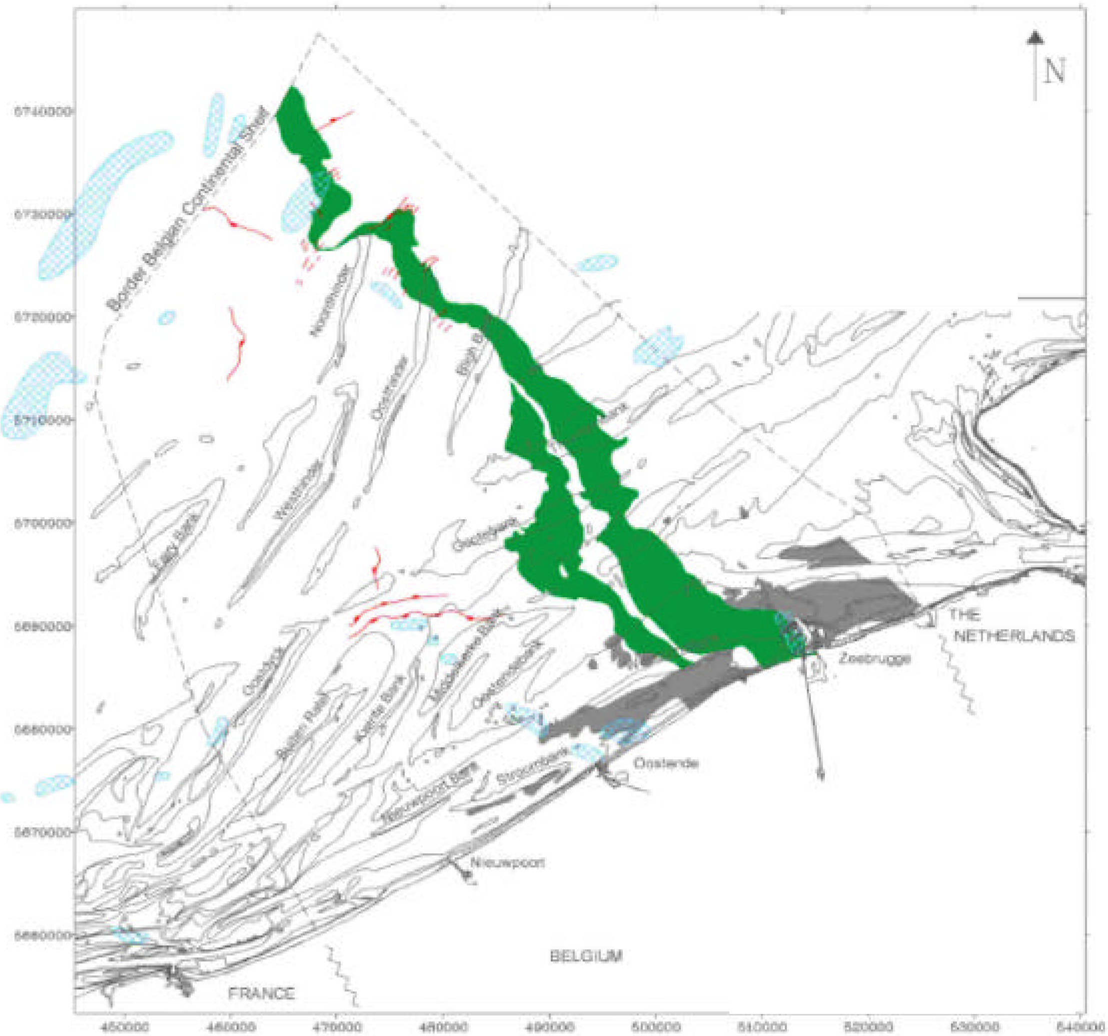

Figure 2: Map of the subsoil of the BCS indicating areas with geotechnical properties with potential hazards for wind farm foundation structures (monopiles). These areas have hard stone layers in solid units (Tertiary), and are marked up in the map in green colour. The scour hollows (light blue) need to be avoided. Furthermore the map shows some zones with important deformations, more specifically faults affecting solid units (marked with red lines).

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2.3 Wind resources

2.3.1 Approach and method

The wind resource of the BCS has been calculated at selected discrete altitudes above mean sea level. In accordance with current practice, the resource is expressed and geographically mapped in terms of the Weibull[6] parameters A (scale parameter) and k (shape parameter) characterising the long-term frequency distribution function of wind speed and wind direction.

In a first approach, existing offshore meteorological stations of the Flemish region have been used. The results of this simulation were not realistic, and showed a very inhomogeneous spatial distribution. For completeness, the approach and results are briefly described in par. 2.3.2.

In a second step, a method was looked after enabling to construct a wind resource map that interfaces well with that of the neighbour countries (UK, Netherlands, France). It was decided to base the resource estimation on the POWER method (ref. 1), which incorporates a very long period of meteorological observations, and gives values all over the European offshore waters. The results of applying this method have been compared with the available measurements of the above mentioned stations. Based on the outcome, a fine-tuning of the parameters was done, more specifically the Weibull shape parameter. The results are presented in the form of maps for various altitudes and are stored in a format suitable for the further steps in the estimation of the potential.

2.3.2 Extrapolation from existing offshore wind measurements

The initial approach was to estimate the wind resources from available long-term data collected at several measuring stations in or near the BCS. The data have been horizontally extrapolated using the software programme WAsP[7]. The resource is calculated at a level of 60, 80 and 100 m above mean sea level.

An overview of the available wind measuring stations is given in Table 3.

Station	Westhinder	Wandelaar	Droogte van 't Schooneveld	Vlakte v/d Raan	Cadzand
Symbol	MOW7	MOW0	MOW5	VR	CAWI
Code on map		B07		NL42	NL05
Responsible Institute	MFC	MFC	MFC	RWS – Dir Zeeland	RWS – Dir Zeeland
Structure	monopile	monopile	monopile	monopile	Onshore mast
Position co-ordinates Lambert72 [m]	(51°23'22"N; 2°26'21"E) (232624N; 15596E)	(51°23'43" N; 3°02'50"E) (232457N; 57928E)	(51°25'30"N; 3°18'59"E) (235426N; 65077E)	(51°30'16" N; 3°14'37"E) (244377N; 71780E)	(51°22'48"N; 3°22'39"E) (230399N; 80892E)
Height [m+TAW]	25.25	19.2	19.01	16.5	16.5
Distance to shore [km]	36.1	10.6	28.8	17.9	30.6

[6] The Weibull function is a probability distribution function, characterised by two parameters A (scale) and k(shape), very often used as a mathematical approximation for the long term frequency distribution of the wind speed.
[7] WAsP is a PC program for predicting wind climates and power productions from wind turbines and wind farms. The predictions are based on wind data measured at stations in the same region. The program includes a complex terrain flow model, a roughness change model and a model for sheltering obstacles.

Station	Westhinder	Wandelaar	Droogte van 't Schooneveld	Vlakte v/d Raan	Cadzand
Period	03/94–09/01	Juni 86–Sept 01	1986-1991	Nov 88–Dec 00	Maa 91-Dec 00
availability	92.58%	72.60%	62.57%	92.04%	96.83%
valid observations	365276	588345	131542	98032	83107
observations per day	144	144	96	24	24
Average wind speed [m/s]	8.5	7.8	8.2	7.6	6.4
Weibull A [m/s]	9.6	8.9	9.3	8.7	7.2
Weibull k[-]	2.18	2.07	2.15	2.22	1.92
Energy density [W/m²]	665	561	608	494	319
Prevailing wind direction	WZW (18.9%)	WZW (16.6%)	WZW (14.8%)	WZW (16.9%)	ZZW (17.3%)

Table 3: Main data about wind measuring stations used for assessing the potential

The positions of these stations are depicted in Fig. 3. The measuring stations are operated by Flemish and Dutch national authorities. The primary aim of the stations was to provide data for ship traffic in the North Sea, and not explicitly to collect data for wind resource analysis. Therefore, a detailed quality and consistency analysis of these data is needed.

A statistical analysis has been carried out for every measuring station. Thereafter, the 'ratio' between these measuring stations has been studied in order to estimate the spatial distribution of the mean wind speed (distance to the coast, North-South gradient) and for the extrapolation to the long term. The data have been extrapolated to relevant heights of 60, 80 and 100 m.

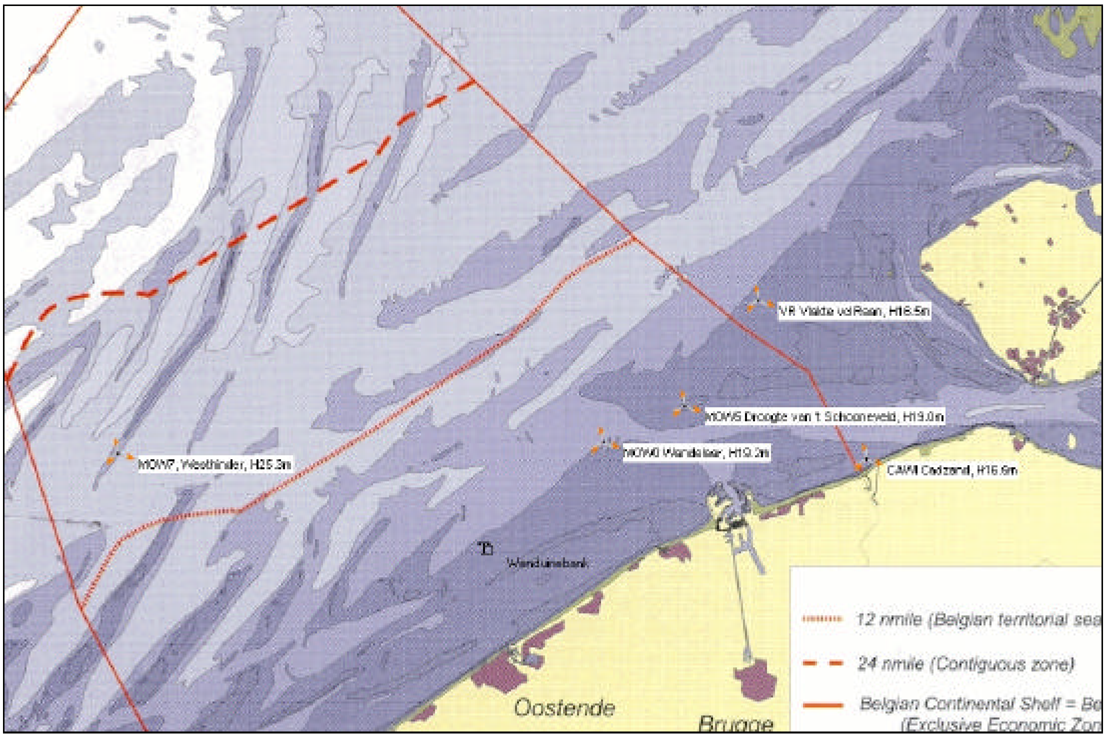

Figure 3: Position of the wind measuring stations used for the first trial calculation of the wind resources.

The data check revealed a high level of uncertainty (due to calibration errors, erroneous positioning of sensors, missing data etc.) for various stations, upon which it was decided to calculate a range for the wind resource (high and low level) rather than to give one specific value. A regional wind atlas of the BCS was constructed with a resolution of 1 x 1 km, in which the wind climate of every grid point was determined by its relative distance to the stations. The results of this extrapolation however were still more disappointing. The local influence of the measuring stations on the results was very strong and there was too little variation in the wind resource over the entire surface of the BCS. These results are clearly not plausible and it was decided to look for more appropriate methods.

The exercise learned that these coastal stations are not suitable for resource estimation of the entire BCS as envisaged for the present study. The main shortcomings are calibration, measurement set up, and data availability. The value of these stations however still is acceptable for estimations in the coastal area and for very specific limited periods.

2.3.3 The POWER (Prediction Offshore Wind Energy Resource) methodology

2.3.3.1 Introduction

POWER is a software tool developed within a European R&D Project[8] by an international consortium of European knowledge institutes. The applicability of the method has been investigated for resource estimation in the BCS because of its ease of operation, and not in the least because it yields an international map with figures compatible with those of the neighbour countries. Assistance for working with the POWER method has been provided by 3E's partner Ecofys BV, one of the POWER consortium partners. In paragraph 2.3.3.2 a description of the POWER method is given based on the project report [1]. A check of the method has been done by comparing its results to actual measurements at a couple of points. Then, wind resource maps of the BCS have been constructed for selected altitudes, and with a resolution suitable for the further potential estimation (1x1 km).

[8] EU project JOR-CT98-0268

2.3.3.2 Description of the POWER method

The POWER methodology does not rely directly on observed anemometer data to predict wind conditions offshore but uses grids of atmospheric pressure data at mean sea level covering the area of interest. The mean sea level pressure gradient is used to calculate the geostrophic wind. The geostrophic wind is transformed to the sea surface layer by applying the Wind Atlas Analysis and Application Program (WAsP). Since historical atmospheric pressure data date back to 1880 and beyond, the methodology allows the long-term variability of the offshore wind resource also to be investigated. A schematic flow diagram of the POWER methodology is shown in Figure 4.

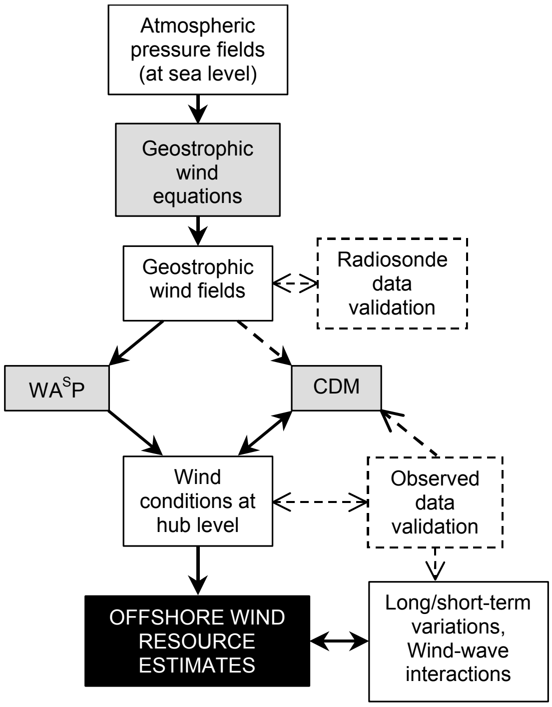

Figure 4: Flow schematic illustrating POWER methodology [ref 1]

Figure 5 shows the spatial distribution of the mean annual geostrophic winds calculated from the NCEP pressure data in the period 1985 to 1997.

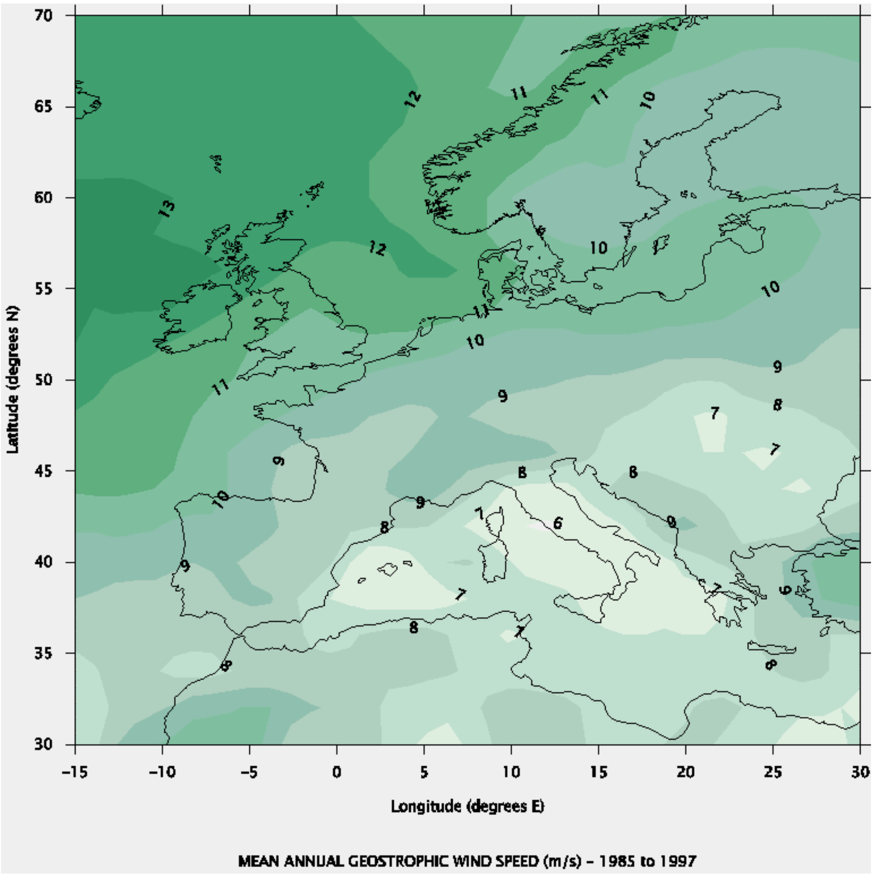

Figure 5: Calculated mean annual geostrophic wind speeds (m s-1) from 1985 to 1997 (ref. 1).

The Wind Atlas Analysis and Application Programme (WAsP) is used to transform geostrophic winds to the surface layer. The model’s calculations are based on the geostrophic drag law combined with models of stability and development of internal boundary layers (IBL). Originally, it was intended in POWER to model coastal effects assuming differences in mean onshore and offshore stability and using internal boundary layer theory to modify wind speed profiles over the width of the coastal zone.

The result of the POWER method is a database containing mean wind conditions for the period 1985-97 at eight hub heights at each POWER grid point over the sea. The hub height levels (10 m, 30 m, 50m, 70 m, 90 m, 110 m, 130 m and 150 m above mean sea level respectively) were chosen to cover the range of expected hub heights of wind turbines that are likely to be sited offshore in the coming years.

The POWER consortium did not succeed in finding an appropriate method for calculating the coastal effects on the wind flow as the input data of stability and coastline resolution were not available in the resolution needed. Therefore the results in the areas influenced by coastal induced flow[9] discontinuities should be taken with some reserve, especially at the altitudes relevant for wind turbines (70 m and above).

An example of the results from the WAsP runs performed is presented in Figure 6, a plot showing the distribution of mean wind speeds for the period 1985-1997 at 50 m above mean sea level throughout the POWER project area. POWER’s WAsP model results were compared by the POWER consortium with measured data from sites off the coasts of The Netherlands (Measuring Network Zeeland (ZEGE) and Measuring Network North Sea (MNZ)). These comparisons indicate that the POWER results show good agreement with the observed data in Dutch waters.

The applicability of the method was formulated in the POWER report as follows:

[9] Coastal induced effects on the wind flow should be accounted for within a distance from approximately 20 – 30 km from the coastline.

On a regional and national scale, POWER has produced state-of-the-art estimates of the extent and distribution of Europe's offshore wind energy resources not only in the coastal zone – the current focus of the offshore wind industry's attention – but also throughout the region's far offshore areas, where there is potential for wind energy to be exploited in the longer-term by turbines mounted on floating structures. Hence, this information will enable the most appropriate and economically attractive areas for offshore wind energy development to be identified, both now and in future.

On a local scale, POWER provides detailed first estimates of the long-term environmental conditions at specific offshore locations. This information is useful to the offshore wind energy industry since this is exactly the type of data required for initial scoping and feasibility studies for new offshore wind energy developments. It may be possible to base preliminary assessments of the turbine power output as well as other key parameters such as initial values of the design parameters for turbine support structures etc. on the POWER results. This enables the broad technical and economic feasibility of an offshore wind farm at a particular site to be established without the need to initiate costly and time-consuming an offshore meteorological data gathering campaign. If the site is suitable, more detailed (and short-term) wind and wave monitoring studies can then be performed at the site, which refine the initial POWER estimates for detailed design purposes.

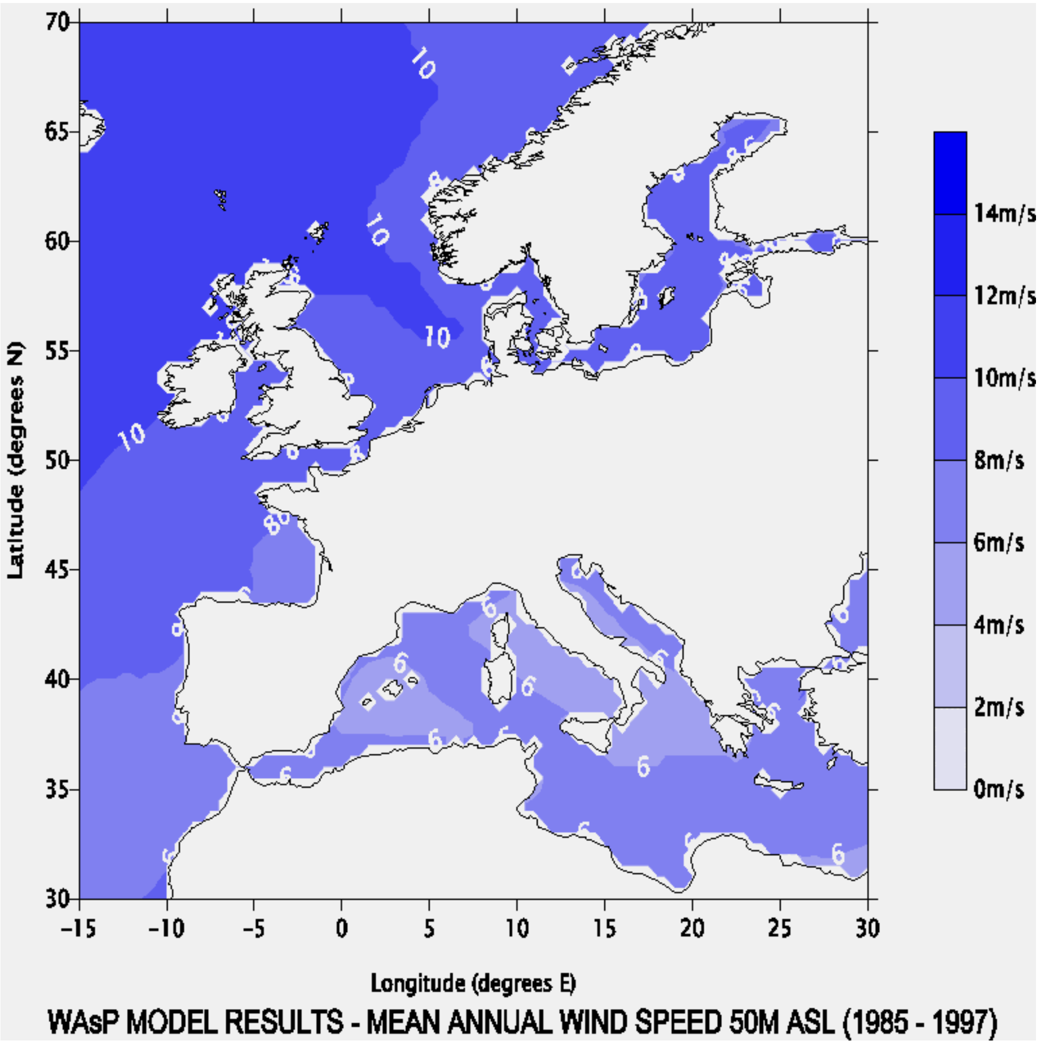

Figure 6: Distribution of mean annual wind speeds at 50m a.s.l. throughout EU waters (ref. 1)

2.3.3.3 Application and results of POWER for the Belgian Continental Shelf

From the POWER grid (0.5°x 0.5°), 7 grid points were selected in and around the Belgian Continental Shelf (BCS). These points are (Table 4) :

Point	Lattitude [°]	Longitude [°]	Lambert x [m]	Lambert y [m]	Dist to coast [km]
1	51.0	2.0	-16346	190314	0.0
2	51.5	2.0	-14571	245915	54.0
3	51.5	2.5	20140	244924	40.9
4	51.5	3.0	54856	244167	22.3
5	52.0	2.0	-12795	301530	106.3
6	52.0	2.5	21541	300550	87.3
7	52.0	3.0	55882	299801	74.9

Table 4: Selected points from POWER for calculation of the wind speed distribution.

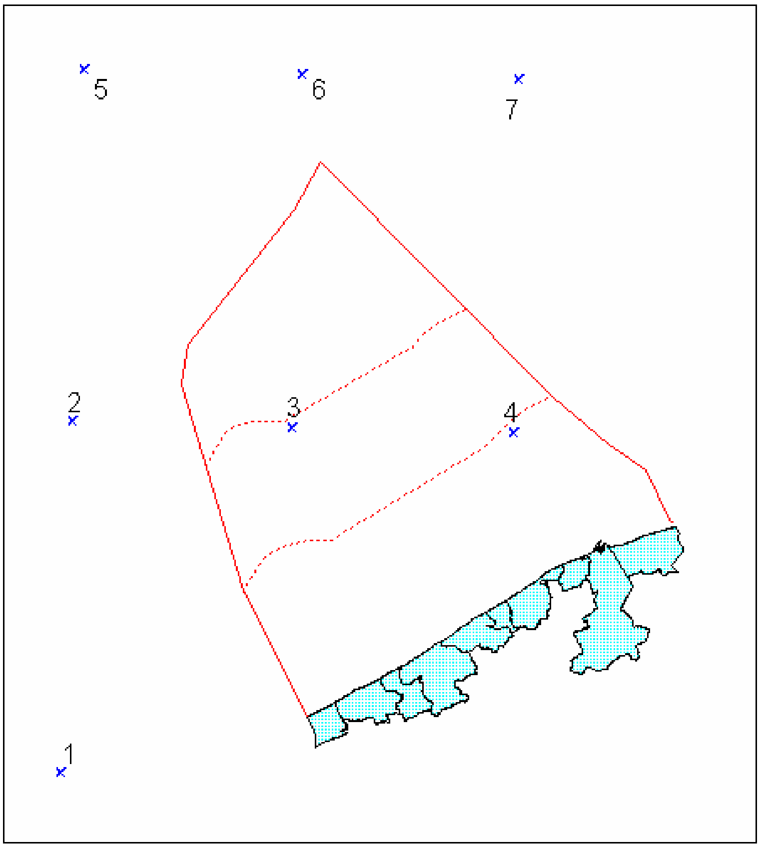

Figure 7: Selected points from POWER for evaluation of the BCS wind resources

For each of the seven points, the wind regime (mean wind speed, Weibull parameters A & k) has been calculated for the heights available in the POWER data base (10 m, 30 m, 50 m, 70 m, 90 m, 110 m, 130 m, 150 m).

The results are presented in Figure 8 and Table 5 as a function of the distance to the coast, at a height of 70 m. The lowest wind speed is 8.4 m/s, the highest is 9.4 m/s at the specific height. The values of the shape factor k vary between 1.7 and 1.8. These k values are much lower than generally found from offshore measurements and therefore have to be examined more carefully.

Grid point	Average wind speed [m/s]	Weibull A (m/s)	Weibull k (-)
1	8.4	9.4	1.8
2	9.2	10.2	1.7
3	9.2	10.3	1.7
4	9.1	10.2	1.7
5	9.4	10.5	1.7
6	9.3	10.5	1.8
7	9.3	10.5	1.8

Table 5: POWER results for the selected points (altitude 70 m)

From a distance of 20 km out of the coast, the wind speed increases almost linearly with the distance to the coast. This linear relationship can safely be used in order to interpolate the wind speed in the desired grid resolution for the estimation of the potential. For the area between 0 and 20 km from the coast, the values can be linearly interpolated between the calculated value at 0 km (point 1) and the value(s) at 20 km (point 4).

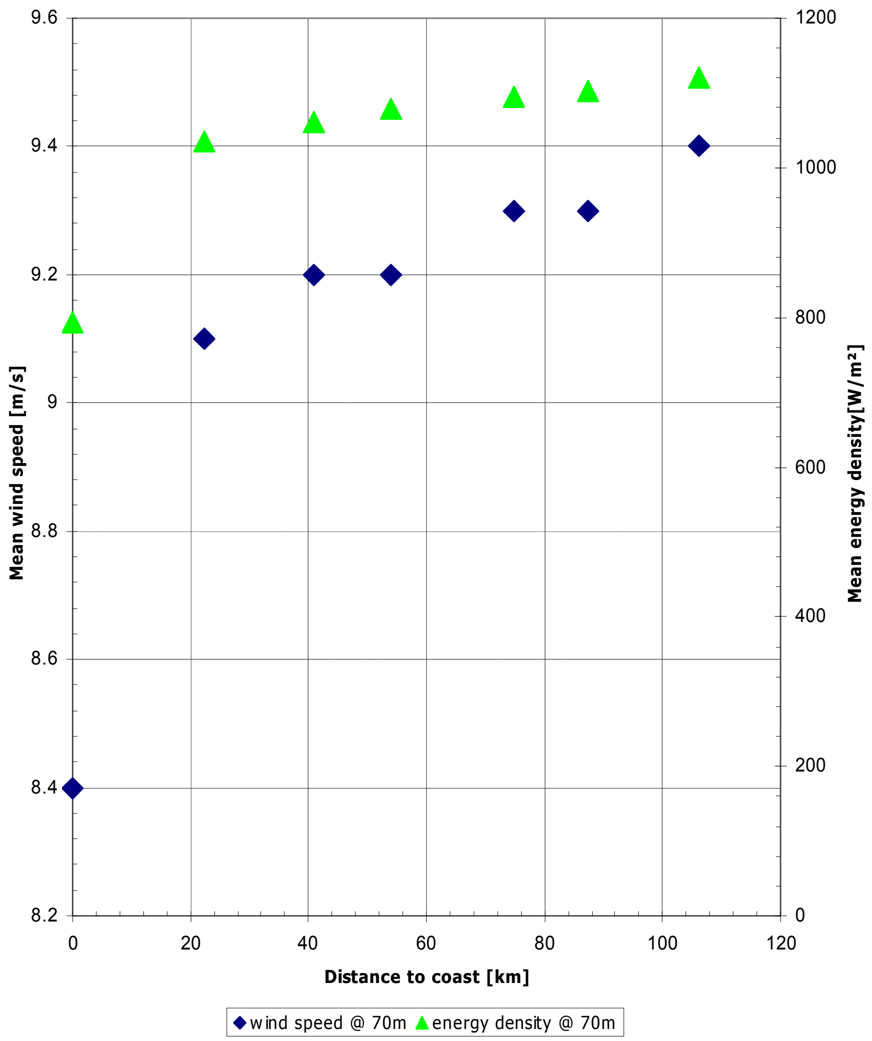

Figure 8: Variation of calculated wind speed as function of distance to the coastline. The corresponding values of the calculated energy density have been indicated as well, however should be taken with reserve because they are calculated with the low values of the Weibull shape parameter from POWER.

2.3.3.4 Verification with measured wind speeds

Verification with the stations MOW0 and MOW7

The calculations based on the POWER method (vertical wind profile) have been checked with the measurements on the Westhinder (MOW7) and the Wandelaar (MOW0). Station characteristics are given in Table 3. The calculated wind profile is given in Table 6.

	MOW0	MOW7
position	(58000,232500)	(15500,232500)
h	[m/s]	[m/s]
10	7.0	7.5
30	7.9	8.4
50	8.4	8.8
70	8.7	9.1
90	9.0	9.4
110	9.3	9.6
130	9.5	9.8
150	9.7	9.9

Table 6: Wind speed calculated from POWER results at the grid points nearest to MOW0 resp. MOW7.

The value at the actual measuring height at the stations position has been obtained by interpolation using a logarithmic vertical wind profile. The results for the two measuring heights for the two stations are:

Station	Measuring height [m]	Measured mean wind speed m/s	Calculated mean wind speed m/s
MOW0	19.2	7.5	7.5
MOW7	25.2	8.5	8.3

Table 7: Measured and calculated wind speed at MOW0 and MOW7

The agreement on the long-term appears to be excellent. The calculated and measured values at position of MOW0 are identical. The discrepancies at MOW7 position are almost nihil and could be attributed to the difference in measuring period (calculations in period 1985 to 1997, measurements only from 1994 to 1997).

An analysis on annual basis has been carried out as well.

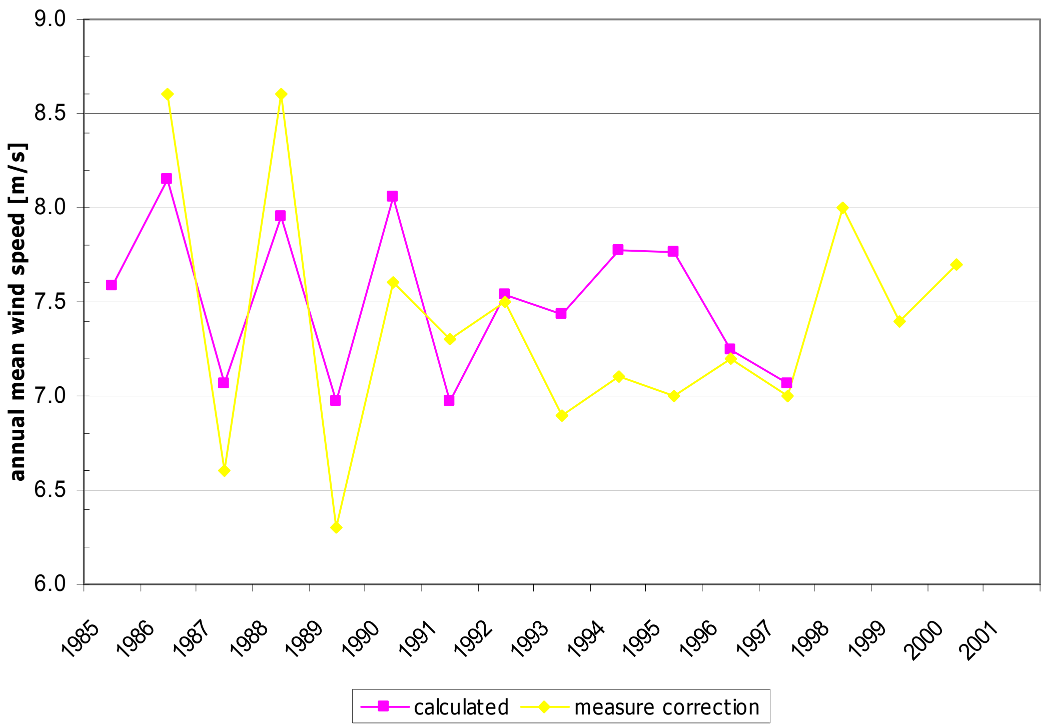

Figure 9: Yearly values of wind speed of MOW0, calculated (POWER) and measured.

year	calculated	measured	deviation	valid
1985	7.6			
1986	8.1	8.6	-5.3%	45.00%
1987	7.1	6.6	7.0%	71.43%
1988	8.0	8.6	-7.5%	62.66%
1989	7.0	6.3	10.6%	81.87%
1990	8.1	7.6	6.0%	77.52%
1991	7.0	7.3	-4.5%	87.84%
1992	7.5	7.5	0.5%	82.32%
1993	7.4	6.9	7.7%	33.08%
1994	7.8	7.1	9.4%	46.67%
1995	7.8	7.0	10.9%	17.91%
1996	7.2	7.2	0.6%	90.26%
1997	7.1	7.0	1.0%	96.81%
1998		8.0		93.55%
1999		7.4		87.36%
2000		7.7		85.63%

Table 8: Yearly values of wind speed of MOW0, calculated and measured.

Figure 9 and Table 8 show the measured annual average wind speed at MOW0 and the predicted annual average wind speed using POWER. The deviation (POWER versus measured values) is also indicated. A good comparison on annual basis is difficult to make because of the low availability and low amount of valid data in the comparison period. Moreover, a very detailed analysis of the MOW0 data[10] revealed that the station overestimates the mean annual wind speed in 1988 and underestimates in 1989. The analysis also made clear that the pattern of the MOW0 mean annual wind speed in the period 1992 -2001 doesn't follow the pattern of other measuring stations (e.g. in the Netherlands). MOW0 systematically indicates lower values in 1992-1996 and too high values in 1997 to 2001.

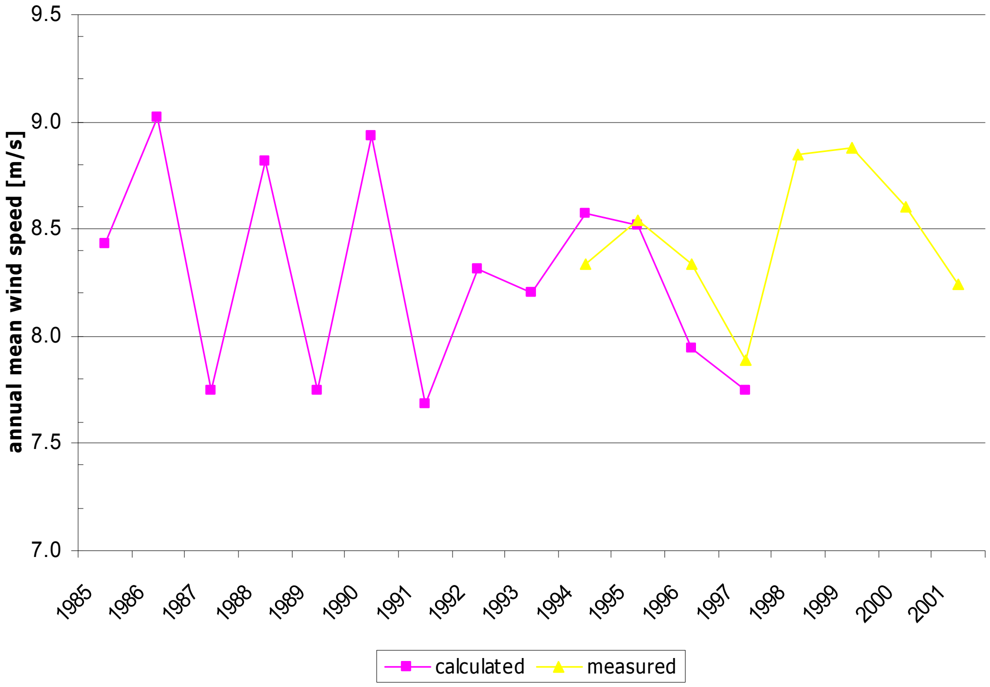

Figure 10: Yearly values of wind speed of MOW7, calculated and measured

Figure 10 and Table 9 show the measured and calculated annual average wind speed at MOW7 position. The difference for the year 1994 is partly caused by the fact that the measurements started only in March, and hence do not cover the complete year 1994. The reason for the discrepancy between the measurement and the prediction for the year 1996 has not been detected.

year	MOW7 calculated	MOW7 measured	MOW7 deviation	valid
1994	8.6	8.3	2.8%	69.14%
1995	8.5	8.5	-0.3%	88.29%
1996	7.9	8.3	-4.8%	96.42%
1997	7.7	7.9	-1.8%	97.13%

Table 9: Yearly values of wind speed of MOW7, calculated and measured.

Conclusion

An analytical method has been used to determine the distribution of the wind resources over the BCS, i.e. the POWER method. Data from this method have been interpolated to determine values in a grid of 1 by 1 km in the whole BCS. The results have been compared with measurements at some selected points in the BCS. On the long term there is agreement between calculated and measured values. A more detailed comparison can hardly be made because of the poor quality of the measurements at these stations.

The POWER method also has its limitations and disadvantages. First of all, the grid is rather coarse. Secondly, it is admitted by the designers of the POWER method that the effects of the coastal discontinuity are improperly taken into account. The method needs further development to correctly

[10] Formerly carried out for a private client of 3E.

calculate the wind speeds in situations where the vertical profile is affected by the coastal discontinuity. Finally, the calculated shape factor k is much lower than values commonly found. The effect of the k value on energy production is presented in Section 4. For the purpose of the present study, a default value k=2 is assumed at hub height (Rayleigh distribution), and the influence of variations of k on the energy production can be estimated from spider diagrams (Annex 3).

It can be concluded that the POWER method gives an acceptable first estimation of the long-term average wind resource in the BCS. The accuracy is good enough for this purpose but not high enough for detailed feasibility assessments. The resulting maps are compatible with those of the neighbour countries. The only way to improve the accuracy is to carry out high quality wind measurements with offshore meteorological masts sufficiently close to the envisaged sites and at altitudes equal or higher than 70 m to reduce the uncertainty on the vertical wind speed profile.

2.3.4 The wind resource in the BCS

2.3.4.1 General

This paragraph describes the long-term wind climate of the Belgian Continental Shelf for the purpose of the potential estimation. The values presented are the long-term mean annual wind speeds as calculated with the POWER method and interpolated as described in the previous paragraphs. Maps are given for five different altitudes (70, 90, 110, 130 and 150 m).

2.3.4.2 Results and discussion

The maps are generated in a GIS programme. The results are presented in contour maps of wind speed with intervals of 0.1 m/s. Because of the applied method, the values increase linearly with the distance to the coast, with a steep increase from 0 to 20 km, and a subsequent gradual increase further offshore. The accuracy in the first 20 km should be considered to be less than in the far shore areas as the coastal induced effects on the wind flow are not fully taken into account.

The range of values obtained is summarised in Table 10.

	70 m	**90 m**	**110 m**	**130 m**	**150 m**
lowest	8.4	8.7	9.1	9.2	9.5
highest	9.4	9.6	9.8	10.0	10.2
WF areas	9.1	9.4	9.6	9.8	10.0

Table 10: Typical values for average wind speed (m/s) at different altitudes in the BCS (from 70 to 150 m). The lowest values apply near the coast, the highest far offshore. "WF areas" indicates: typical average wind speeds in the area where actual wind energy developments in the BCS are ongoing (Thornton Bank) or envisaged (designated area considered by the Belgian Federal Authorities).

The long-term average wind speed at hub heights of wind turbines (above 70 m) in the BCS varies between 8.4 and 10.2 m/s. The frequency of occurrence of the wind speeds can be assumed to be Rayleigh[11] distributed (Weibull shape factor k=2). The prevailing wind direction is West-Southwest.

Detailed maps are given in the following.

[11] The Rayleigh distribution is a Weibull probability distribution function where the value of k equals 2.

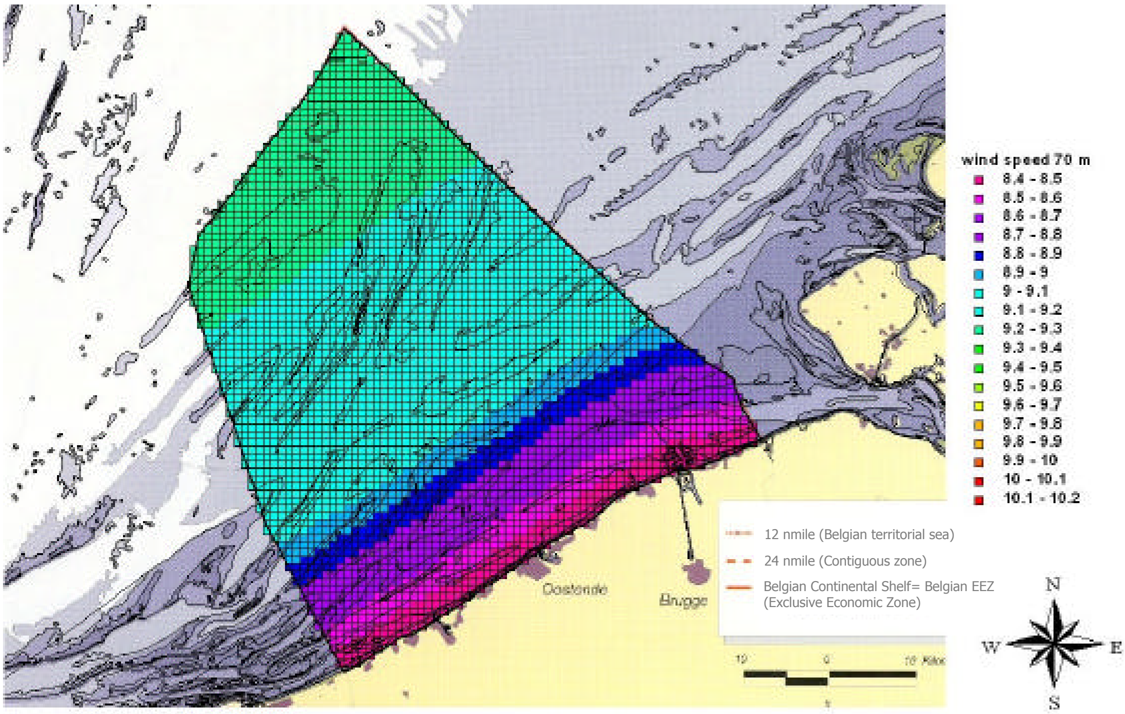

Figure 11: Wind speed at 70 m above mean sea level

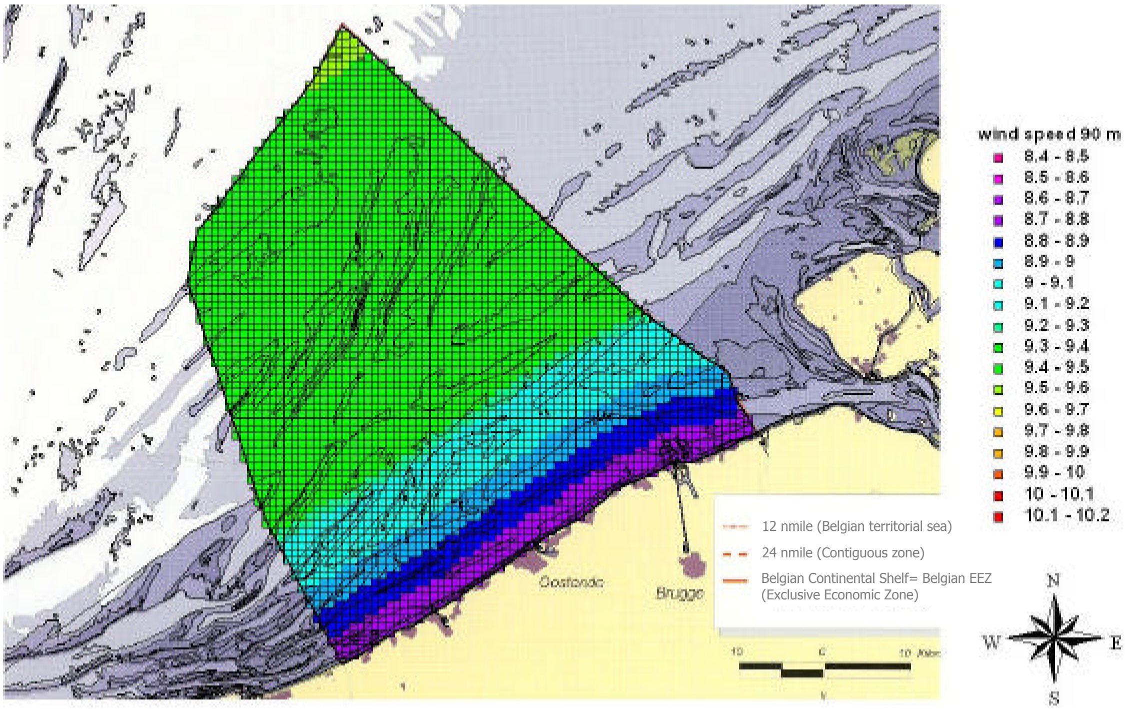

Figure 12: Wind speed at 90 m above mean sea level.

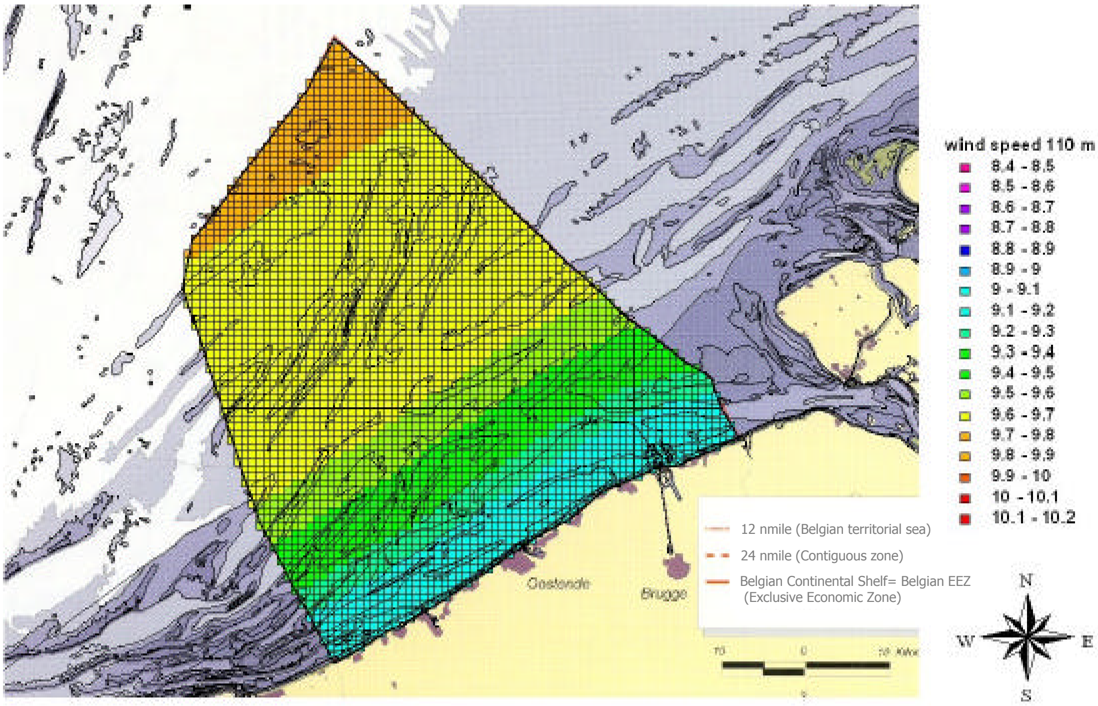

Figure 13: Wind speed at 110 m above mean sea level.

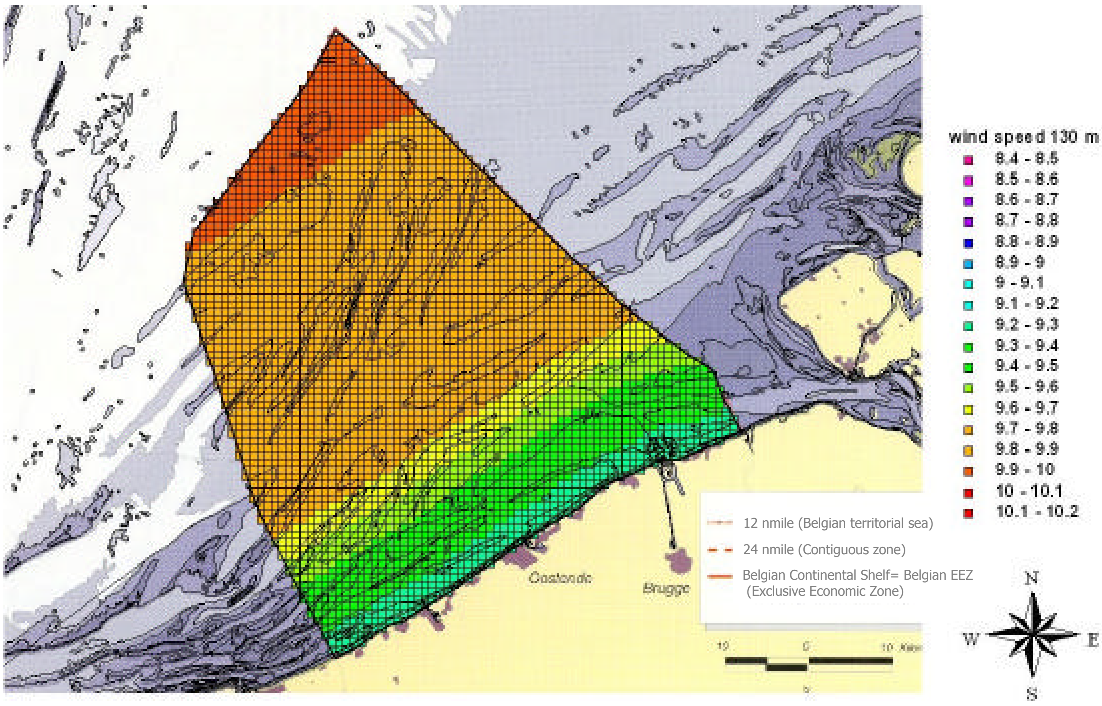

Figure 14: Wind speed at 130 m above mean sea level

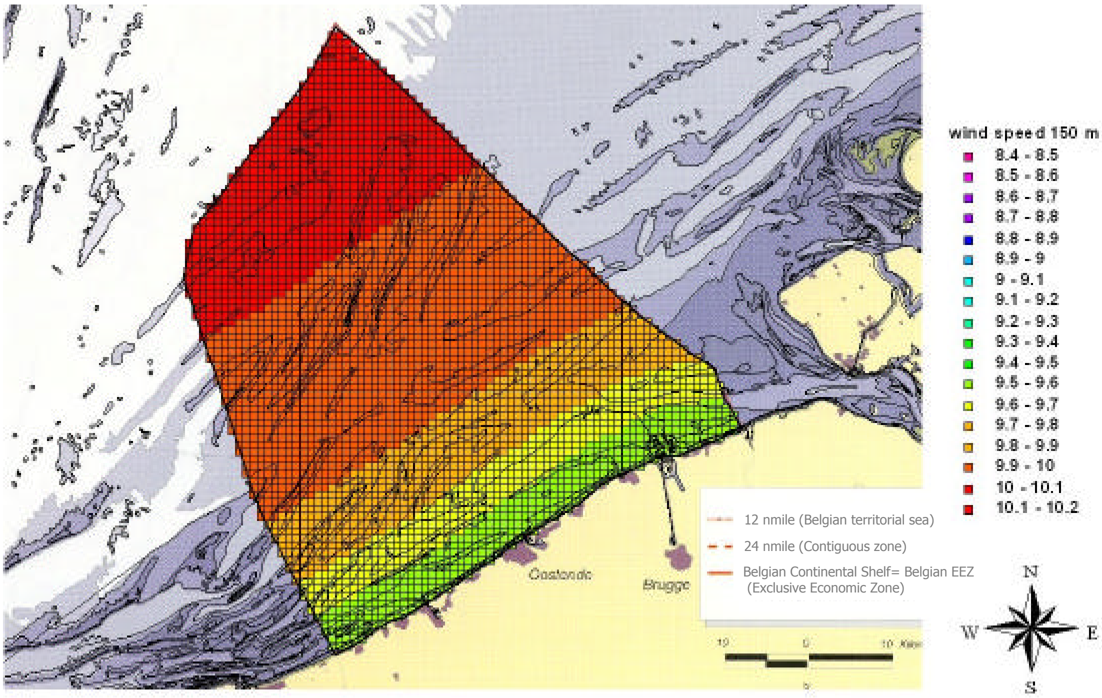

Figure 15: Wind speed at 150 m above mean sea level

2.3.5 Wind speed spatial distribution from satellite observations with Synthetic Aperture Radar SAR

An innovative technology can be mentioned here for the estimation of the spatial distribution of wind speeds, based on Earth Observation techniques, namely Satellite Synthetic Aperture Radar (SAR) wind mapping.

SAR utilises active systems carried onboard several present satellites, i.e. the European satellites ERS-2 and Envisat and the Canadian satellite Radarsat-1. The SAR antenna sends pulses of microwave radiation (at C-band) to the side of the satellite track and records the signal scattered back to the antenna. Over the sea, the backscattered energy is related to the amount of wind-generated capillary and short wave length gravity waves on the sea surface. Therefore, a relationship exists between the wind speed and the normalised radar backscattering cross section over the sea. With this relationship, one tries to derive high spatial resolution offshore wind maps from SAR images for use in offshore wind farm siting.

The SAR image presented here is from the ERS-1 and ERS-2 satellites with a ground coverage of 100 km x 100 km. The image is calibrated to an absolute reference to obtain values for the normalised radar cross section (NRCS). These values are translated into wind speed at 10 m above sea level using an empirical C-band model function and the local incidence angle and wind direction. The wind direction is derived from the direction of wind streaks on the sea surface.

The project team had the opportunity to obtain an image from the Norwegian Institute NERSC, which is specialised in this technology. It has been included in the report mainly for illustration purpose. A meteorological situation has been selected where the average wind speed, measured at one of the coastal stations, is close to the annual average wind speed offshore (ca. 9 m/s) and the wind direction close to the prevailing wind direction (Southwest).

Figure 16 shows a wind map retrieved from SAR images. The wind directions on the map are derived from FFT within 8x8 boxes over the image. Although not completely covering the BCS, at first look the image tends to confirm the initial steep and later on more gradual increase of wind speed with distance from the coast. Very close to the coast, the wind speed values shown are probably not correct. The wave patterns in this region are strongly influenced by other effects than wind, namely tidal currents, bathymetry etc.

It has to be remarked that the image only gives a snapshot! Typically, about 50 images as a minimum are required in order to allow drawing up a long-term frequency distribution. More information can be found at the web site[12] of the ESA sponsored project EO-Windfarm, which investigates the market potential of this technique for wind farming purposes more in detail.

For potential studies, such as the present one, such information is not (yet) adequate.

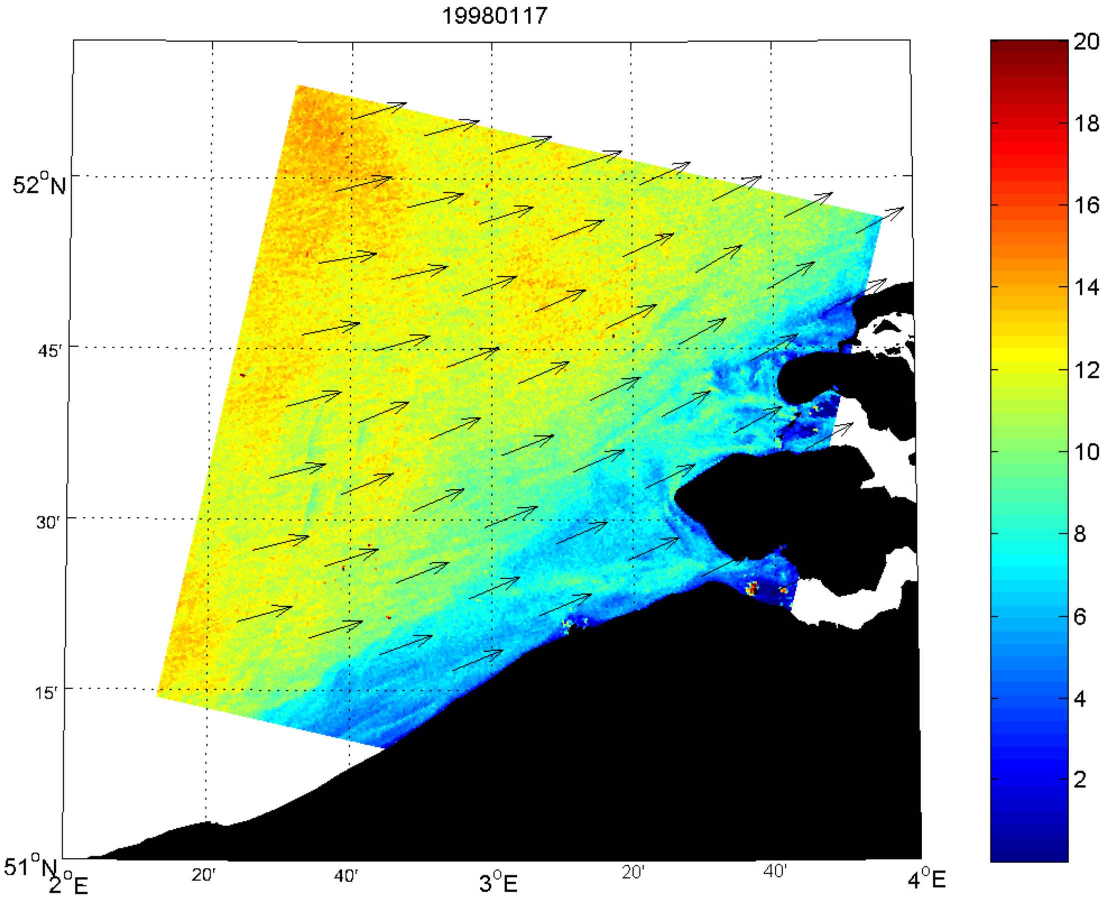

Figure 16: SAR Wind Mapping from Satellite Observations (17 January 1998)

2.3.6 Conclusions, summary

An attempt has been made to derive the long-term wind climate distribution in the BCS by extrapolation from measurements at coastal stations. The resulting wind maps are not plausible, the main reason is the low quality of the data sets in view of wind potential assessments.

Thereupon it has been decided to base the wind mapping on the POWER method. The distribution over the BCS of the long term average wind speed has been derived from seven data positions of POWER and by linear interpolation as function of the distance from the coastline. As opposed to POWER, the wind speed frequency is assumed to be Rayleigh distributed. Maps have been constructed with a resolution of 1x1 km and for five relevant altitudes, from 70 to 150 m. The average wind speed varies between 8.4 m/s at 70 m height near the coast to 10.1 m/s at 150 m height far offshore. In the areas where wind farm development can be expected in the near future, the values vary between 9.1 and 10.0 m/s, depending on altitude and distance from the coast.

[12] http://www.nersc.no/EO-WINDFARM

The estimation of the long-term offshore wind characteristics still cannot be performed very accurately. The modelling of the flow is not yet fully developed and does not yet permit an accurate description of the wind characteristics at any location and at altitudes relevant for wind energy (higher than 70 m above sea level). Insufficient offshore measuring stations are available which record the wind parameters continuously at sufficient altitudes.

In order to make better evaluations of the resource, it is recommended to set up an improved offshore wind measurement campaign in the BCS. It is recommended to measure as close as possible to wind turbine hub height, that means at least at 70 m above mean sea level. It is also recommended to explore the potential for innovative possibly cost effective techniques and methodologies based on remote sensing (EO based wind resource mapping, SODAR, Lidar) to develop an even better understanding of the wind energy resource offshore.

2.3.7 References

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2.4 Availability of High Voltage grid connection

2.4.1 Approach and method

Static and dynamic simulations have been performed in order to investigate to which extent the Belgian HV-grid can cope with offshore wind power.

The dynamic behaviour of the system is very closely related to the grid connection scheme of the wind farm. Therefore, the dynamic behaviour will be discussed in 3.3.

As input of the calculations, a model of the Belgian HV-grid is used. That model includes every Belgian node in the range from 380 kV down to 70 kV and also the main nearby foreign nodes. The parameters of the lines, transformers and capacitor banks are known and included in the model. For the load and generation pattern, reference scenarios are considered.

The wind turbine model used for the static load flow the calculations is the constant speed induction generator model, leading to worst case conclusions.

Furthermore, the power transit from France to the Netherlands, partially passing through Belgium and partially through Germany, is taken into account, as this power transit also affects the loading of the critical link between Rodenhuize and Heimolen.

As every potential Belgian offshore wind farm will most likely be connected to the nodes in Zeebrugge or Slijkens, the static load flow calculations are focused on the maximal power that can be injected at Zeebrugge or Slijkens, before causing electrical problems on the grid. The impact of a possible additional link between Koksijde and Slijkens, and of a reinforcement of the connection Rodenhuize-Heimolen is studied.

2.4.2 Existing power system

Figure 17 shows the main existing power plants in Belgium.
Figure 18 shows the 400 kV, 220 kV and 150 kV high-voltage lines. There are three 150-kV nodes in the coastal region: Zeebrugge and Slijkens in the Northeast and Koksijde in the Southwest.

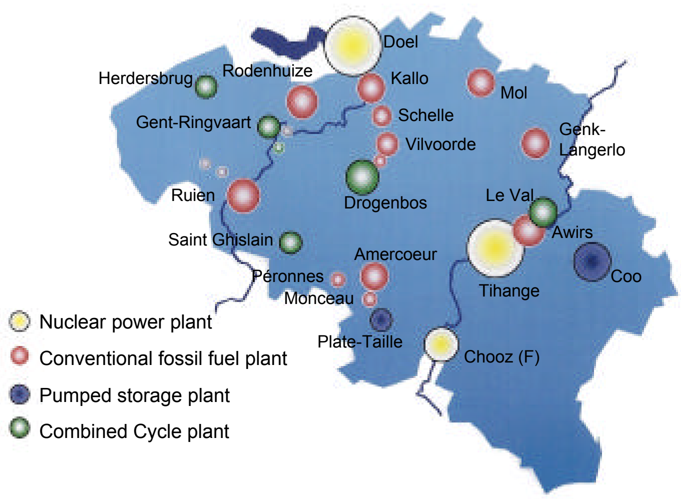

Figure 17: Main power plants of Belgium

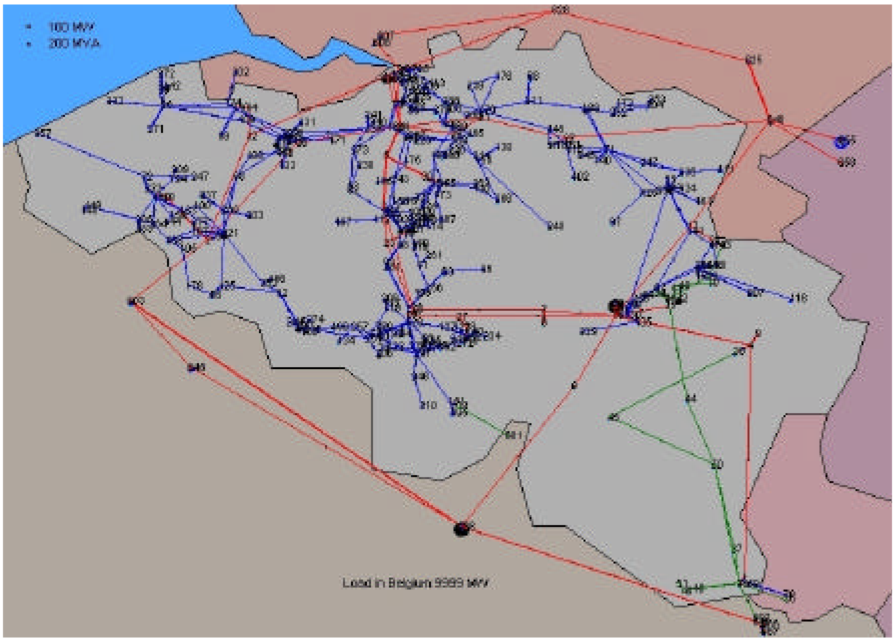

Figure 18: Belgian HV-grid (380, 220 and 150 kV)

With the power plants in Herdersbrug (460 MW), Gent-Ringvaart (460 MW), and Rodenhuize, there already is over-capacity in production in the northern part of Western Flanders, compared to the relatively light load. To the south, there is the main power plant of Ruien. All these power plants are connected to the 150 kV-grid. As a consequence, the dominant power flow in this part of the Belgian 150 kV power system is from the coast inland to the area around Gent-Rodenhuize, and from there via Heimolen towards Mercator, the main node between the Antwerpen-Brussel area, as shown in Figure 19. Line overload problems are most likely to occur at the link between Rodenhuize and Heimolen, as will be explained in the calculation results.

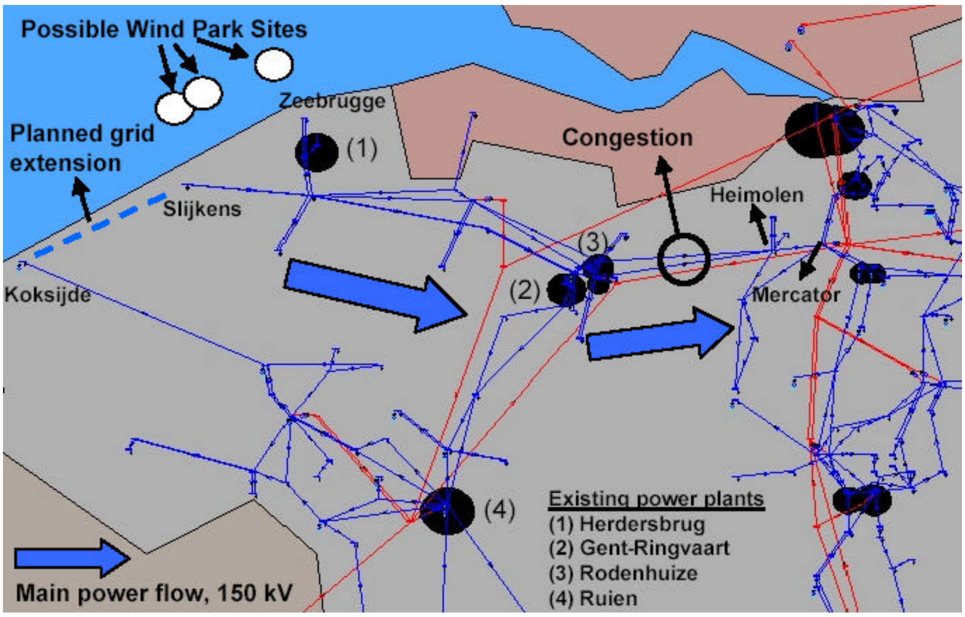

Figure 19: Main power flow on the 150 kV lines in Western Flanders.

2.4.3 Static load flow calculations

2.4.3.1 Procedure

Static load flow calculations investigate the risk of system overload, voltage instability and (N-1)-safety problems.

System overload occurs when the transmitted power through certain lines or transformers is above the capacity of these lines/transformers.

System static voltage instability may be caused by a high reactive power demand of wind turbine generators. Depending on the type of generator chosen for the wind turbine, the reactive power demand (in MVAr) can be as high as 40% of the active power produced (in MW). Generally speaking, a high reactive power demand causes the system voltage to drop. By a static voltage stability study, the system voltage in steady state is investigated.

For the calculations, a worst case scenario was used, i.e. wind turbines equipped with induction generators without compensation for the high reactive power demand.

(N-1)-safety means that any single element in the power system may fail without causing a succession of other failures leading to a total system collapse. Together with avoiding constant overloading of grid elements, (N-1)-safety is a main concern for the grid operator.

As input of the calculations, a model of the Belgian HV-grid is used. That model includes every Belgian node in the range from 380 kV down to 70 kV and also the main nearby foreign nodes. The parameters of the lines, transformers and capacitor banks are known and included in the model. For the load and generation pattern, 24 reference scenarios are considered, as defined in Table 11.

Loading, GW			Summer	Intermediate	Winter
Weekends	night		6	7	8
	day	low	7.25	8	9
		high	8.5	9	10
Weekdays	night	low	8	8	9
		high	8.5	9	10
	day	low	9	10	11
		high	10	11	12
		peak	10.5	12	13

Table 11: Load levels of reference scenarios

The load and generation patterns depend on:

- the season (summer / winter / intermediate)
- weekday or weekend
- time of the day (night / day off-peak hour / day peak hour)

Furthermore, the power transit from France to the Netherlands and further to Germany is taken into account, as this power transit also affects the loading of the critical link between Rodenhuize and Heimolen. The power transit was modelled by an extra power flow from Avelin (F) to Avelgem (B) and from Lonny (F) to Achène (B), ranging from 800 MW to 2000 MW in total, and an extra power demand at the Dutch border nodes.

As every potential Belgian offshore wind farm will most likely be connected to the nodes in Zeebrugge or Slijkens, the static load flow calculations are focused on the maximal power that can be injected at Zeebrugge or Slijkens, before causing system overload, static voltage instability or (N-1) –safety problems. The impact of a possible link between Koksijde and Slijkens, and of a reinforcement of the connection Rodenhuize-Heimolen is studied.

2.4.3.2 Results

The results are presented in Annex 1.

These tables show the maximum amount of power that can be injected at Zeebrugge or Slijkens before a line is overloaded or before (N-1)-safety is no longer assured. Voltage stability did not turn out to be a problem in a static regime, even not with the high reactive power consumption of the induction generators in the turbines.

During off-peak hours (weekends and weeknights), the limiting factor in the present grid is simply the power line capacity from Slijkens to Brugge (i.e. 300 MVA) or from Zeebrugge to Brugge (i.e. ca. 400 MVA). With local loads in Slijkens and Zeebrugge, injection capacity can become somewhat higher. With a connection Koksijde-Slijkens, power can be transported to Koksijde, increasing the injection limit, up to 500 MW in Slijkens (the highest value that was checked). The addition of extra transmission capacity further inland (i.e. Rodenhuize-Heimolen) does not influence this limit.

Very often, lower limits are found. These are due to overloads further inland, in the Rodenhuize-Heimolen region, i.e. well beyond Brugge and even beyond Gent. This overload is only slightly alleviated by the Koksijde-Slijkens link. Obviously, the Rodenhuize-Heimolen reinforcement does alleviate this overload.

It must be stressed that the grid limitations encountered here are not due only to offshore wind power. They are a combination of:

- off-shore wind power,
- the already present power flow from the region around Brugge towards Gent and beyond,
- cross-border power transits.

With the present grid and the presently existing power plants operating at their normal output level, only a very limited amount of power from offshore wind farms can be transported during weekdays, which is the period where electricity has the highest economic value. Thereby it has been assumed that the wind farm power factor cannot be controlled, which is a worst case assumption. In practice wind power plants can be controlled to a large extent in order to optimise the power quality.

Without attaching too much importance to the precise values obtained here (calculations are based partly on precise information, partly on educated guesses), it is clear that grid improvements are required to give offshore wind power a real chance in the market place. The main improvement comes from extending the transmission capacity in the Rodenhuize-Heimolen region. This grid improvement would incidentally also allow higher transit levels.

2.4.4 Conclusion

Concluding from the result tables, the amount of offshore wind power that the HV-grid can absorb may vary from 50 MW to 750 MW, depending on the load scenarios and the grid reinforcements. When the installed offshore wind power exceeds 500 MW, major grid reinforcements will be required to ensure grid availability for most load scenarios. These grid reinforcements include probably the extension of the 400 kV- grid towards the coastal substations of Slijkens or Zeebrugge, which is a major investment.

2.5 Limitations to the available sea area of the BCS

2.5.1 Approach and method

A survey is made of the factors that are limiting the wind energy resource and as such are excluding areas for siting of wind farms of the BCS. These are related to different types of external boundary conditions:

1. Historical assignment of areas of the BCS for various economical and other activities such as sea traffic, extraction of sand, military exercises etc.
2. Restriction on areas for wind farm development for protection of the marine environment;
3. Restriction on available areas by possible socio-economic impact (fishery, visual impact, tourism etc);
4. Future expected zoning in the North Sea. This is depending on short and long term national policies and on the relative success of the various actors planning to make use of the various resources in the sea.

In view of the high level of uncertainty of future planning, the last of the above listed items is not taken into consideration in the estimation of the potential.

The remaining aspects are considered further as three categories (existing restrictions, environmental protection and socio-economic impact), and will be discussed separately.

In order to clarify the basics, at first a description is given of the various zones of the BCS in paragraph 2.5.2. Bathymetry (water depth), a very important parameter in the feasibility assessments of offshore wind projects, is described in paragraph 2.5.3.

2.5.2 Maritime zones in the North Sea

2.5.2.1 Definitions

- Maritime zones are measured from the baseline, usually the low-water line along the coast or a straight line where the coast line is deeply indented.
- The territorial sea is that part of the sea which is adjacent to the coastal states, up to a limit of 12 nautical miles[13] from the baseline.
- The contiguous zone is a zone adjacent to the territorial sea up to 24 nautical miles from the baseline.
- The continental shelf is considered as the natural extension of the land territory. Division of the continental shelf in the North Sea between the coastal states is a result of delimitation agreements. In the nineties Belgium concluded delimitation agreements with France, the UK, and the Netherlands
- The exclusive economic zone: every coastal state is entitled to an exclusive economic zone (EEZ) no further than 200 nautical miles from the baseline. For Belgium, the borders of the EEZ coincide with the continental shelf.
- Fishery zones of the North Sea are limited to 200 nautical miles from the baseline.

2.5.2.2 Belgian maritime zones

The Belgian maritime zones are presented in Figure 20.

[13] 1 nautical mile = 1.86 km

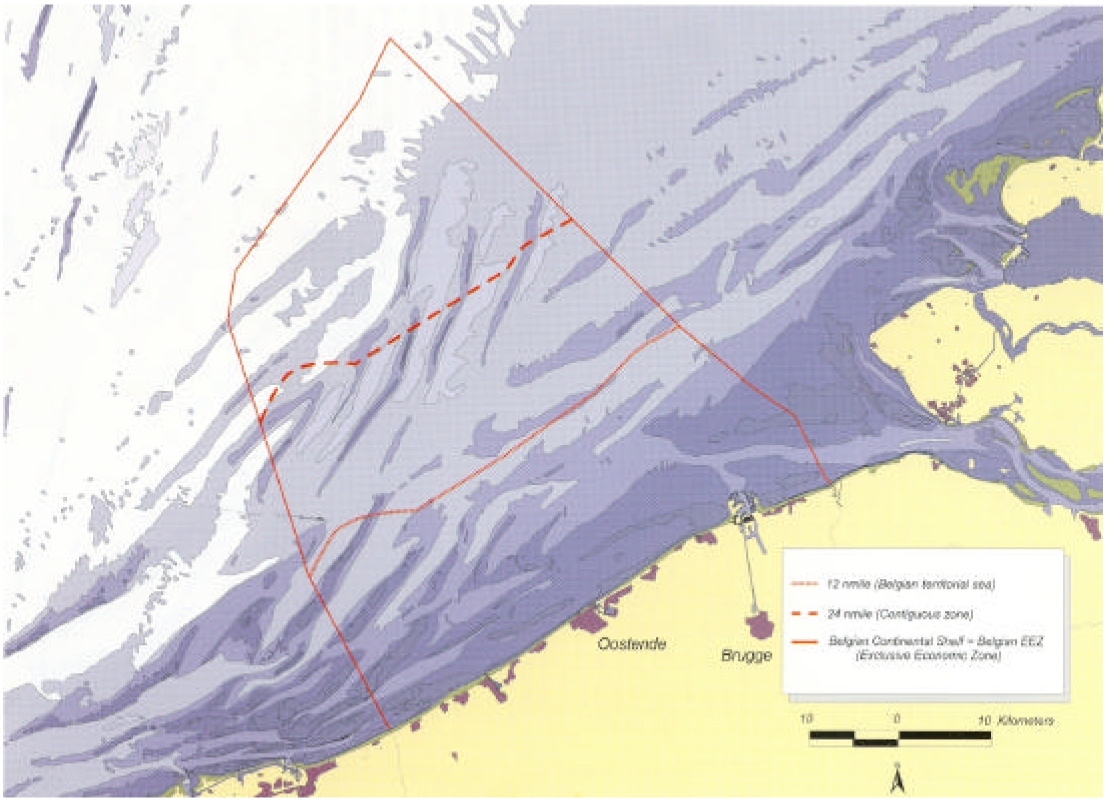

Figure 20: The Belgian Continental Shelf (ref.5)

The baseline is the low water line along the coast. The outermost points of the harbour extension in Zeebrugge constitutes part of the coast. The **territorial sea** extends 12 nautical miles from the baseline (coast) and is expressed in the following co-ordinates:

	East	North
France/Belgium limits	2°32'37"	51°05'37"
	2°23'25"	51°16'09"
The Netherlands/ Belgium limits	03°21'52"	51°22'25"
	03°21'14"	51°22'46"
	03°17'47"	51°27'00"
	03°12'44"	51°29'05"
	03°04'53"	51°33'06"

Table 12: Belgian territorial sea (ref. 5)

The **contiguous zone** is limited by a parallel line to the territorial limit. It is also considered as the customs zone.

The **continental shelf** of Belgium is about 3600 km^2 with a maximum distance to the coast of 87 km. The co-ordinates of the limits are presented in Table 13. According to the Belgian law, exploitation of non-living resources on the continental shelf requires an environmental impact assessment (EIA).

	East	North
France/Belgium limits	02°23'25"	51°16'09"
	02°14'18"	51°33'28"
UK/Belgium limits	02°14'18"	51°33'28"
	02°15'12"	51°36'47"
	02°28'54"	51°48'18"
The Netherlands/ Belgium limits	02°33'21,59"	51°52'12"
	03°04'53"	51°33'06"

Table 13: Borderlines of the Continental shelf of Belgium (ref.5).

The exclusive economic zone of Belgium coincides with the borders of the continental shelf. In its exclusive economic zone a coastal state has rights for the purpose of exploring and exploiting, conserving and managing the natural resources, whether living or non-living, of the waters above the sea-bed, the sea-bed itself and subsoil. A coastal state has also the jurisdiction regarding to installations and structures.

Finally, a remark about the fishery zones. Fishing in the 12 miles zone is exclusively reserved for Belgian fishermen and for French and Dutch fishermen under certain conditions. Outside this 12 miles zone, the principle of free access applies.

The Belgian coastline has a total length of 65 km.

2.5.3 Bathymetry

Sea depth is measured by the Ministry of the Flemish Community, Administration Waterways, Infrastructure and Nautical Affairs, Waterways and Coastal Section (AWZ- Waterwegen Kust). The data used for the present study have been supplied by AWZ. Figure 21 shows the points of measurement of the sea depth. Bathymetry is not measured on a regular grid. The maximum measured water depth in the BCS is 42 m.

These measured data have been interpolated in ArcView to construct a continuous map (Figure 22).

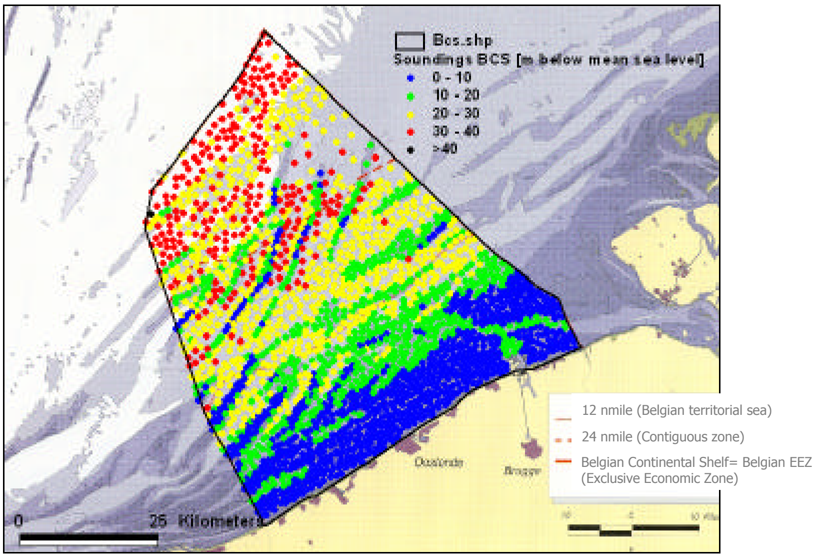

Figure 21: Bathymetry soundings in the BCS (data provided by AWZ).

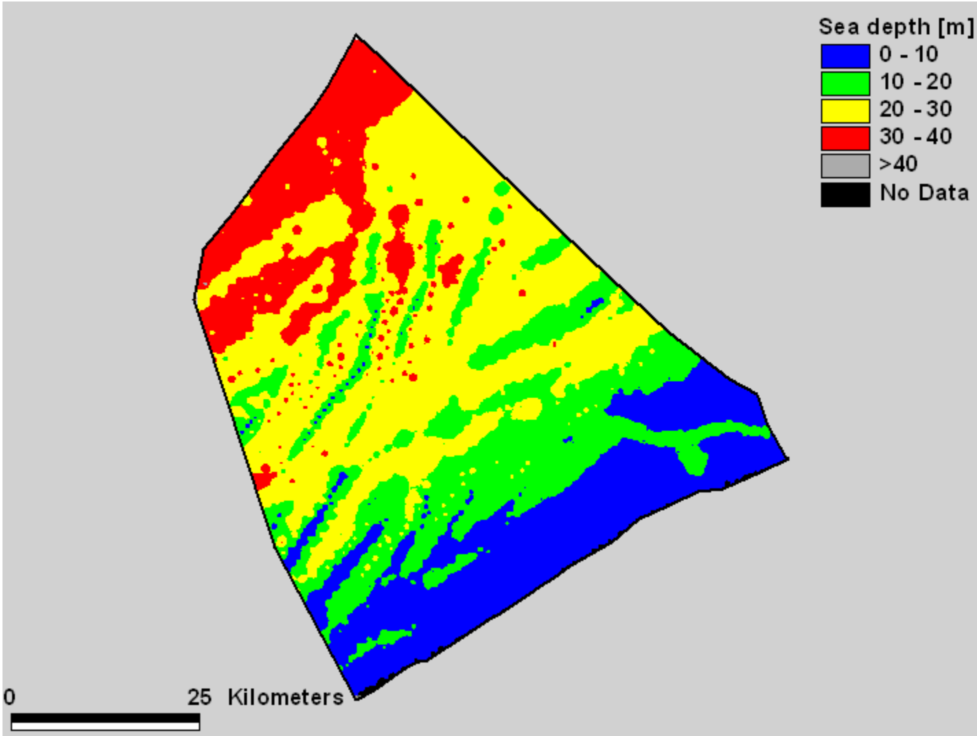

Figure 22: Continuous map of the water depth of the BCS (interpolated from AWZ data)

The results of the interpolation of the sea depth as depicted in the map above show that 38% of the sea surface is less than 10 m deep, 26% between 10 and 20 m, 26% between 20 and 30 m and 10% is more than 30 m deep. The shallow water depths are logically situated close to the coast line.

Table 14 and Figure 23 give an overview of the sandbanks on the BCS.

N°	Sandbank	Area [km²]	Dist to coast [km]	Depth [m]
1	Akkaertbank	70	15	10-20
2	Balandbank	0.55	4	<5
3	Bergues Bank	0.85	23	6-10
4	Bligh Bank	11	37	10-15
5	Bol van Heist	NA	0-6	<10
6	Braekebank	NA	1	<2
7	Broersbank	NA	1	<3
8	Buiten Ratel	29.5	12.5	5-10
9	Fairy Bank	18.5	35	10-20
10	Goote Bank	38	22	13-20
11	Kwinte Bank	10	11	<10
12	Middelkerkebank	10	10	<10
13	Nieuwpoortbank	6	5	<6
14	Noordhinder	9.3	45	10-20
15	Oostdyck	20	14	5-10
16	Oostendebank	25	10	<10

N°	Sandbank	Area [km²]	Dist to coast [km]	Depth [m]
17	Oosthinder	16.7	34	10-20
18	Paardenmarkt	nvt	1	<5
19	Smal Bank	21	4.5	<5
20	Stroombank	7.4	1.5	<5
21	Thorntonbank	28.4	27	10-10
22	Trapegeer	31	2	<6
23	Vlakte van de Raan	130	8-15	<10
24	Wandelaar	100	8.5-13	<10
25	Wenduinebank	86	5-8	5-13
26	Westdiep	25	4	10-15
27	Westhinder	7.7	31	5-10

Table 14: Sandbanks on the BCS

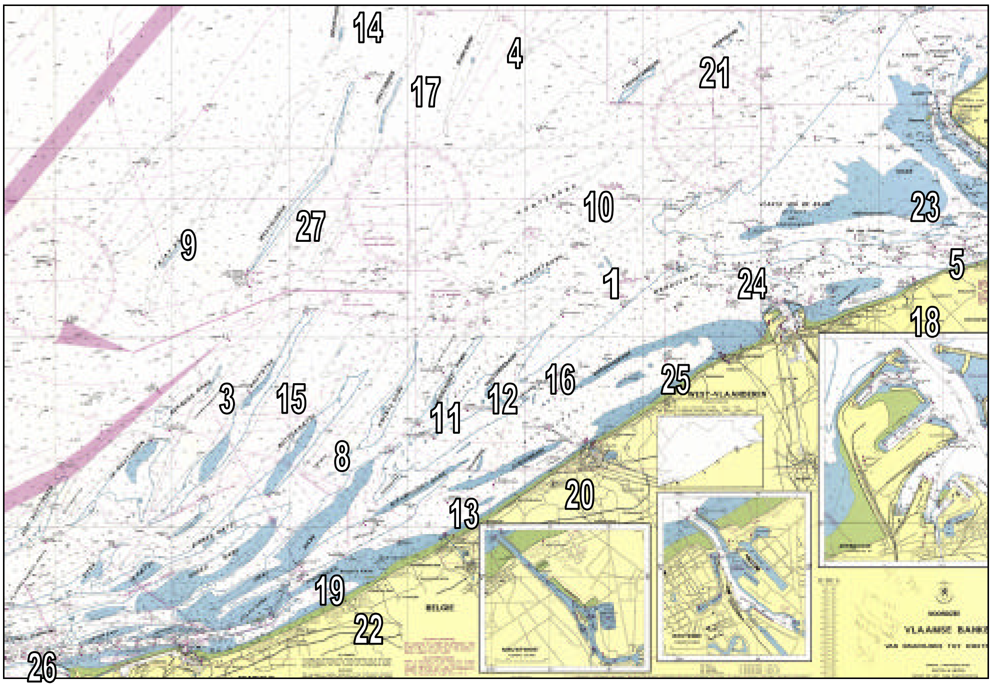

Figure 23: Position of sandbanks of the BCS

The sandbanks called Westdiep, Smalbank, Trapegeer, Oostdyck, Berguesbank and Fairy Bank are partly situated in the French waters whereas Vlakte van de Raan, Thorntonbank en Bol van Heist also extend into the Dutch continental Shelf.

2.5.4 Areas excluded by historical assignments

In the Belgian North Sea, the following activities take place and several zones are reserved. All these zones are to be considered as hard exclusion zones, and are in general not available for wind farming purpose.

2.5.4.1 Sand and gravel extraction

Sand and gravel extraction are limited to two economic zones. Concessions are granted by the federal ministry of economic affairs according to the Royal Decree of 16 may 1977. Parts of the extraction zones are the Thornton Bank, the Goote bank, Oostdijck bank, Kwinte bank and Buitenratel. These banks are separated by the shipping route to the harbour of Antwerp. Concessions might be temporary and are therefore not considered as hard exclusion factors.

2.5.4.2 Dredging zones

Dredging zones are situated within the 12 miles zone. Dredging is done to ensure the entrance to the Belgian harbours and the Westerschelde. These areas are by nature excluded from wind farming.

2.5.4.3 Shipping routes

The shipping routes are indicated on the sea maps with buoys. Traffic separation schemes are used to separate opposing streams. Beside these traffic lanes, there are various other routes for ships not bound by a separate traffic lane, these of course cannot be taken into account in the estimation of the potential.

2.5.4.4 Industrial waste sites and dumping site of war munitions

After World War 1 the sandbank "De Paardenmarkt", about 1 km of the coast of Duinbergen was used as a dumping site for war ammunition. A part of the sea outside the coast of Dunkerque (France and De Panne (Belgium) is an old mining site. These areas are precluded for wind energy, however they are so close to the shore that wind farming would never be considered in view of visual impact.

From the sixties onward, the North Sea was used for dumping of industrial waste. From 1989 the dumping of industrial waste was banned. The areas are not a priori excluded from wind farming

2.5.4.5 Military exercises

Military shooting exercises are directed seawards from the military base of Lombardszijde on a regular basis. The exercises are announced and vessels are to stay out of the zone. A low helicopter-flying zone is present as well. This area is situated within the 12 miles zone. It forms a large obstruction to other uses.

2.5.4.6 Cables and pipelines

The main cables and pipelines are indicated in Figure 24. Three underground gas pipelines cross the North Sea in the BCS.

- The "Seapipe": operational since October 1, 1993. Connects the terminal of Distrigaz in the harbour of Zeebrugge with the Sleipner zone in the Nors continental shelf (length 814 km)
- The "Interconnector" between Zeebrugge and Bacton, at the south coast of England, operational since October 1998 (length 215 km)
- The "NorFra", operational since 1998, connects the Draupner E platform in the Norwegian continental Shelf with the harbour of Dunkerque in France (length 840 km)

Beside gas pipelines, there are also several tracks for telephone cables that cross the BCS.

Further in this study, gas pipelines and telephone lines will not be mentioned as zones to be excluded, since their dimensions are small and wind farms can be installed in the close vicinity of these lines. In fact, the track of a gas pipe line or telephone line can run across a wind farm between the wind turbines.

2.5.4.7 Other assignments

Details about other assignments than the above listed were not available to the project team and have not been taken into consideration.

2.5.5 Areas with environmental protection restrictions

2.5.5.1 Background

The marine environment contains several natural habitats and is the home of a diversity of natural species: plankton, benthos, nekton (predominantly fishes), marine birds and marine mammals. Further, there is the sea fauna and the seabed itself. The biodiversity of the BCS has been described in detail in a study carried out by the Royal Institute of Natural Sciences (ref 2).

One of the findings of the study was that the role of biodiversity in ecosystem functioning is poorly documented in marine ecosystems. Little is known about the initial biological conditions in a certain area. Thus a careful monitoring is necessary prior to and during operation of new projects in the BCS. On the other hand, and in view of potential estimation, the lack of knowledge makes it difficult to take the environmental protection along as a quantitative parameter in the estimation of the available area for wind power.

However, a legal framework is being developed in Belgium, in parallel with international developments. This is briefly described in 2.5.5.3. Based on these elements – and in view of potential estimation, an attempt is made to define areas, which could be excluded a priori.

Prior to the indication of estimation of the available areas, a description is given in paragraph 2.5.5.2 of the potential impacts of wind energy plants on the environment.

2.5.5.2 Potential environmental impacts of wind power plants

The information in this paragraph is partly based on the results of a European Research Project (ref. 3), exploring the prospects of offshore wind power in the European seas.

Hard substrate

Offshore wind turbine foundation can to a limited extent act as artificial reefs for seabed-dwelling organisms, thus increasing the amount of food available to fish.

Noise and vibrations

Available knowledge about the effect of underwater noise and vibration on marine life suggests that the underwater noise generated by offshore wind farms will be in the same range of frequencies as existing sources such as shipping vessels, wind and waves (ref. 4). Therefore, the noise may merely contribute to the background level of low frequency noise present in the sea. Also it should be noted that the design of an offshore turbine and support structure is driven by the overriding objective of avoiding resonance, therefore vibration should be "designed-out" as far as possible, in order to prolong machine life.

Birds

Little is known about the real impacts of operating offshore wind farms on birds. The most extensive recent study available showing factual results is a a three year study of the impact of Tuno Knob on Eider Duck populations by the Danish National Environmental Research Institute. This study concluded that observed changes in the abundance of the ducks could not be attributed to the construction of the wind farm, but to natural variations in the food supply. Experiments involving stopping and starting the turbines and using decoys to attract birds to the turbines concluded that there was no detectable difference in behaviour when the turbines were rotating, but that the ducks were reluctant to approach nearer than 100 metres. In other words, this study concluded with the statement that offshore wind turbines have no significant effect on water birds.

The results of the extensive environmental monitoring projects in large offshore wind farms like Horns Rev, and Nysted are not yet publicly available, so little can be said until now based on experience with large wind farms. However, there are almost no indications until now that offshore wind farms will have significant negative effects on birds.

Impacts during wind farm construction

The effects of moving installation equipment to the site, the temporary disturbance of the seabed during construction and cable laying and the disturbance caused by maintenance vessels will all be site specific. These effects are generic to all offshore industries and are well understood and mitigation measures are available in many cases. It is important during the site selection and initial scoping stage of the project to identify potential areas of conflict and to minimise interference with other activities e.g. shipping, fishing and defence activity.

The environmental effects of both laying cables and installing foundations include the loss of habitat and possible direct loss of marine life during the installation process. There can also be disturbance from sediment movement and noise. It is important that any chemicals or oils used offshore are checked upon safety for the marine environment and be registered for use offshore.

2.5.5.3 Legal framework

The legal framework has been screened in view of determination of special protection areas which could preclude the implementation of offshore wind power.

International treaties: OSPAR, Ramsar

The first impulse in the creation of Marine Protected Areas was the Ramsar convention, ratified by Belgium in 1975 (see further paragraph 2.5.5.4). Belgium is also involved in the OSPAR convention for the designation of threatened and declining species and habitats. This would provide a basis for designating areas, however the translation of species and habitats to designated areas is very complex process which is still under development.

European Directives

The European Birds Directive provides for designation of Special Protection Areas. Under the European Habitats Directive, the member states have to designate Special Areas of Conservation (SACs). Following this, a European ecological network called Natura 2000 has been defined. Belgium has proposed the entire three nautical miles zone along the Belgian coast as Special Area of Conservation. A study on the designation of SPAs is still going on.

MMM law[14]

This Belgian law of 20 January 1999 is based on the international framework indicated above. The law still has to be implemented and foresees the creation of five types of Marine Protected Areas. The existing situation of the law does not allow precluding areas from wind farming based on this law.

2.5.5.4 Existing Special protection areas

Important bird areas

Under the above mentioned legal framework five important bird areas are appointed in order to protect several bird species. The areas closer to the coast are more important for breeding birds. The zones with the sandbanks from Oostende to the Belgian-France border are important bird areas for winter resting period. Detailed and reliable statements on the exclusion of areas for bird breeding and migration can only be made based on extensive studies covering the entire BCS. Such study was not available. For the estimation of the potential only those areas close to the coast have been excluded and are indicated in Figure 24.

Ramsar sites

The area with sandbanks from Oostende to the Belgian-France border is bound to the Ramsar Convention. This area extends 3 nautical miles out of the coast, and is restricted to sandbanks with a maximum depth of 6 m. The area is indicated in Figure 24.

[14] Law on the "Maritieme Milieu Maritime"

Special conservation zones

An area of 170 km^2, that also covers the Ramsar sites, is presented to the European Commission to become a special conservation zone according to the EC Habitats Guidelines. The area is indicated in Figure 24.

2.5.6 Socio-economic restrictions

Visual impact

Tools for qualitative and quantitative assessment of visual impact are available[15]. Such tools show how many wind turbines are visible from what location and how dominant they appear. The techniques include photomontage, which places computer-generated images of wind turbines on a photographic image of the landscape and animations, which show moving turbines superimposed on the landscape. The visual impact of an offshore wind farm is part of the Environmental Assessment, and the more important the less the distance to the coast (and vice versa).

Project developers have attempted - without success - to start wind energy projects in the BCS at the Wenduinebank (5-8 km from the coast). An environmental permit was not granted because of the suspected visual impact (disturbance) of their project. The project planned at Vlakte van de Raan underwent a comparable experience. Based on these experiences, it is assumed for the evaluation of the potential that it will not be realistic to implement wind farms within the 3 nautical miles zone (corresponding to 5.5 km from the coast). This entire zone is excluded in our estimations of the wind potential. Further away, the effects have to be judged case by case. It is not realistic however that projects will be planned within visible distance in the short term. In view of the large sea area available, the visual factor is not considered critical in the determination of the potential.

Acoustic noise

The level of acoustic noise emission of modern wind turbines is so low, that from a short distance (less than one km) it is lower than the background noise of the sea and thus not audible any more. This factor does not play any role in excluding areas of the BCS from wind farming.

Interference with electro-magnetic radiation

Wind turbines can cause interference with radar transmission. One early study concluded that with the exception of low level air-defence radar no problems were anticipated with AM radio, navigation systems or (other radar) transmission. There is evidence from independent studies suggesting wind farms do not have a significant adverse effect on military radar operation. However, in the experience of wind energy developers, military radar safeguarding remains a significant, unresolved issue. As EM interference has to be judged case by case, no areas are excluded a priori.

Navigation safety

Outside the navigation routes, there is also a probability of encountering ships. The safety issue of navigation is not treated as exclusion factor in the estimation of the potential. It is indirectly included in the generation cost, by means of including the insurance premium in the annual returning costs.

[15] mapping the zone of the visual influence (ZVI)

2.5.7 Summary: exclusion zones and calculation of available area for offshore wind energy

The following areas of the BCS have to be excluded for wind energy projects.

category	Main type	Exclusion	exclusion	remark
1	Historical assignments	Navigation routes	Yes	All, with safety band
		Sand and gravel	No	Temporary concessions
		Dredging	Yes	Coincides with navigation
		Dumping sites	Yes	Included in 3 miles
		Military exercises	Yes	Figure 24
		Cables and pipelines	No	Minor interference
2	Environmental Protection	Bird protection	Yes	3 miles
		Ramsar sites	Yes	Figure 24
		Special conservation areas	Yes	Figure 24
3	Socio-economic restrictions	Visual impact	Yes	Not critical
		Acoustic noise	No	not relevant
		EM-interference	No	case by case
		Navigation Safety	No	project design and insurance

Table 15: Summary of exclusion zones

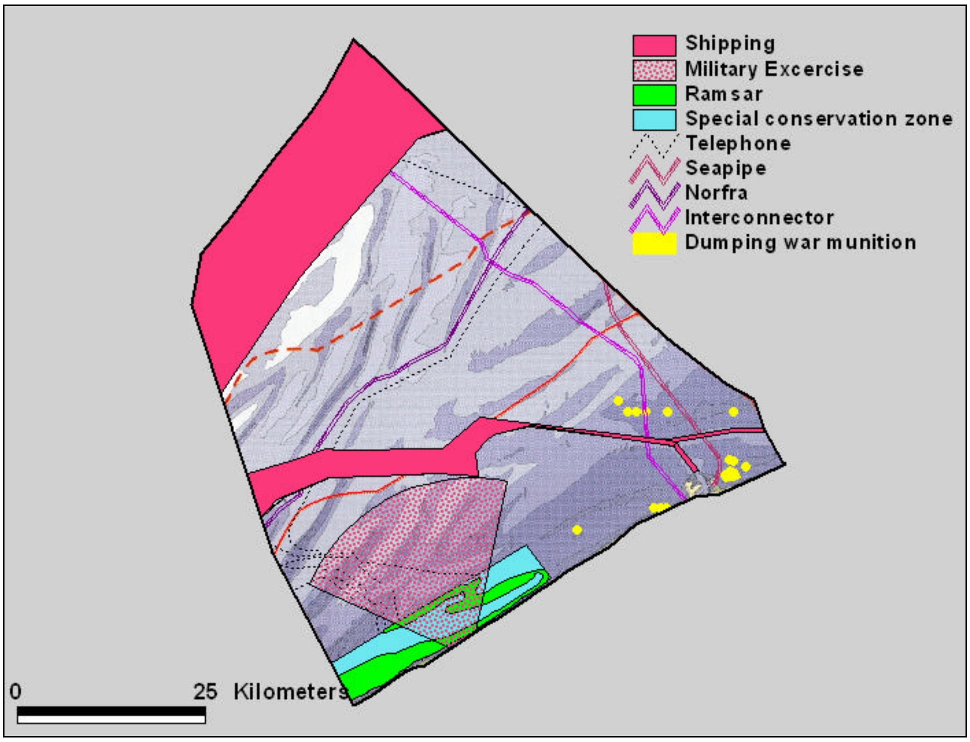

Figure 24: Zones of exclusion of the BCS due to external factors.

Including the 12 miles zone, the result of all the exclusion zones is shown in Figure 25.

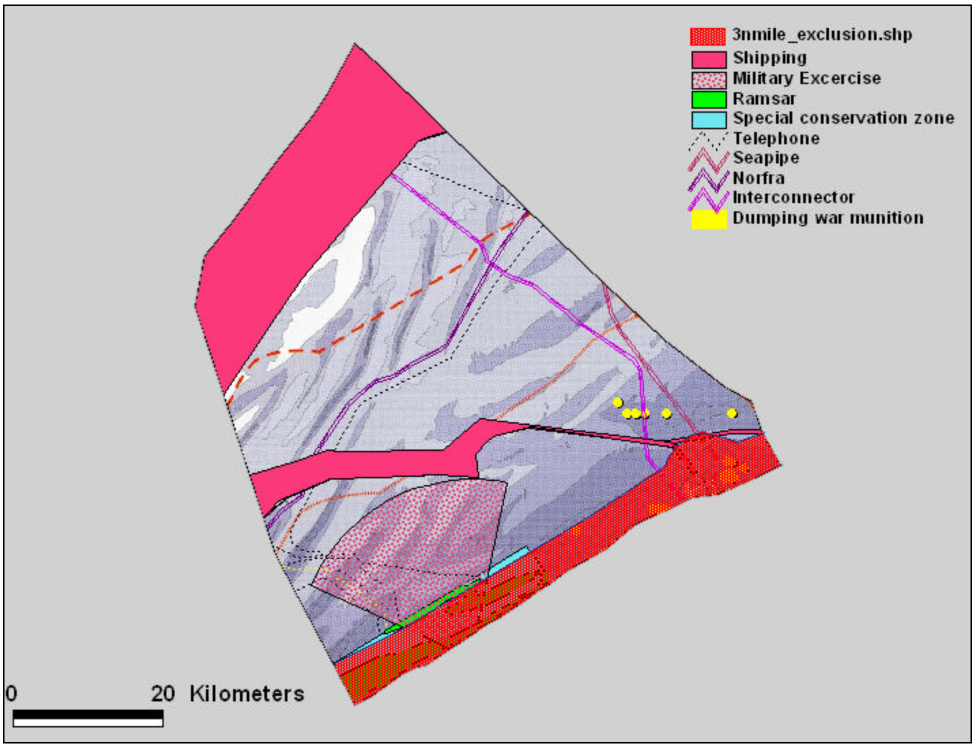

Figure 25: BCS with an indication of all zones of exclusion for wind farming

After the exclusions discussed in this chapter, the area available for wind energy projects amounts to 2101 km².

2.5.8 References

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3. Prospects for offshore wind energy, a report written for the EU (Altener contract XVII/4.1030/Z/98-395) by The British Wind Energy Association (BWEA).
4. Assessment of the effects of noise and vibration from offshore wind farms on marine wildlife. ETSU W/13/00566/REP, DTI/PUB.URN01/1341 February 2001
5. Maes, F., Clicquet, A., Seys, J., Meire, P. & Offringa, H. (2000). Limited Atlas of the Belgian part of the North Sea. Federal Office for Scientific, Technical and Cultural Affairs: Brussel, Belgium.

2.6 Wrapping up: conclusions with respect to resources

From the various paragraphs in Section 2, the following can be concluded with respect to resources for offshore wind energy. The sea bottom in principle is suitable for the installation of monopile foundations for wind turbines, however in a particular narrow area the soil structure could possibly include some hazards. These hazards nor the possible consequences on foundation costs however being easy to quantify, it is concluded that in principle there are no zones excluded with regards to soil properties.

The wind resources are very favourable because of the much higher values of wind speed than on land. In the BCS, the average wind speed varies in a range from 8.4 to 10.1 m/s at heights between 70 m and 150 m above sea level. In the first 20 km from the coast, the average wind speed increases quite fast with distance, and from 20 km distance on the increase is very modest. In addition, the increase of wind speed with height is very moderate from 70 m onwards. In this respect, it is recommended to try to exploit the resource not too far offshore and to be modest with tower heights, in view of optimal generation costs.

Various other activities on the sea, and environmental protection reasons limit the available sea area for offshore wind power. These constraints affect in total almost one third of the BCS, and consequently out of the total area of 3600 km², a net area of 2100 km² theoretically remains for wind power, which still is enormous.

The main limitation at this moment is the available electrical grid. A static analysis demonstrates an available capacity of between 50 and 750 MW wind power that could be downloaded from the sea (under conservative assumptions). A further increase would involve additional grid reinforcements or alternative routes for the wind power. The technical aspects and possibilities are further discussed in Section 3.

3 Technological options for offshore wind energy

3.1 General, introduction

In this section, the technological factors are analysed in view of their influence on the offshore wind energy potential. The section comprises of the analysis of the offshore wind energy technology and its projected development, and of the analysis of the interaction between wind farms and the electrical grid.

Paragraph 3.2 focuses at the characterisation of offshore wind energy technology. The method chosen for the project is to characterise the technology for two time stamps, i.e. 2005 and 2015. It defines the technical and economical characteristics for 'improved technology' and 'highly improved technology'. In order to allow calculating the potential (installed capacity, estimated energy output and related costs), characteristics are determined for a so-called synthetic or generic wind farm. The cost parameters and model are determined that are going to be the input for the determination of the economic potential in Section 4.

Paragraph 3.3 concentrates on grid issues. The dynamic behaviour of a wind farm is investigated in order to obtain a better understanding of the ability of a wind farm to provide 'grid support'. For this purpose, a dedicated wind farm model is built. Simulations are performed to investigate the electrical impact of offshore wind power plants on the Belgian grid, looking also at the effect of different degrees of electrical controllability of the wind farm.

3.2 Offshore wind farm technology

3.2.1 Approach and method

The future offshore wind potential is considered to depend on technological developments, which for example reduce the production cost or allow better access to further and deeper sites.

The approach followed in this analysis therefore consists of a description of the offshore wind energy technology enabling to quantify the effect of technological options on the wind energy potential, and provide input for models for energy and cost calculations. It was decided to make a snapshot of the technology for the time frames 2005 and 2015.

The projection of the technological development is based on observations of state-of-the-art technology, perceived trends and engineering judgements. Multiple sources are used: direct information from manufacturers, researchers, engineering companies, published results from relevant international research projects.

The result of this analysis, as described in Section 3.2 includes

- description of tendencies in offshore wind technology
- definition of main characteristics of offshore wind technology in timeframes 2005 and 2015
- definition of a 'synthetic' wind farm for wind potential calculations
- identification of cost developments of the relevant components for economic calculations

3.2.2 State-of-the-art description

3.2.2.1 General

The technology characterisation is taking into account developments in the following main categories:

- Wind turbine design concept and typologies;
- Supporting structures (tower and foundation);
- Wind farm concept and lay-out;
- Electrical grid connection (sea HV system, sea cable, landing and onshore facilities);

- Installation / on site assembly procedures and related technologies (including transportation to site)
- Operation and maintenance procedures and related technologies (including advanced operating procedures, condition monitoring)

The description intends to focus on those aspects which are relevant for the calculation of the potential taking into account the expected technological developments, and does not pretend to give an extensive and detailed description of the technology, for which we would like to refer to more specialised literature.

3.2.2.2 Wind turbines

General characteristics of offshore wind turbines

In order to get a picture of the present status of wind turbine technology relevant for offshore application, we have looked at a selected group of manufacturers known to aim at large scale offshore development.

Table 16 and Table 17 give general technical characteristics of wind turbines nowadays offered for wind energy offshore projects (status end 2003). All these machines are offered both for onshore and for offshore projects. The diameters range from 80 to 104 m, the rated power from 2 to 3.6 MW. The specific rated power (installed wind turbine power per m^2 rotor area) is around 400 W/m^2. The specific tower top mass (kg/m^2) which is a measure for the 'material and cost efficiency' varies between 17 and 30 kg/m^2 [16]. It can be seen that the latter value increases with rotor diameter, which is obvious with respect to the square cube law[17]. It has to be remarked that these numbers change fast, as the actual pace of technical development is high.

manufacturer	Type name	Rotor diameter	rated power	specific power	Tower top mass	specific TTM
		m	MW	W/m2	Tonnes	kg/m²
Vestas	V80	80	2.00	398	98	20
NEG-Micon	NM 92 2.75	92	2.75	414	-	-
NEG-Micon	NM 80	80	2.00	398	-	-
GE Wind	GE 3.6 MW	104	3.60	424	260	30
Bonus	Bonus 2.3 MW	82.4	2.30	431	135	24
Repower	MM82	82	2.0	379	94	19
Nordex	N80	80	2.50	497	100	17
Nordex	N90	90	2.30	362	146	26

Table 16: Today wind turbines specifically offered for offshore projects

Some of the wind turbines on test or on the drawing board (in 2003) are listed in Table 17. The sizes are continuously increasing, diameters range between 90 m and 125 m, rated power between 3 and 5 MW. The specific tower top mass (total mass of rotor + nacelle) has a tendency to increase, which indicates there are still efforts required to increase the 'material efficiency' and thus the cost efficiency of the wind turbines.

[16] The specific TTM has been calculated as follows: kg of head mass (nacelle + rotor) divided by rotor surface area. The resulting value has been adjusted for the specific rated wind turbine power. The larger specific power the lower the specific TTM. Thus, in order to obtain comparable values between WTS in the table, the specific TTM has been divided by the relative specific power (specific power divided by the average of the series, i.e. 413 W/m²).
[17] Square cube law: Energy capture of wind turbines is proportional to L^2 whereas weight (thus cost) is proportional to L^3, hence by scaling up specific costs (per kW) tend to increase with the size; the law can only be 'broken' by technology 'step' changes

Manufacturer	Type	Diameter	rated power	specific power	Tower Top Mass	specific TTM
		m	MW	W/m2	Tonnes	kg/m²
Repower	5M	126.5	5.0	398	350	32
Nordex	NXX	115	5.0	481	-	-
Vestas	V90	90	3.0	472	110	17
Vestas (NEG–Micon)	NM 110/4200	110	4.20	442	214	23
Vestas	VXX	110	4.6	484	-	-
Bonus		?	4.6	-	-	-
Pfleiderer / Prokon	Multibrid M5000	116	5.0	473	259	26
Enercon	E-112	114	4.5	441	500	51

Table 17: Offshore wind turbines on test or on the drawing table

The wind turbine tower heights are comprised between 70 m and ~100 m, although most of present day offshore wind turbines have hub heights under 90 m. Most of the wind turbines are offered with a choice of (discrete, standard) tower heights. Custom tower heights are also possible, within the limitations of dynamic behaviour of the turbines (some tower lengths are to be avoided because of possible resonance with excitation and natural frequencies in the wind turbine rotor and drive train).

Design aspects of the offshore wind turbines

General

The usual offshore wind turbine concept – presently without exceptions - is horizontal axis, upwind position of rotor, three bladed, active yaw, tubular tower. The wind turbines structural design is executed according to well defined / prescribed[18] wind and operational conditions, and wind turbine safety concept (protection systems, electrical safety, installation, operation and maintenance) complies to well defined requirements. The present day significant differences in wind turbine design concept – which may render concepts more or less suitable for offshore applications - are:

- Power regulation and controllability
- Drive train lay-out (gearbox versus direct drive,)
- RAMS concept (reliability, availability, maintainability, serviceability)

These aspects are discussed below.

Power regulation and controllability

Because the principal power regulation starts at the wind turbine rotor, it is appropriate to distinguish power regulation into two basic methods: stall regulation and blade pitch regulation. It has to be remarked that the majority of wind turbine concepts adheres to some form of active blade pitch control.

In the pitch regulated category the aerodynamic power is controlled by changing the blade pitch angle towards feather position (turning blade nose into the wind). This way of operation is nowadays always combined with variable speed operation, which in turn is enabled by the electrical conversion system concept (mostly double fed induction generator which allows a limited range of variable speed, in a limited number of cases synchronous generator allowing fully variable speed). As a consequence, the power output (rate and quality) of this category of wind turbines is in general well controllable (e.g. imposing power production modes from a central wind farm controller, see also 3.2.2.4 and section 3.3), because both the aerodynamic power and the electrical system can be controlled actively.

[18] Prescribed in IEC 61400-XX standards

In the stall regulated category, the aerodynamic power is controlled by actively turning the blade pitch towards stall position (turning blade nose away from the wind). The former 'passive' stall regulation method (fixed blade pitch) is presently no longer applied in the larger wind turbines. Active stall regulation implies keeping the rotational speed constant. Examples are the wind turbine types from the manufacturers Bonus (so-called Combi Stall) and NEG-Micon (double speed active stall). The external control possibilities of this category of regulation are more limited than of the former category.

The two methods of power regulation still are being used. The power performance of both type of wind turbines is comparable (in terms of AEO per square meter rotor area). The external controllability (relevant for grid integration of large wind farms) is better in the first category.

Drive train layout

Three main types of drive train layout are distinguished

1. The classical drive train consists of rotor, main shaft with main bearings, gearbox including fixed or elastic mounting to machine bed frame, high-speed shaft including coupling and mechanical disc brake and generator. With increasing turbine size, gearboxes become more complex (fourth stage has to be added). Examples: most of the present day wind turbines.
2. The direct drive concept where the rotor is directly connected to a slow running (multipole) generator. Examples: Enercon, Winwind and Zephyros. Direct drive concepts sometimes tend to be relatively heavy as a consequence of the large generator mass.
3. The hybrid concept, which includes a combination of a slow running generator with a gearbox with low transmission ratio. The Multibrid concept, presently implemented by Prokon Engineering is an example of the hybrid concept.

Direct drive types are in general more heavy (higher TTM), which will have consequences in transportation and installation. The operation and maintenance is simplified because of smaller number of parts (less complex).

For the purpose of this study, it is assumed that the choice for either system does not affect the basic parameters of the potential. It is assumed that competition between the various types will assist in cost reduction and that the market will automatically select the most cost-effective technical solution.

RAMS concept and 'marinisation'

Present day wind turbines in offshore wind farms are basically modified land versions. Modifications include add-ons and special attention to RAMS aspects (reliability and maintainability). The objective is to achieve as high as possible wind turbine availability and minimisation of maintenance efforts. This is achieved by increasing wind turbine reliability level (e.g. redundancy or higher safety margins) and by special attention to features facilitating / minimising turbine maintenance. Examples are nacelle integrated additional hoisting systems, access facilities (heli-deck), improved coatings etc. A further step is to integrate condition monitoring[19] in the machine (in the rotor blades and drive train).

In general the additional efforts for 'RAMS' related objectives increase the initial investment costs (10-15 %) over the cost of the onshore wind turbine versions but should enable a higher production (increased availability) and lower O&M costs. For the purpose of this study it has been assumed that the additional cost (over onshore versions) is 15% in 2005 and reduces to 10 % in 2015, keeping availability levels up to 88 % in 2005 and up 98 % in 2015.

3.2.2.3 Support structures

The support structure is the combination of wind turbine tower and its offshore foundation. Out of the possible options (Figure 26) the following types of offshore foundations are most frequently used at present in offshore wind energy projects:

- Monopile (hammered and/or drilled into the seabed)
- GBS Monotower

[19] Condition monitoring systems automatically monitor the condition of critical components (e.g. drive train components) through for example vibration monitoring. This allows to early detect potential failures and replace 'suspect' components in time during scheduled servicing operations, avoiding unscheduled shut-downs caused by catastrophic component failures.

The monopile support structure is far the most used by now. In shallow waters and seas with high probability of ice, GBS structures are more appropriate. The limiting water depth for monopile structures is approximately 30 m, above that value other solutions like braced monotower (for example tripod – three legs) are more cost effective. The legs are anchored in the seabed with piles or skirt caissons (suction buckets).

For shallow waters a recent development is the skirted caisson (ref. 1). This type of foundation is presently being tested for wind energy applications. In the cost estimations, it has not yet been taken into account.

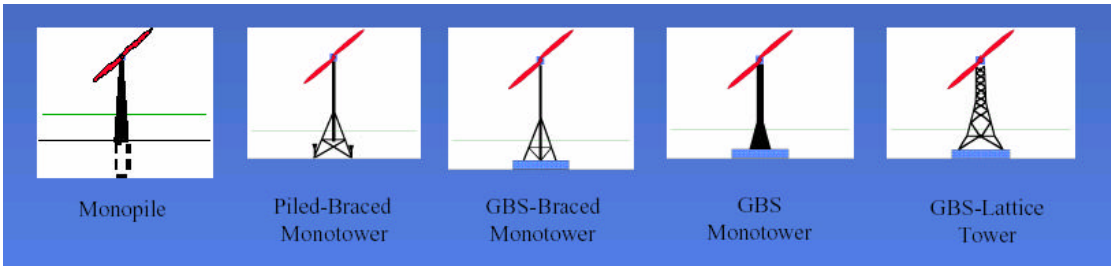

Figure 26: Types of foundations used for offshore wind turbines (from ref.1)

3.2.2.4 Wind farm concept

General

Beside the concept of individual wind turbines, the concept of the wind farm has a number of elements that determine the technological and economical development. These elements are:

- array layout
- wind farm control

These aspects are highlighted in the following paragraphs

Wind farm array layout

Present day wind farm arrays consist of individually seabed mounted wind turbines, positioned in one or more lines. The layout is dictated by:

- Optimisation of available sea space (sea surface area versus installed capacity and GWh per square kilometre)
- Minimisation of array losses, caused by wake effects[20]
- Taking account of environmental, planning and geo-technical constraints

Table 18 gives examples of present day offshore wind farms with characteristic numbers about the arrays.

The wind turbine wake effects are minimised by properly taking into account the occurrence of wake situations. For a given wind turbine concept (characterised by rotor axial thrust curve[21]) wind farm geometry, and ambient turbulence intensity are the most important parameters determining array losses.

[20] Wake effects are the mutual influences of wind turbines on each other (reduced wind speed, increased turbulence)
[21]The calculation of the wake effect, the rotor drag on the wind flow, characterised by the so-called thrust coefficient C_t as a function of wind speed is needed (C_t= D/ 0.5 ρ v² A)

project	Total wind farm area	nr of WTs	WT rated power	nr / km2	Rated wind farm power	Power density	WT rotor diameter	Array geometry[22]
	Km²	-	MW	-	MW	MW/km²	m	D x D
Horns Rev (DK)	20	80	2	4.0	160	8	80	7 x 7
Roedsand (DK)	23	72	2.3	3.1	165.6	7	82.4	10.3 x 5.8
C-Power (BE)	14	60	3.6	4.3	216	15	104	6.5 x 5
DOWEC (NL)	45	80	6	1.8	480	11	129	
North Hoyle (UK)	5.4	30	2	5.6	60	11	80	10 x 4.2

Table 18: Characteristic numbers of offshore wind farms

Experience has shown that for wind turbines spaced 8 to 10 diameters (D) apart in the prevailing downwind direction and 5D in the crosswind direction, array losses are less than 10 %.

Array effects offshore are felt at larger distances than onshore because of the lower ambient turbulence intensity offshore and thus a more persistent disturbed flow situation. For this reason, offshore spacing – and thus the related power density – in general is less dense than onshore.

For the evaluation of the potential in the present study, a 7D x 5D array geometry has been assumed, with corresponding array losses of 10 % in the wind climate of the BCS (see 3.2.5), this results in a installed wind power density[23] of 10 MW/km².

The wind farm geometry and layout has to take into account the seabed morphology. For example, when wind farms are implanted on sandbanks, a cost optimisation will be done by trying to position the wind turbines as much as possible in the lowest water depth and away from slopes. Furthermore, array geometry in the vicinity of the coast will have to take into account the visual effects and radar interference.

Central wind farm control

Because of the increasing amount of offshore wind power, the wind farms have to meet some new requirements with respect to grid connection, more specifically with respect to power control and dynamic stability of the wind farm during grid faults. Because of the difficult access to the turbines, an extensive monitoring and remote control system is required. Central wind farm controllers have been developed – e.g. in the case of the Horns Rev wind farm - which communicate with the individual turbines and the remote control system.

Such systems – in combination with the individual controlling possibilities of wind turbines - enable the operator to actively control the wind farm, and to optimise the operation in combination with the specific grid requirements.

A new development, still under investigation (ref. 3) is using the central wind farm controller to maximise the power output of the wind farm as a function of the wind direction, by minimising the occurring array losses.

3.2.2.5 Transportation, installation, operation and maintenance

The technology for this part of the offshore wind power projects relies heavily on the existing practices in offshore industry. Besides, in view of the particularities of offshore wind power technology, dedicated solutions are being designed. The requirements are considerable and are certainly not routine in any offshore industry.

[22] Array geometry is represented as <spacing downwind x spacing crosswind> with respect to prevailing wind direction
[23] For more detailed planning, the figure of 10 MW/km² should be reduced with approximately 20 % to take into account proper spacing between individual wind farm projects in order to minimise mutual influences.

Transportation and installation

The vessels currently available fall into two categories, large floating craft and jack-up construction vessels, each with their own specific advantages and disadvantages. Dedicated vessels have been developed and successfully deployed, for example the A2SEA (Figure 27) used for the construction of the wind farms in Denmark.

Figure 27: A2SEA vessel used for the installation of the Horns Rev wind farm in 2002 (from A2SEAwebsite).

Dedicated planning, pre-assembly etc. has allowed construction of the Horns Rev wind farm (80 wind turbines) in less than 2 months time with 2 installation vessels. The distance of that wind farm to the nearest harbour is approximately 20 km whereas the water depth is between 10 and 15 m.

Besides the vessels, there is a need for temporary dispatch, assembly and storage facilities in the nearby ports.

Operation and maintenance

O&M may form a large part of overall energy costs (25 to 30%) of offshore wind energy. The increased cost of transport to the wind farm and reduced access are the major cost drivers. Therefore, to have an efficient O&M strategy is extremely important.

Several studies have shown that the costs for operation and maintenance of offshore wind turbines will be substantially higher than for onshore turbines. Typical figures for the offshore situation are (including costs for maintaining the wind farm infrastructure, civil structures, etc.):

- preventive maintenance 0,003 to 0,006 (€/kWh)
- corrective maintenance 0,005 to 0,010 (€/kWh)

The large range in the O&M costs is influenced by aspects such as

- size and reliability of the turbines (small onshore turbines vs. large turbines optimised for offshore applications)
- maintenance concept chosen (access systems, hoisting facilities, etc)
- distance to the shore, water depth, size of the wind farm
- wind and wave climate.

A tool to improve the returns of operating wind farms is short term wind power prediction. For this purpose, wind power predictor models are designed to address the needs of offshore wind farm operators that need to provide accurate predictions of the output of their wind farm 24 hours in advance in order to minimise imbalance penalties imposed by the grid operator. Sophisticated models are applied to weather forecasts provided by the meteorological institutes for predicting power output at the specific wind farm site. In combination with the given imbalance pricing system exercised by the grid operator, the wind farm may be operated in such a way as to obtain the best financial results.

3.2.2.6 Grid connection

General

Technology with respect to grid connection of offshore wind farms relates to:

- Power collection system in the wind farm
- Offshore transmission system and landing

Issues related to electrical interconnection are discussed in detail in sections 2.4 and 3.3.

Electrical power collection system and offshore HV substation

Wind turbines in offshore wind farms are interconnected via underwater MV cables (11 – 36 kV). The primary transformer (LV-MV) usually is mounted in the individual wind turbines (e.g. in the nacelle). The electrical interconnection configuration reflects the division in wind farm clusters to be grouped for improved O&M and safety reasons. Furthermore, the aim is to minimise electrical losses in the cables.

The offshore HV substation includes the central wind farm transformer (MV-HV), which is normally mounted on a separate platform. The voltage for the long distance transport is 150 kV or higher.

Offshore HV transmission system and onshore substation

The state-of-the-art method for long distance electrical transportation from the central wind farm transformer to the onshore grid connection point is using HV AC connections. Given the current equipment and installation costs, this is the most effective solution. This method of transportation also requires reactive power compensation facilities onshore, to compensate for the induced effects in the cable. HV DC transmission would only be more cost-effective from transportation distances larger than approximately 80 km. The HV cables are normally buried in the seabed - which in general is possible in the BCS. Cable routes have to take account of other restrictions in the BCS, and cannot always follow the shortest route. For the purpose of this study, the effective cable length is assumed to be equal to the distance between offshore transformer and onshore substation multiplied by 1.25.

3.2.3 Standards and certification

Parallel to the technological development, a system of standards and certification for offshore wind energy technology is being developed internationally, which is a basis for safety and quality. There exists a series of international standards for wind energy within IEC (International Electrotechnical Commission). The first issuing of a specific standard for offshore wind energy technology (IEC 61400-3) is expected in the course of 2004.

The certification system for wind energy technology is described in the certification standard IEC WT01. In most of present days offshore wind farms, certification is carried out according the international standards, by certification bodies such as GL WindEnergie (Germany) and DNV (Denmark) who have developed specific certification systems for offshore wind energy.

3.2.4 Factors determining the development of the offshore wind energy technology, trends

3.2.4.1 General

In this paragraph a few elements considered to characterise the technological trends for the future are highlighted.

- Development of wind turbine unit dimensions
- Integrated design method
- Design suitability for offshore environment
- Grid integration aspects

- New concepts
- Cost developments

3.2.4.2 Wind turbine unit size

Historically the increase of wind turbine unit size has been exponential in the past ten years. This trend is expected to continue. The growth rate of the last decade – which in fact resulted mainly from onshore wind energy developments - is not likely persist forever.

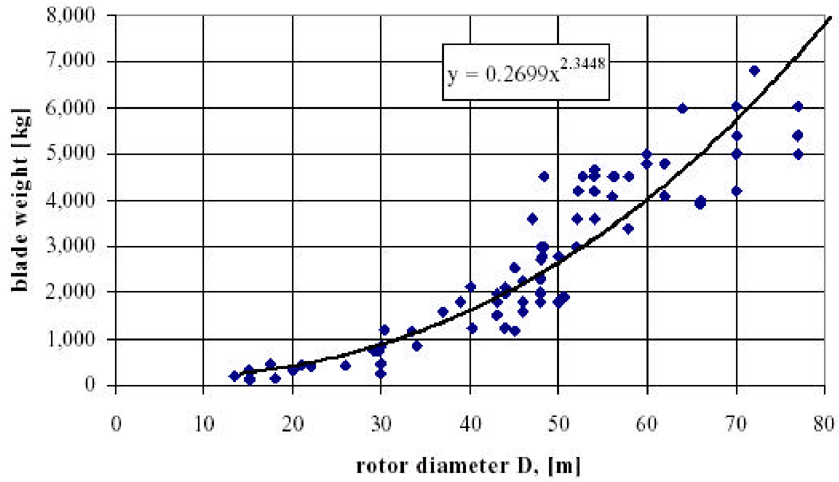

Figure 28: Blade weight versus rotor diameter (ref.10)

The growth in unit size is sustained by an improved understanding of the essential design aspects (e.g. structural behaviour, aerodynamics, material properties, and controls), by improved manufacturing and installation methods and by the relative high unit costs of locations and foundations.

A major physical factor limiting the growth is the Square Cube Law (see 3.2.2.2). This is illustrated in Figure 28, where the increase of rotor blade mass with increasing diameter has an exponent higher than two. Technological developments and the use of new lighter materials (e.g. Carbon Fibre Reinforced Plastics) might stretch the possibilities for a while.

Another factor limiting the growth is the increased complexity of transporting and handling the large individual wind turbine components. The possibilities might be stretched by locating manufacturing facilities near the water, avoiding the need of transportation onshore. Furthermore improved design could aim at a division of the large components (for example blades) in smaller pieces to be assembled on the site.

Finally, it has to be remarked that the selection of the tower height in offshore applications follows different principles than onshore. Because of the lower windshear offshore, the hub height can be kept relatively low. The tower should mainly ensure sufficient clearance from the sea surface, taking into account high waves that might occur. Therefore, towers at sea are going to be lower than towers on land.

3.2.4.3 Integrated design approach

Until now, the design of the wind turbines used for offshore applications is largely originating from the design of onshore technology. The integrated design approach is proposed in ref. 2 to achieve more cost-effective and reliable offshore wind power plants. The objectives are (quoted from ref. 2):

- Tailored distribution of investment and O&M costs over the entire wind farm and its lifetime;
- High reliability of the OWECS as a whole and of essential sub-systems
- Adaptation to economy of scale and partial redundancy of single wind turbines;

- Symbiosis of experience from wind energy technology, offshore technology and power management.

These objectives are translated into more detailed design principles. One of the first applications of this approach is the Opti-OWECS project in the Netherlands (ref. 11). It is foreseen that this approach will find its way to the major planned offshore wind projects in the near future, and will contribute to the substantial decrease in generation cost by offshore wind farms expected in the future.

3.2.4.4 Design suitability for typical offshore environment

In view of the suitability for offshore environment the major elements characterising future trends are:

- Increased wind turbine reliability to achieve the required availability
- Adapted operation and maintenance strategies
- Appropriate design for deeper waters

The required reliability levels to achieve sufficient availability have been investigated with Monte Carlo techniques within the OptiOwecs study. The results are summarised in Figure 29. It shows for various levels of reliability of the technology how the wind farm availability varies as a function of the accessibility (percentage of the time in which the plant is available for service operations, depending on weather circumstances). For example: in typical offshore situations (as relevant for the BCS) the accessibility is 60 %. Today onshore wind turbines reliability levels result in an estimated availability of only 75% due to the limited access. Improved technology will lead to availability of 88 %. In order to increase availability to 98 %, the technology should be highly improved technology.

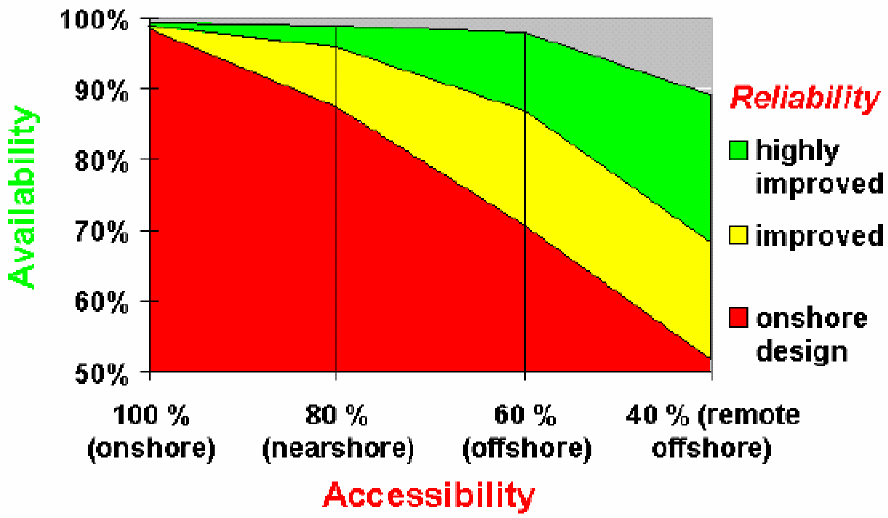

Figure 29: Calculated relationships between availability and accessibility for different grades of wind turbine reliability (ref. 11)

The Opti-OWECS study (ref. 11) examined a range of maintenance philosophies and practical solutions to O&M tasks. The overall conclusions reached by the Opti-OWECS study with respect to O&M strategy include:

- O&M strategy should be optimised with respect to levelised production costs rather than pure O&M costs,
- the lifting equipment required for exchanging major components, such as blades, gearboxes, etc, together with the devices for crew transportation are identified as the main cost drivers of installation costs,
- a self propelled, modified jack up platform is very promising in cases where at least 20 lift operations per year are required,

- remote control and (condition) monitoring are mandatory to reduce the number of visits
- an opportunity maintenance strategy is likely to provide the best maintenance philosophy.

Developments in foundation technology will render wind turbines more suitable for installation in deeper waters. The first option is the so-called braced monopile (for example tripod) foundation, which makes installation possible in water depths more than 30 m. Suction caissons provide solutions for anchoring the braced monopile structures into the seabed. Deeper waters can be accessed with the so-called floating OWECS concept, based on semi-submersible technology.

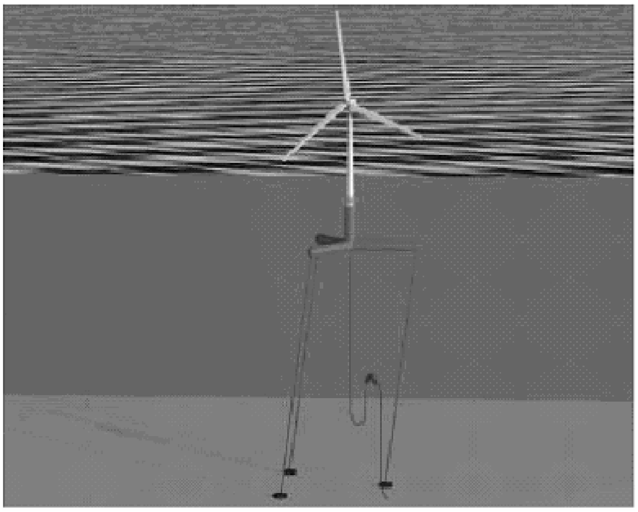

Figure 30: Tensioned leg platform (ref. 20)

3.2.4.5 Grid connection and integration

In order to enable a practical realisation of all the foreseen offshore projects in Europe (10 GW by 2010, 50 GW in the pipeline), substantial developments are expected in the area of grid connection and integration.

The first issue is related to the transportation of the power from the offshore wind farm to the shore. Presently, HV AC is absolutely the most economic solution. Because of the lower cable losses and improved controllability, HV DC would be preferable, especially for larger distances. Because of the expected substantial cost reductions of HV DC, the economic 'break even cable length' compared to HVAC could decrease from the present 80 km (2003) to around 20 km in 2015.

It also can be expected that in parallel with the international development of many projects in the European waters, the installation of a sea grid will be undertaken.

The second issue relates to the integration of large quantities of offshore wind power in the electrical power networks. This touches both the wind energy technology and the grid side. On the side of the wind turbines, the expected development consists of improved control possibilities of the wind farms, despite the fluctuating nature of the wind. Besides the technical requirements to the wind turbines themselves (active variable pitch control, electrical control, electrical fault ride through capability), more effort will be spent in short term prediction of wind power (hourly values, a few days ahead) and in development of central control strategies of several wind farms which allow them to participate in electrical network management. On the side of the electrical grid, technical and management measures will be taken to properly guide the wind generated power in synchrony with the other generating units.

3.2.4.6 Cost reductions

Wind energy generation underwent substantial cost reductions in the past ten years, and there is ample evidence that this trend will persist in the future. The higher capital costs of offshore wind with respect to onshore wind farms are offset by higher returns from energy production taking into account the target availability levels offshore. The future cost reductions are expected from economy of scale: much larger wind turbines in far larger groups, sharing of infrastructure costs by adequate geographical grouping. Furthermore more favourable financing conditions will evolve, when the technology becomes more established. All the mentioned reasons added up feed the expectation that there is enough potential for offshore wind prices to fall to a point where they compete with the cheapest power in the market (ref. 8).

A typical installed offshore wind farm price nowadays is 1500 € / kW. This is illustrated in Table 19, which lists typical realised offshore wind farm prices. It should be remarked that UK prices in general are at the high side because of the high electrical connection costs.

location	Numbers and MW of units	Total MW	Cost M€	Cost € / kW
Middelgrunden (DK)	20 x 2.0	40	50	1250
Horns Rev (DK)	80 x 2.0	160	268	1675
Nysted (DK)	72 x2.3	166	245	1476
North Hoyle (UK)	30 x 2.0	60	111	1851
Kentish Flats (UK)	30 x 2.75	82.5	148	1792
Yttre Stengrunden (SW)	5 x 2.0	10	13	1300

Table 19: installed costs of realised offshore projects

For cost projections in the future, the cost developments of the major constituents of offshore wind farms have to be investigated. An illustration of the cost reduction scenario was described by David Milborrow in ref. 8, largely based on actual cost numbers of executed projects and on a study carried out by DTI in UK. The study was giving cost projections until 2012. Table 20 gives an overview of the expected cost developments for these aspects.

item	Cost reduction with respect to 2003 (%)	2012 cost (€ / kW)
Wind turbine	40	450
Foundation	20	200
Transportation and installation	20	16 - 24

Table 20: Potential cost reductions and projected cost in 2012 for the main parts of offshore wind plants (ref. 8)

The specific costs of electrical grid connection are primarily depending on the project size, and furthermore vary with the distance to the shore. Typical target cost levels in 2012 amount to 40 – 100 €/kW, for large projects (>300 MW). The costs for operation and maintenance are expected to drop by 50 % because of improved O&M strategies and improved wind turbine reliability levels.

The subject of expected cost developments is discussed in paragraph 3.2.6, where the assumptions used for the calculation the economical potential are given. The results of the cost calculations in the present study (production costs in 2015 approximately 40 % lower than costs in 2005) are in accordance with numbers quoted in the specialised literature.

3.2.4.7 Alternative offshore wind energy concepts

Beside the classic offshore wind farm concept (three bladed wind turbine, individually seabed mounted) there are a number of innovative concepts, some of which could evolve into competitors to the classic concept.

Among the 'alternative' concepts which might evolve in the future, the following could be mentioned:

- **Wind turbines with 2-bladed rotors**. Although two-bladed wind turbine designs have been quite common before, they are almost extinct presently for large scale wind turbines, mainly because of the lower visual attraction and, paradoxically, because of the more complex character of the dynamic design, despite of the apparent simplicity. Two bladed rotors still have the potential for leading to lower generation costs because of lower investment and installation costs**.**

- **Multi-wind-turbines** (Figure 31): The basic concept is the utilisation of a common mast or platform for multiple turbine units. Again, the concept has potential for reduction of foundation costs and installation costs.
- **Vertical axis wind turbines (VAWT)**: The development of vertical axis wind turbines stopped in the early nineties, mainly because of the lack of comparative advantages of the concept with respect to HATs in onshore applications. This picture might change when considering the VAWT concept for offshore application, not in the least because of the basic simplicity of the concept, and the fact that all major components (e.g. generator) are situated not too far above sea level.
- **Floating wind farms:** this idea is already mentioned briefly above (foundations). Exploring studies (ref. 20) yield quite positive conclusions on the applicability of the concept both in deep and shallow waters.

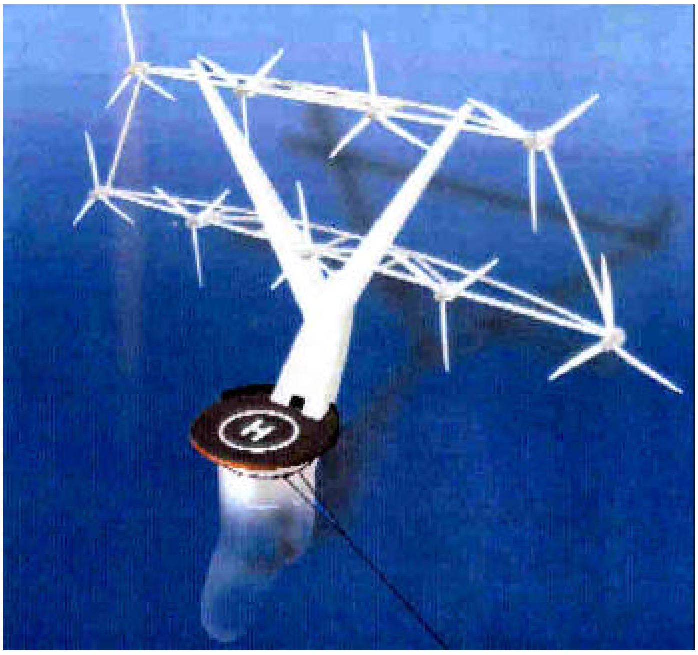

Figure 31: Multi wind turbine (artist impression, Lagerwey wind turbine)

3.2.5 Technology figures used for the evaluation of the potential: technical characteristics

3.2.5.1 General

For the evaluation of the technical and economic potential, a number of main offshore wind technology characteristics have been frozen, based upon the analysis described earlier in this section. The terminology used further in the study is:

Improved Technology: which is basically the same as best available technology, and corresponds to the present day technology as described in 3.2.2. It is the technology to depict the potential for the time frame of 2005. The qualification 'improved' refers to improvements, which make the wind turbines better suitable for use in marine environment.

Highly Improved Technology: this term is used for the technology envisaged for 2015, yielding much higher availability levels, reduced cost, improved maintainability and serviceability etc. It is the result of expected developments described earlier in this section.

3.2.5.2 Offshore wind technology characteristics: 2005, improved technology

Main category	Subsystem, component	Characteristic descriptor
Wind turbine	Rotor, number of blades, materials, tip speed Rotor diameter range	Upwind , three bladed, GRP, tip speed < 70 m/s 80 – 110 m
	Rated Power Specific rated power	2 – 3.6 MW at around 14 m/s 400 - 500 W/m²
	Operational concept	Variable blade pitch, variable speed
	Wind turbine protection systems	Aerodynamic brakes (blade pitch, mechanical brake on fast shaft)
	Drive train system	▪ Geared ▪ direct drive
	Electric conversion system	▪ doubly fed induction generator ▪ direct driven synchronous or PM nacelle system voltage MV 11 – 36 kV
	Tower Tower height range	Tubular steel tower Approximately 70 to 90 m (tailored to site)
Support structure	Support structure	▪ Monopile (free standing) ▪ Gravity Based System (GBS)
Wind farm design	Wind farm concept	Array min 5D x 7D
	Wind farm control	individual wind turbine control (remotely supervised) possibly combined with central wind farm controller
Transportation and Installation	Vessel technology Hoisting devices	▪ Classic offshore rig ▪ Dedicated installation vessel Nacelle crane for lifting tower top parts
Operation & Maintenance	Maintenance intervals Access methods Supervisory control Target wind farm availability	Once per year Helicopter, vessel, nacelle crane SCADA Condition monitoring machinery parts 88 %
Grid connection	Electrical power collection system Offshore HV transport	MV interconnections (11-36 kV), central WF transformer Individual WF HV AC marine cable (150 kV)

Table 21: Overview of characteristics of offshore wind technology: 2005 improved technology

3.2.5.3 Wind turbine characteristics: 2015, highly improved technology

Main category	**Subsystem, component**	**Characteristic descriptor**
Wind turbine	Rotor, number of blades, materials, tip speed Rotor diameter range	Upwind , three (2?) bladed, GRP, CRP tip speed > 70 m/s 110 - >130 m
	Rated Power Specific rated power	4.6 – 6 MW as a minimum at around 14 m/s 400 - 500 W/m²
	Operational concept	Variable blade pitch, variable speed
	Wind turbine protection systems	Aerodynamic brakes (blade pitch, mechanical brake on fast shaft)
	Drive train system	▪ Geared (integrated design) ▪ direct drive (gearless)
	Electric conversion system	▪ doubly fed induction generator ▪ direct driven synchronous or PM nacelle system voltage MV 11 – 36 kV
	Tower Tower height range	Tubular steel tower, integration with support structure Approx 70 to 110 m (tailored to site)
Support structure	Support structure	▪ Monopile ▪ Braced mono pile ▪ Gravity Based System (GBS) ▪ Floating ▪ Suction caisson
Wind farm design	Wind farm concept	Array min 5D x 7D Multi wind turbine?
	Wind farm control	Highly sophisticated central wind farm control with grid responsibility
Transportation and Installation	Vessel technology Hoisting devices	Dedicated installation vessels Nacelle crane for lifting tower top parts
Operation & Maintenance	Maintenance intervals Access methods Supervisory control Target wind farm availability as consequence of reliability	Condition based maintenance Helicopter, vessel, nacelle crane SCADA Condition monitoring blades and machinery parts 98 %
Grid connection	Electrical power collection system Offshore HV transport	MV interconnections, central WF transformer Common sea grid, WF HV AC or competitively priced HV DC technology marine cable

Table 22: Overview of characteristics of offshore wind technology: 2015 highly improved technology

3.2.5.4 Wind farm power curve for calculation of the offshore potential

For the calculation of the potential, assumptions have been made with respect to the relationship between wind resources and wind farm output. The standard method for calculating the energy output is to multiply the wind turbine power curve with the site specific wind speed frequency distribution at hub height.

Array efficiency

For the purpose of this study, it is important that the power curve reflects the state of the technology. A power curve has been defined of a group of wind turbines that would optimally occupy one square kilometre of sea, taking also into account the array efficiency.

The array efficiency was determined by a number of simulations (in the wind farm design tool WindPro®) for various representative wind turbine types. The simulations included energy production calculations for a wind farm of 100 machines, grouped in 10 rows in a 7D (downwind) 5D (cross wind) arrangement oriented to the prevailing wind. The array efficiency has been calculated for selected wind turbine types (GE 3.6 MW, Vestas V80, Bonus 2.3 MW, Enercon E66/20.70). The average array efficiency found is 90%, independent of hub height. The spread in the results is very small.

Synthetic power curve

For state of the art technology as well as for future technology, the maximum installed power per km² is fixed at 10 MW/km². This has been calculated with the simulated layout configurations described above.

A synthetic power curve of 10 MW has been defined in order to calculate the specific energy production. This power curve is based on measured power curves of the above mentioned wind turbine types and includes the array losses.

The 'average' power curve of these turbines has been extrapolated to a rated power of 10 MW. The result is presented in Figure 32. The cut-in wind speed is 3 m/s, rated wind speed is 17 m/s and cut out wind speed is 25 m/s.

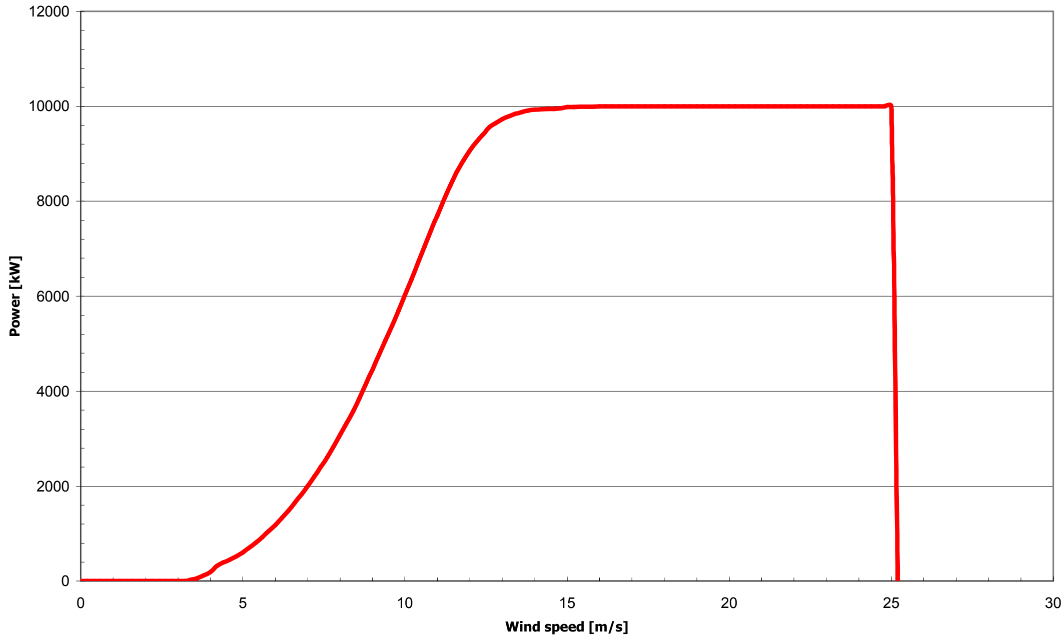

Figure 32: Defined synthetic power curve of 10 MW wind farm.

Electrical losses

The calculated energy production of the wind farm has to be corrected for electrical losses between the individual wind turbines and the onshore grid connection point. These consist of:

- Electrical losses in the wind farm power collection system;
- Transformer or converter losses in the wind farm;
- Transmission losses in the HV submarine cable between the wind farm transformer and the onshore grid connection point

The electrical losses in the wind farm power collection system have been determined as function of the relative power output of the wind farm (Figure 33) based on method developed by Brakelmann (ref. 19). For example, at 40% of rated power, the electrical loss in the power collection system is 0.37% of the rated power.

The resulting total electrical losses at rated power are approximately 3% of rated power for a wind farm situated at a distance of 50 km from the shore.

Cable routes have to take account of other restrictions in the BCS, and cannot always follow the shortest route. For the purpose of this study, the effective cable length is assumed equal to the distance between offshore transformer and onshore substation multiplied by 1.25.

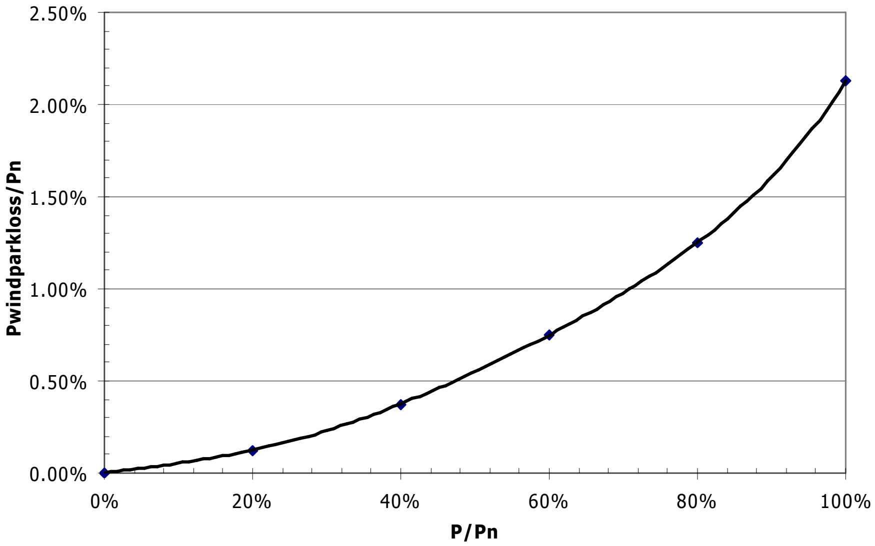

Figure 33: Electrical loss in offshore wind farm power collection system with 30 kV AC cables.

Transformer losses consist of a fixed loss (iron loss) and a variable loss (copper loss). The fixed loss is estimated at 0.03% - 0.06% of rated transformer power, the copper loss is estimated between 0.25% and 0.40% of actual transformer power.

The losses in the HV AC transmission line between the wind farm and the grid connection point are estimated at 0.0195% - 0.024% of actual power per km (ref. 7).

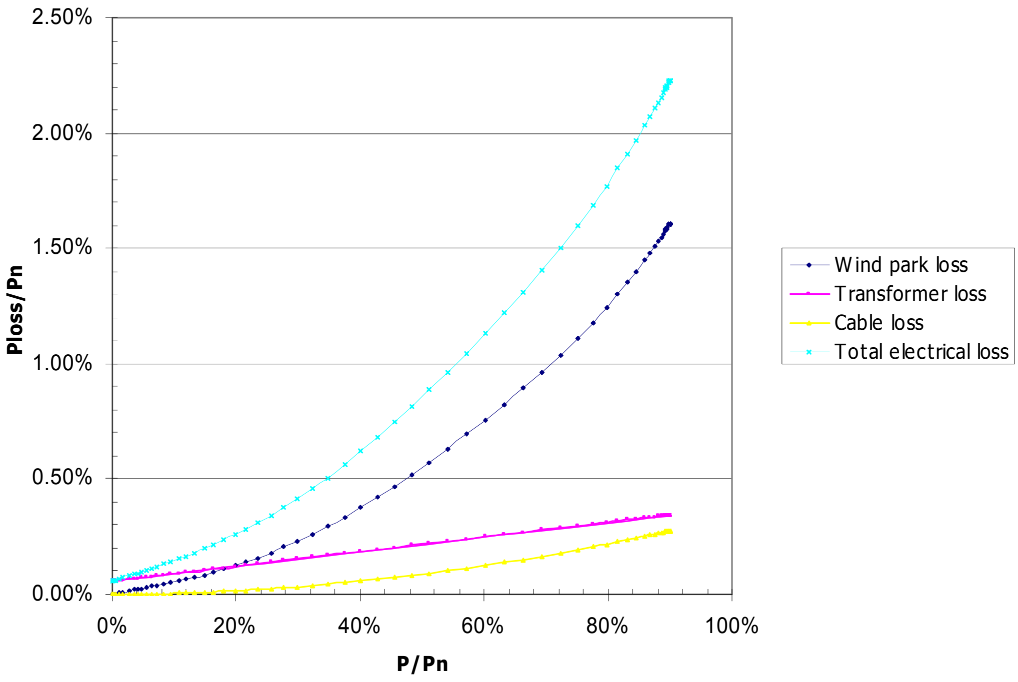

Figure 34: Electrical loss in wind farm, transformer and cable connection for a cable length of 50 km

3.2.6 Assumptions for offshore wind energy costs calculations

This paragraph gives the investment cost assumptions used in the calculation of the economic potential. They are based on actual cost figures and expected developments, already mentioned in 3.2.4.6. Based on these assumptions, levelised production costs will be calculated in section 4.4.

The investment costs consist of costs from the following main categories:

- Wind turbines
- Foundation including installation
- Electrical grid connection
- Other (development and engineering, project management, operation & maintenance facilities)

Wind turbines

Figure 35 shows the wind turbine investment costs for wind turbines assumed in the calculations. They have been derived from actual (2005) and estimated (2015) investment costs (ex-factory cost) for onshore wind turbines. A cost increment for adjusting to offshore condition requirements has been applied. This increment over the onshore version is assumed to be 15% for 2005 and 10% for 2015. For the hub heights higher than 70 m, an increase in investment of 0.75 €/m/kW is used.

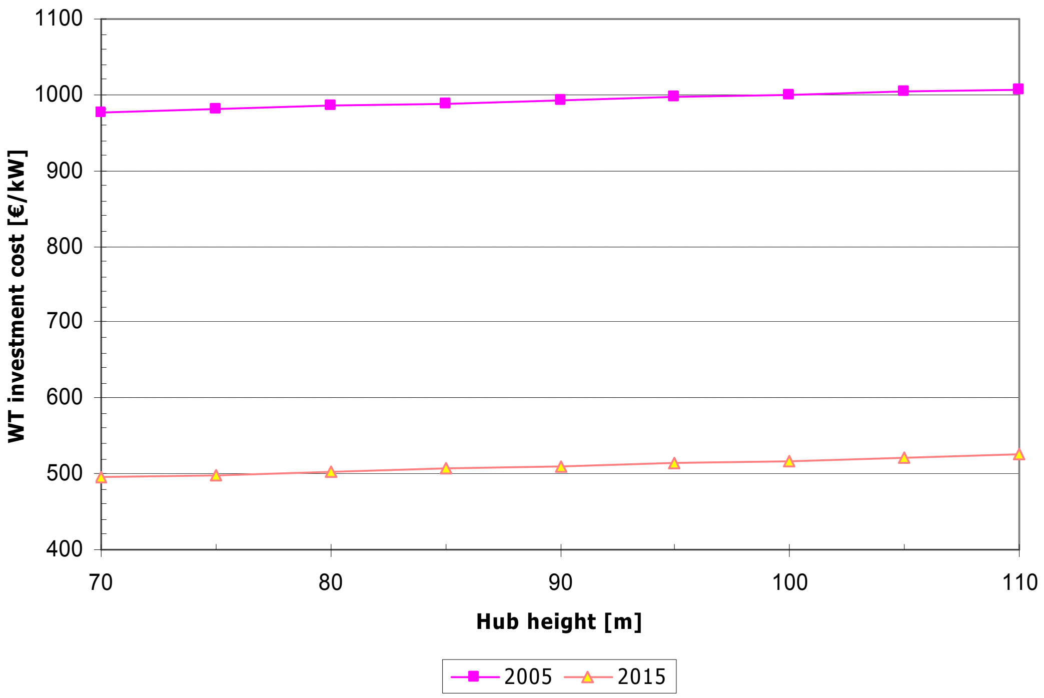

Figure 35: Wind turbine investment cost as function of hub height for 2005 and 2015.

Foundation

The investment cost estimation for the foundation is based on values found in literature for monopile and tripod foundation type.

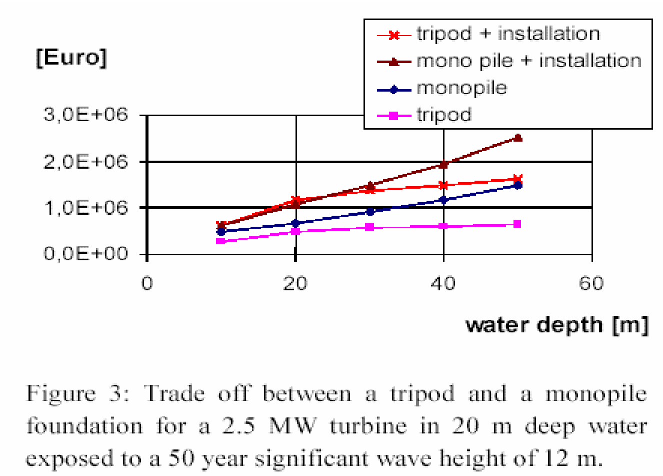

Figure 36: Investment cost for monopile and tripod foundation (ref. 4)

Figure 36 shows that from 30 m water depth, a tripod foundation becomes more economic than a monopile structure.

Foundation costs have been calculated as function of a number of technological parameters and water depths. The calculation takes guidance from the methods described in ref. 4. The cost estimations shown in Figure 37 and Figure 38 include the cost of foundation installation.

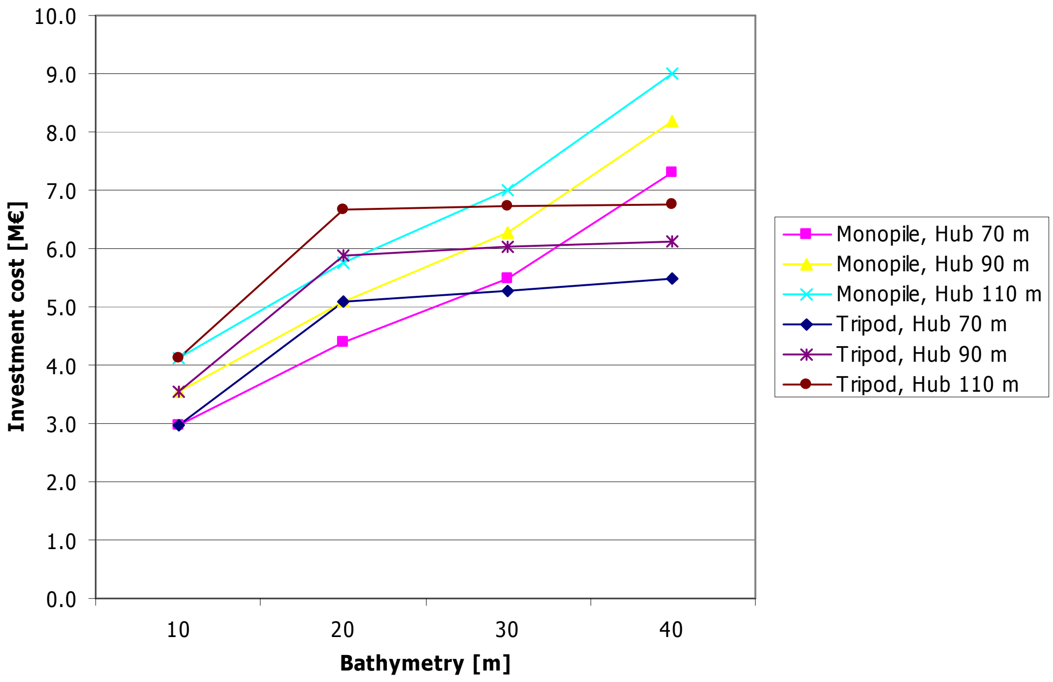

Figure 37: Investment cost for monopile and tripod foundation, 2005, for 10 MW installed wind power

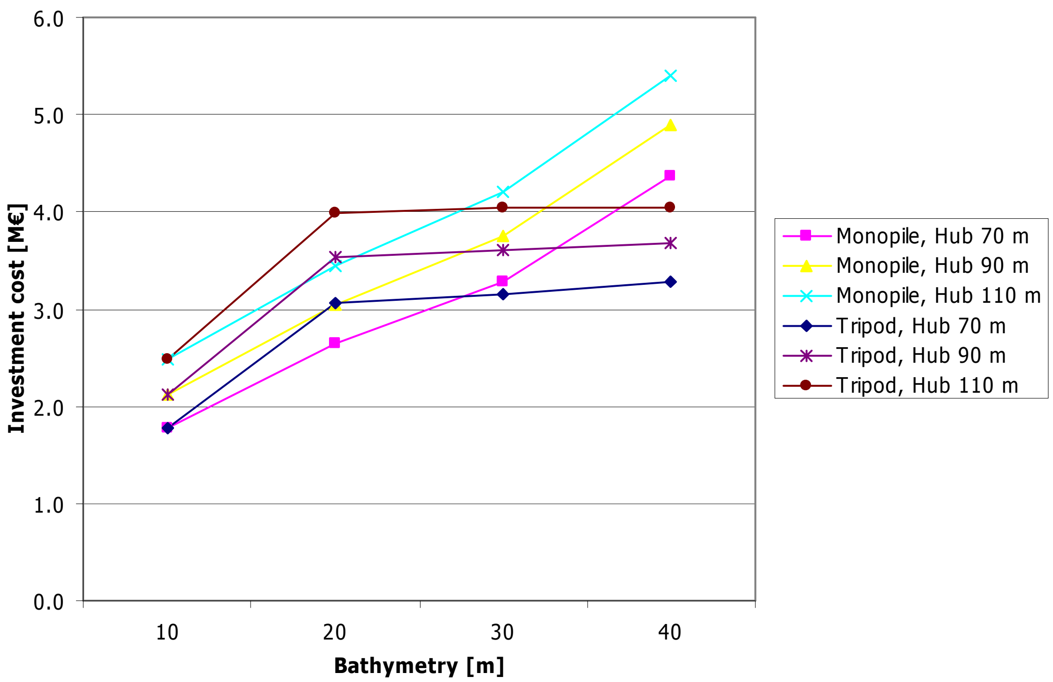

Figure 38: Investment cost for monopile and tripod foundation, 2015, for 10 MW installed wind power

The cost reduction in 2015 is a result of the increased size of wind turbines. The estimates for 2005 have been based on a commercial 3 MW turbine. With the estimated rated power of 10 MW/km², this results in 3.3 turbines/foundations per km². For 2015, a commercial 5 MW turbine has been taken in account. This results in the installation of only 2 turbines per km², with a significant reduction in cost for the foundation per 10 MW installed power.

Electrical connection

Electrical investment cost has been estimated based on assumptions described in ref. 5. The investment cost for the electrical equipment (wind farm power collection system, transformers, submarine HV transmission line) have been interpolated for a wind farm with a rated power of 300 MW. The calculated costs include the cost for installation of cables, transformers etc.

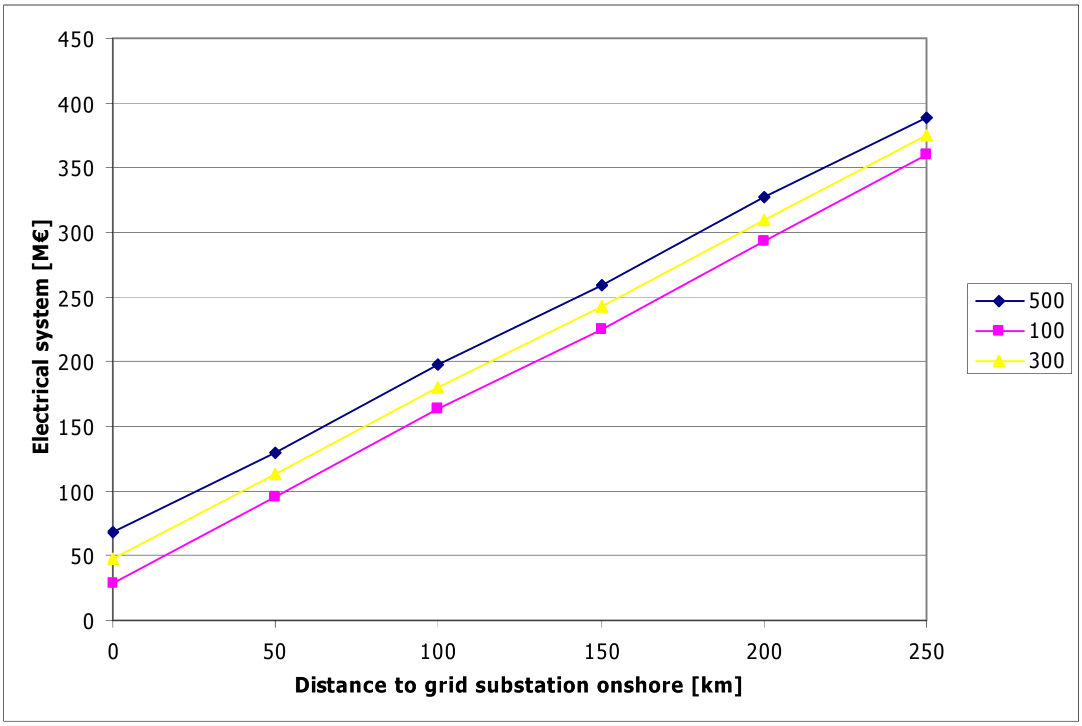

Figure 39: Investment cost for the electrical equipment for a 100, 300 and 500 MW wind farm.

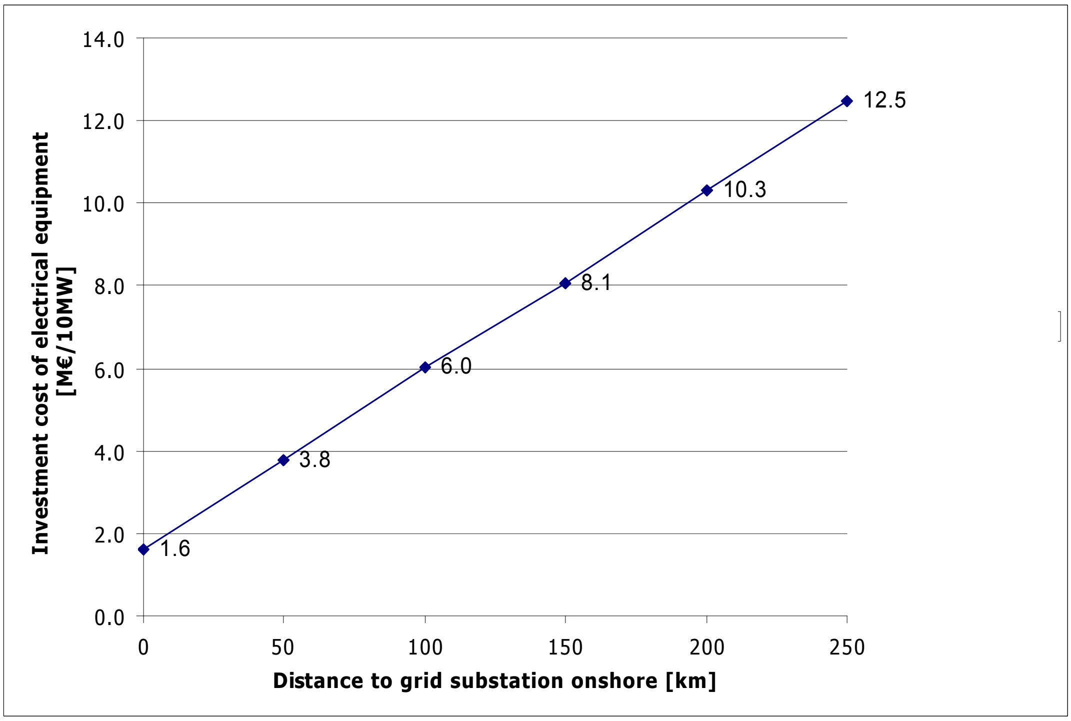

Figure 40: Investment cost for the electrical equipment, for installed power of 10 MW/km²

Other investment costs

Cost for project development, engineering, management and operation and maintenance facilities have been fixed at respectively 4% and 2% of initial investment cost (Ref. 7).

Total initial investment cost breakdown: example

Figure 41 shows the cost breakdown into the above items for a 10 MW wind farm 30 km in the sea, with a hub height of 70 m, improved technology level, and a distance of 40 km to the onshore grid connection point. The annual energy production is 31.6 GWh/yr. The local water depth is 16 m, the foundation is a monopile and the total initial investment cost is 1815 €/kW.

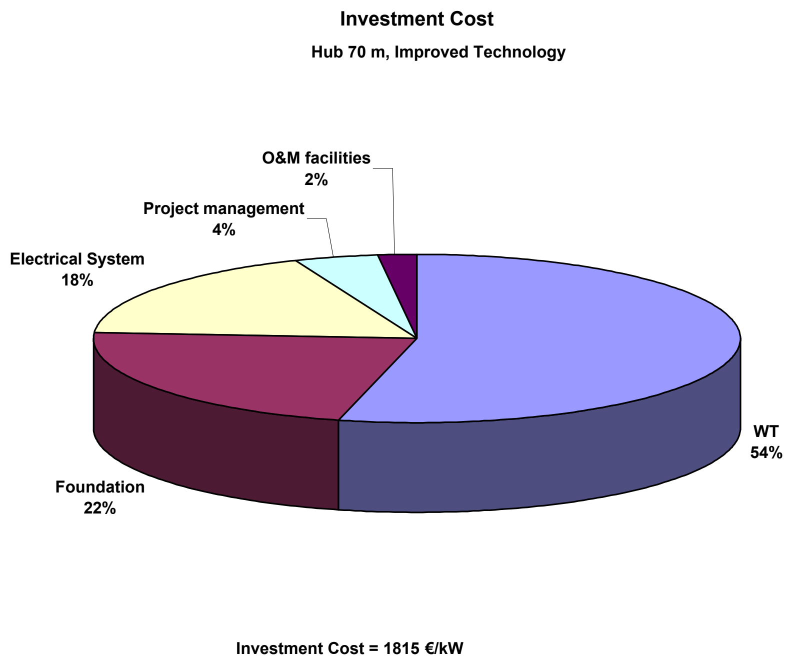

Figure 41: Breakdown of investment cost for 10 MW/km², hub height 70 m, improved technology

The breakdown of the investment cost of the 2015 technology level is given in Figure 42.

Because of the earlier described projected developments, the total investment cost decreases to a level of 1130 €/kW for that particular situation. The relative contribution of the wind turbine cost is significantly lower, because this cost item is supposed to undergo the most drastic cost change. On the other hand, the relative electrical infrastructure cost is quite high in this particular example. In reality this will depend very much on developments with respect to dedicated sea grids and on the way the costs are shared between the various actors.

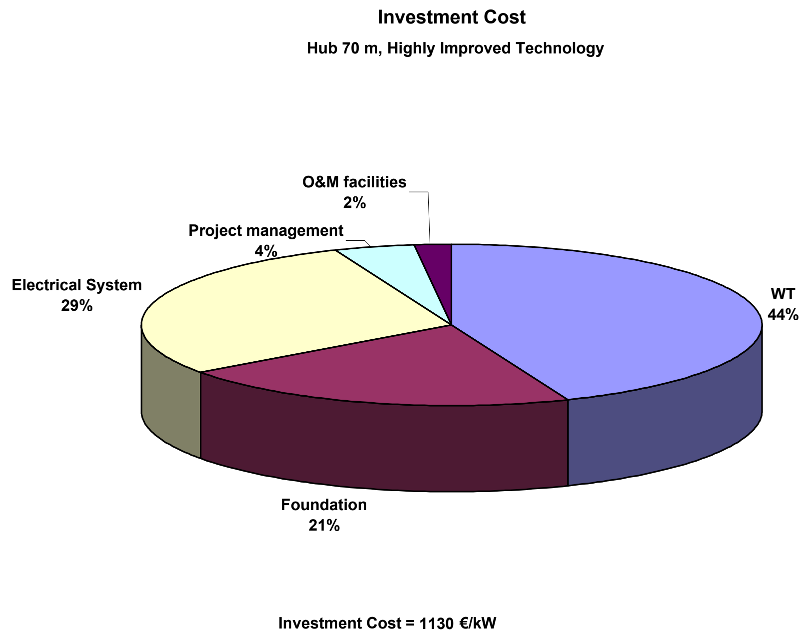

Figure 42: Breakdown of investment cost for 10 MW/km², hub height 70 m, highly improved technology

3.2.7 References

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3.3 Electrical interconnection and grid-connection schemes

3.3.1 Approach and method

The static impact of offshore wind power on the Belgian power grid was discussed in paragraph 2.4. There, it was concluded that the maximum amount of wind power that can be injected into the coastal grid points is around 500 MW, taken into account the grid reinforcements between Slijkens and Koksijde and the alleviation of the most heavily loaded points further inland. However, for higher power levels, the 400 kV grid will need to be extended towards the coast.

Apart from the static impact on the power grid, also the dynamic behaviour of a wind farm is investigated. This way, more insight is obtained about the ability of a wind farm to provide 'grid support'. 'Grid support', also known as 'ancillary services', represents a number of services that the power system operator requires from power generators, in order to secure a safe, reliable, stable and economically manageable grid operation. These 'ancillary services' include support for [1]:

- (fast) output power or frequency control;
- voltage control;
- black start capability;
- economic dispatch and financial trade reinforcements.

The relation between wind farms and grid support has been extensively discussed over the past years, especially in Denmark and Germany, where the relative amount of wind power in the power grid is the highest of Europe. Specific grid connection requirements for wind turbines were issued first by the Danish and German grid operators (refs. 2 3), and are used as a reference by most European grid operators who have to take a large amount of wind power in their power system into account.

The Danish and German grid connection requirements for wind turbines typically give values for:

- active power controllability, especially the fast reduction of power production when demanded by the grid operator;
- reactive power controllability (strongly related with voltage control), in case of normal and disturbed grid operation;
- ride-through capability, i.e. the capability to continue normal operation and power production in case of a grid disturbance nearby.

Thus, the actual existing grid connection requirements are mainly focussed on the first two mentioned ancillary services. With advanced technology for wind turbines generators, the performance of those generators can be considered as high as with conventional generators, regarding voltage control and fast reduction of power reduction.

On the other hand, even the most advanced turbine technology does hardly improve the capability of wind power to facilitate the economic dispatch of the power market and financial trade reinforcements. These issues can not be enforced by technical grid connection requirements, but must be part of the economical risk that a wind farm operator is willing to take. The criterion for success in these issues is mainly the accuracy of wind speed predictions on a (mid-)long term, rather than the turbine technology.

The work done here focuses on the grid impact items that can be optimised using advanced technology (i.e. active and reactive power controllability on a short term). Simulations are performed to illustrate the impact of using advanced technology – from the electrical point of view - on the grid behaviour. As the amount of scenarios (considering various grid disturbances and various sizes of wind farms with various generator types) is very high, the following approach is used:

- First, a dynamic wind farm model is developed (ref. 4), using the power system simulation tool EUROSTAG. The model does not envisage a very high accuracy and does not support accurate simulations of faults in the wind farm itself. However, it summarizes a wind farm electrical behaviour using a limited amount of parameters that have a direct impact on it. It is well suited for generic studies to estimate the impact of a hypothetical wind farm on a given grid point.

- As a demonstration of this model, simulation results are shown for the case where a wind farm is connected by a 150kV submarine cable at the 150kV substation of Slijkens (one of the three 150kV-substations near the Belgian coast). Three levels of technological advancement for the turbine generators are assumed, using three different parameter sets in the generic model. Also the impact of the cable length is illustrated. The impact of the wind farm on the grid voltage in case of a wind gust and a grid fault further inland is shown. The simulation results allow to set up 'rules of thumb' for the choice of generator type.

3.3.2 Wind Farm Generic Dynamic Model Development

3.3.2.1 Active power model

Detailed GE Wind Energy wind turbine model

The active power model is based on a model of a GE Wind Energy turbine. Those wind turbines are equipped with a doubly fed induction generator and have a rated power of e.g. 1.5 MW (the GE15 turbine model) or 3.6 MW (GE36). The power curve of the GE36 wind turbine is shown in Figure 43.

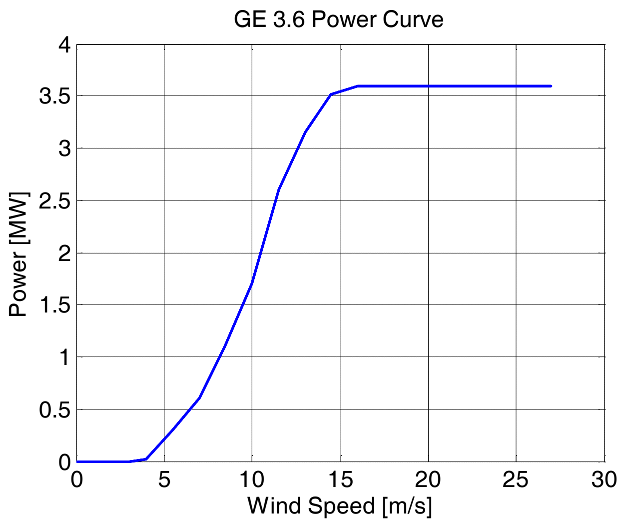

Figure 43: GE 3.6 Power Curve

The documentation for a detailed model of a GE-15/36 turbine, including the values for the various physical quantities and controller parameters, is found in [5]. The only difference between the GE15 and the GE36 model lays in the parameter set. The model is structured as in Figure 44 and is used as a starting point to calculate a more simplified active power model.

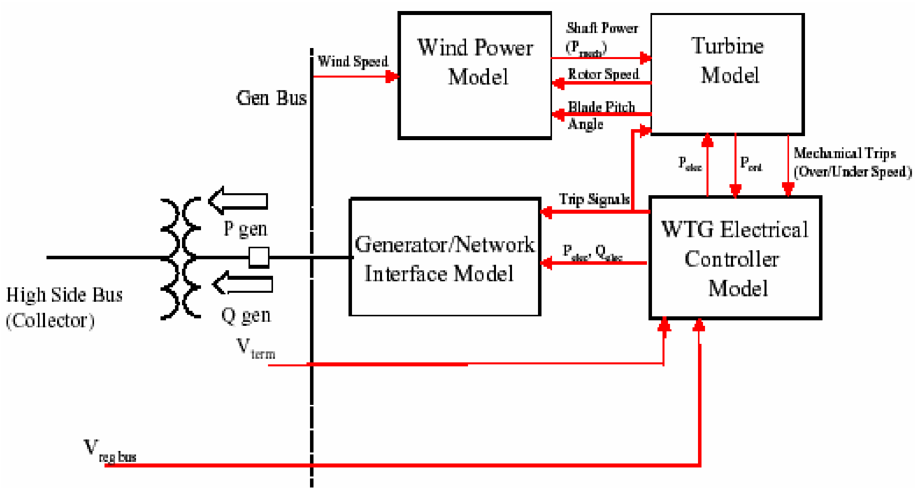

Figure 44: Model structure for a GE15 or GE36 wind turbine

When looking further into the details in the full model documentation [5], it appears a reasonable assumption that the main turbine characteristics related to transient response under 'normal' wind speed fluctuations are given by the 'Turbine Model'-block. This block contains the turbine motion equation, the speed and pitch control mechanism, and also an equivalent transfer function representing the shaft stiffness. The 'Wind Power Model' is basically an approximation for the $C_p(\lambda, \beta)$ function, in which λ is the tip speed/wind speed ratio and β is the pitch angle, and C_p the performance coefficient, i.e. the fraction of the kinetic energy in the wind that is converted by the turbine into mechanical energy.

Simplified equivalent model

Simulations were performed with a simplified model containing only the blocks 'Wind Power Model' and 'Turbine Model', to characterize the frequency response of P_{ord} (Figure 44), i.e. the mechanical power that is available for the generator. Wind speed signals were generated as a superposition of a sine wave (with amplitude 1 m/s and varying frequency) on an average value. With these wind speed signals as input, the turbine active power consists also of a sine wave of the same frequency as the input signal, superposed on a constant value. This suggests that, for a fixed value of average wind speed, the entire system is linear, and can be approximated by a simple transfer function. The amplitude of the power oscillations depends on the mean value of the wind speed signal and on the frequency of its fluctuations.

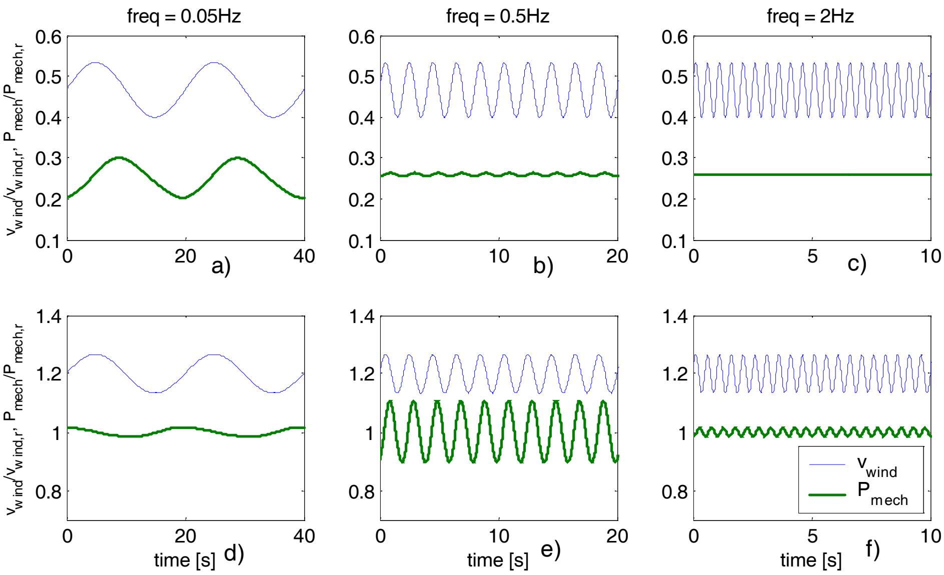

Figure 45: Wind speed and mechanical power for two values of average wind speed and three different wind speed fluctuation frequencies

Figure 45 shows examples from wind speed signals with an average value of 7 m/s (= 0.5•vwind,rated) (figures a, b and c) , and 17 m/s (= 1.2•vwind,rated) (figures d, e and f). Also the corresponding power output is shown.

All simulation results, for a large range of frequencies and average wind speeds, are summarized in Figure 46. The amplitude of the power oscillations is plotted against the frequency of the wind speed oscillations. This plot can be interpreted as a Bode diagram, and it allows writing equivalent transfer functions for the variable speed pitch-controlled turbine system.

In the Bode plot of Figure 46, two sets of curves can be distinguished:

Low average wind speed (below rated wind speed)

The curves for low average wind speeds show the behaviour of a low-pass filter: the amplitude of the output power oscillation remains constant as a function of the frequency, for low fluctuation frequencies. For higher fluctuation frequencies, the amplitude of the power oscillations decreases with a constant slope (20dB/decade).

At low average wind speeds, the wind turbine blade pitch angle remains at zero degrees to maximize Cp, and only the turbine speed control is active.

For slow wind speed fluctuations, the turbine speed is adjusted to obtain the maximum Cp-value, and the optimal turbine speed can be achieved at every moment. The output power is at every moment the maximum from the wind extractable power, as given by the power curve. The amplitude of the power output oscillations in Figure 46 depends on the average wind speed, as the power curve is not linear for low wind speeds.

For fast wind speed fluctuations, the turbine operates as a flywheel. It accelerates and decelerates to dampen the fluctuations in the output power. The system transfer function has the characteristic of a low-pass first order filter. The time constant of the filter depends on the average wind speed value but is between 1s and 10s, corresponding with a pulsation between 0.1 and 1 rad/s.

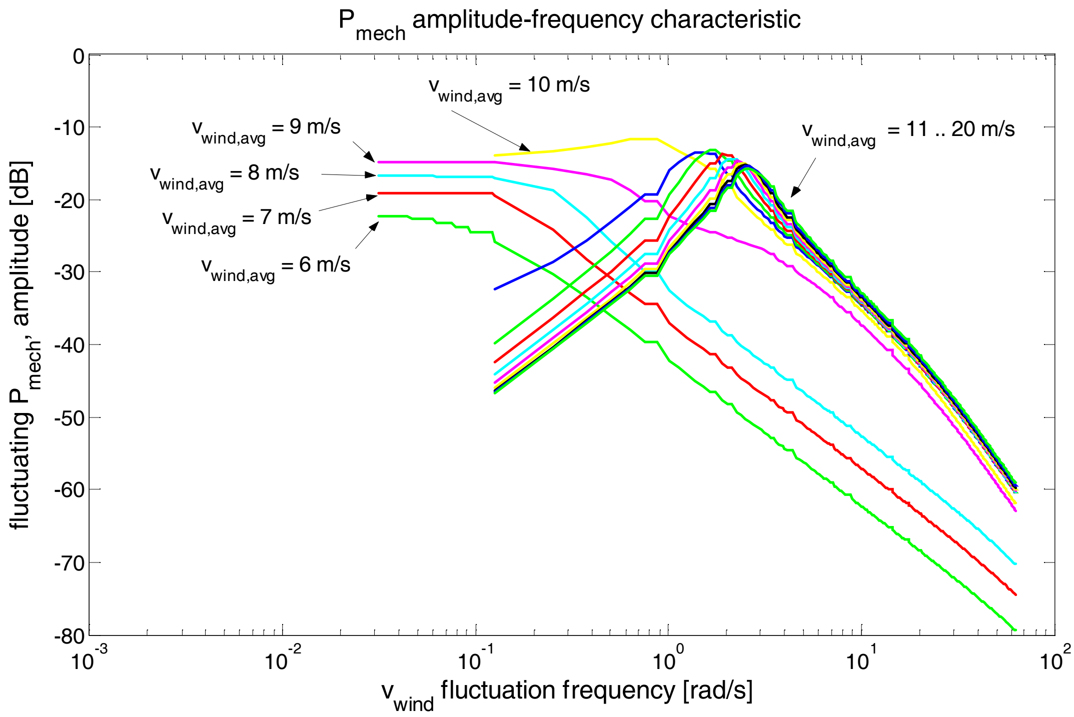

Figure 46: Frequency Characteristic of Power Fluctuation Amplitude

High average wind speed (above rated wind speed)

For high average wind speeds, the frequency characteristic is influenced by the action of both the pitch and the speed controller. The turbine speed is at its maximal rated value (e.g. 120% of nominal speed) but a small margin for speed variation above and below rated speed is still allowed, to dampen the power oscillations.

The pitch control limits the output power at its rated value, if the wind speed goes above the rated wind speed. However, the pitch control action is rather slow. Only for very low frequencies of wind speed fluctuation, the pitch control is able to maintain the output power at 1 p.u. at every moment. The amplitude of the power fluctuation is then very low (Figure 45d).

For very high frequencies of wind speed fluctuation, the slow pitch control is not able to follow the fluctuations, but the power output fluctuations are then damped by the variation of turbine speed (the right side of the curves for high wind speed in Figure 46). This is again the behaviour of a low-pass filter, and the output power remains approximately constant at 1 p.u (Figure 45f).

Between the region of power control by means of pitch angle adjustment on the one hand, and fluctuation damping through speed variation on the other hand, there is a frequency zone for which fluctuations of wind speed result in relatively high fluctuations of output power, as can be seen in Figure 45e and Figure 46. In the design of turbine controllers, it must be avoided that this frequency is in the same zone as the most common fluctuation frequencies of the wind speed. The wind speed seen by the turbine is affected by, amongst others, the tower blockage and vertical wind shear effect, which results in apparent fluctuation frequencies of wind speed of around 0.5 - 1Hz.

The transition between low wind speed regime (only speed control in steady state) and high wind speed regime (speed and pitch control in steady state) would be expected to occur around the turbine rated speed. However, the turbine dynamics are designed in such a way that the pitch control is already in operation at (slightly) lower wind speed values than the rated wind speed, to assist the output power control and damping in case of wind speed fluctuations. For the turbine simulated here, the transition between the two frequency behaviour patterns occurs at a wind speed of around 12 m/s. For wind speed close to this value, the system behaves strongly non-linear.

Equivalent Transfer Function: Power Response to Wind Speed Variation

From the Bode plots in Figure 46, it can be concluded that an equivalent transfer function must be a first order low-pass filter for low wind speeds, and a higher order transfer function for high wind speeds. This is shown in Figure 47. The function input is the available wind speed. The output is the mechanical turbine power that is available to produce electricity.

In the upper part of Figure 47, the wind speed is low-pass filtered and converted into active power using the turbine power curve. The time constant of the low-pass filter corresponds to the frequency at which the slope of the first group of bode plots in Figure 46 evolve from 0 dB/decade to -20 dB/decade. This time constant is dependent on the average wind speed, but is assumed constant for this simplified model.

The power curve has an upper limit for the output power, being 1 p.u. The output power will remain constantly 1 p.u. for high wind speeds. The impact of wind speed fluctuations on power fluctuations above 1 p.u. is taken into account by a second transfer function (in the lower part of Figure 47) that matches the second group of curves in Figure 46.

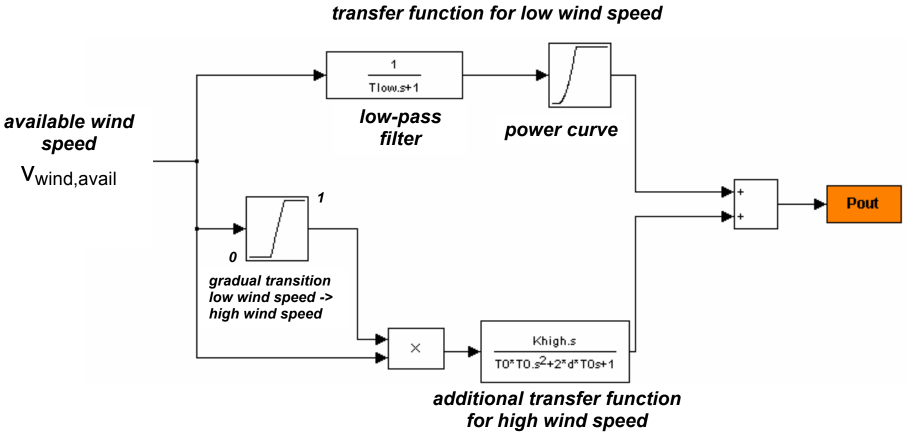

Figure 47: Equivalent Transfer Function for Active Power

The simplified model contains a gradual transition between the low wind speed and high wind speed region. For wind speeds below 11 m/s, the transfer function for high wind speeds is not taken into account (factor 0). For wind speeds above 13 m/s, the transfer function for high wind speeds is fully taken into account (factor 1). A linear interpolation is used for the intermediate wind speeds.

The parameters that result in an optimal match between the equivalent transfer function and the curves from Figure 46 were found to be:

$T_{low} = 7$ s $d = 0.3$

$T_0 = 0.52$ s $K_{high} = 0.06$

A comparison between the simulated output as calculated by the detailed turbine model and by the equivalent transfer functions is given in Figure 48, for a randomly generated wind speed signal with low average value (left) and high average value (right). There is a satisfying correspondence between the two results.

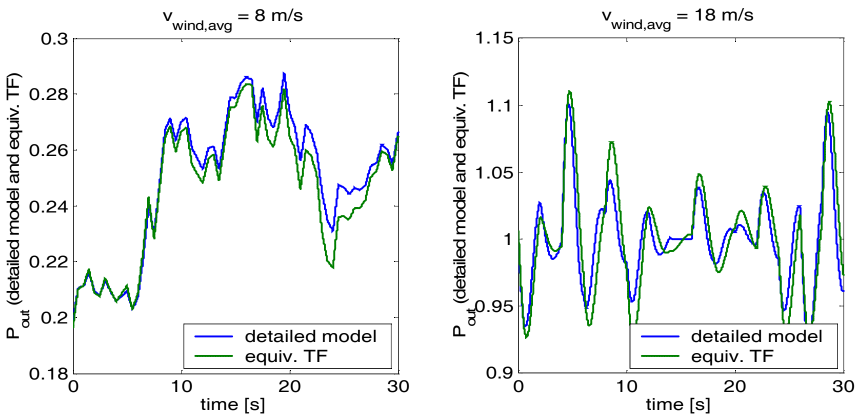

Figure 48: Comparison between output power from the detailed model and the equivalent transfer functions

Equivalent Turbine Yaw model: Response to Wind Direction Variation

A change in wind speed direction results in a loss of available active power, as the available active power is proportional to the apparent rotor area seen by the wind, and thus with the cosine of the angle mismatch between the turbine orientation and the wind speed direction. The turbine may then be yawed, to set this angle mismatch to zero. This is modelled as shown in Figure 49.

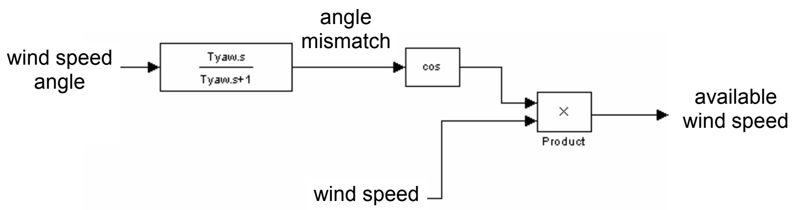

Figure 49: Model of farm yawing

If the wind speed direction remains constant, the angle mismatch is zero in steady state. When the angle of the wind speed direction changes suddenly, the angle mismatch undergoes a step change, and evolves than back to zero with a time constant Tyaw. Only the wind component that is orthogonal to the turbine area can be used to produce mechanical power. This available wind speed is used as input for the equivalent transfer function of Figure 47.

The value of Tyaw is set at 50 s, significantly higher than the time constants of the equivalent transfer function, as the yawing system reacts considerably slower than e.g. the turbine speed or pitch angle.

It would be more realistic to model the turbine yawing with a constant yaw speed, which would result in an angle mismatch curve with a constant slope (the yaw speed) in Figure 50. However, for numerical reasons, a first-order function is more suitable, and the approximation error is acceptable.

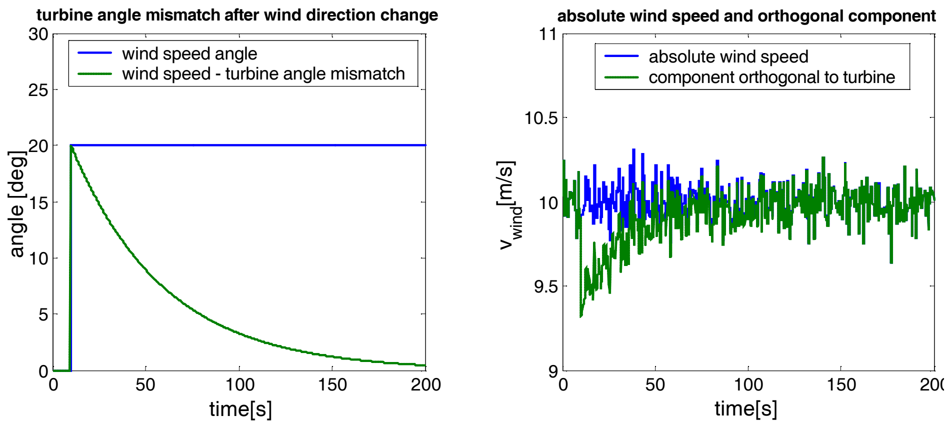

Figure 50: Mismatch between wind speed direction and farm orientation after a sudden change of wind speed direction (left), and absolute wind speed and its orthogonal component (right)

Aggregated Wind Farm Active Power Model

The accuracy of the simulation results for entire wind farms depends mainly on the accuracy of the wind speed data that are seen by each individual turbine. These wind speeds are mostly calculated for each individual turbine, using one reference wind speed and mathematical models that take turbulence, farm losses etc into account. With highly accurate wind speeds, a network model for the wind farm internal grid can be built using power system simulation software.

However, a high accuracy for the calculated wind speeds requires extensive modelling and computational efforts, and this is in contradiction with the original idea, i.e. to construct a generic simplified wind farm model for models that aim to estimate the grid potential to absorb an amount of wind power. Furthermore, for power system simulations, it is desirable that a wind farm can be considered as one generating unit with a specific behaviour.

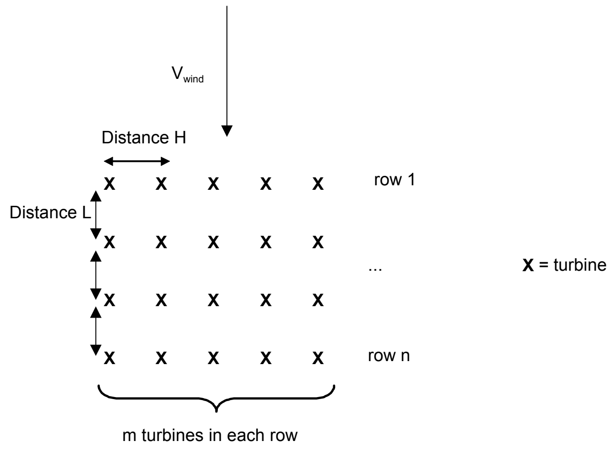

Figure 51: Assumed Wind Farm Layout

Therefore the following aggregated farm model is proposed. The distance between the turbine rows is L, the distance between the turbines in a row is H, the number of rows is n, and the number of turbines in a row is m. The initial wind speed is assumed to be orthogonally oriented with regard to the first turbine row. The wind speed is assumed to be equal for every turbine in a row. A wind speed change is assumed to propagate through the park in the wind direction, with a propagation speed equal to the wind speed: this means that a wind speed change at row 1 will be perceived at row 2 after L/v_{wind} seconds.

The wind speeds seen by each turbine row are calculated as in Figure 52. The wind speed time series for the 2nd and 3rd row are delayed time series of the original wind speed signal.

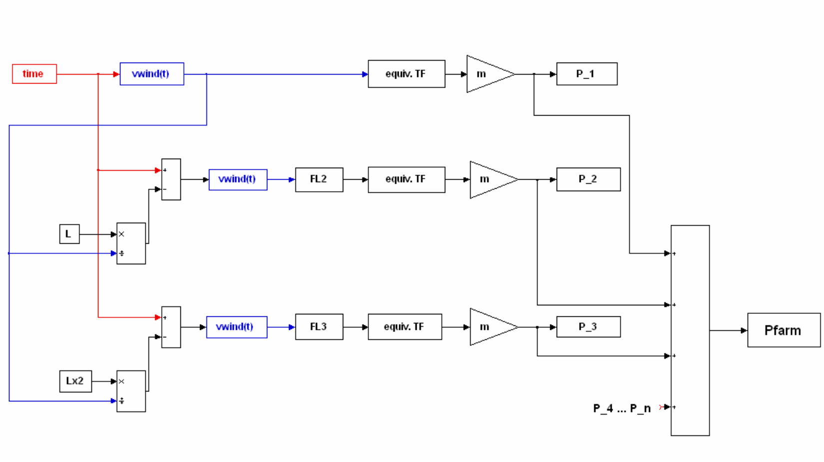

Figure 52: Aggregated Farm Active Power Model

A loss factor is incorporated to take the farm losses into account. Farm losses cause - due to turbulence and shadow effects – a reduction of wind speed for the turbines behind the first row. In Figure 52, for instance, the farm loss factor FL2 for the second row is set to 0.9 (wind speed reduced by 10% for the turbines on the second row) and for the third row to 0.9^2, i.e. 0.81.

When the wind speed is orthogonal to the wind speed shown in Figure 51, another aggregated power model is used in which the parameters 'm', 'n' and 'L' are switched with respectively 'n', 'm' and 'H'. For wind speed directions between those two extreme values, a linear interpolation between those two models is used.

This farm model is highly approximate; neither can it take full account of non-rectangular farm layouts. However, it is well suited for estimating the impact of extreme cases of wind gusts in a typical farm.

Controlled Active Power Modes

The grid operator may command the wind farm to reduce its output power for reasons of viable grid management. Three control modes are proposed here:

In the 'Full Power' mode, the wind farm converts all available mechanical power to electricity and injects it in the grid. In the 'Limited' mode, the electricity production does not exceed a maximal value. The 'Limited' mode can be requested e.g. to prevent line overloading, and can be realized by pitching the turbine blades partially out of the wind. In the 'Balancing' mode, the turbine blades are also partially pitched out of the wind, to maintain a fixed amount of available wind energy as balancing power. This last service can have a high economic value for the farm operator, but is only very rarely applied because of the limited accuracy of actual wind speed predictions.

The three operation modes ('Full', 'Limited' and 'Balanced') are shown graphically in Figure 53. The upper line is the available power from the wind speed. The lower, bold line in the figures 'Balancing' and 'Limited' represents the actually delivered power for these operation modes (assuming perfect control).

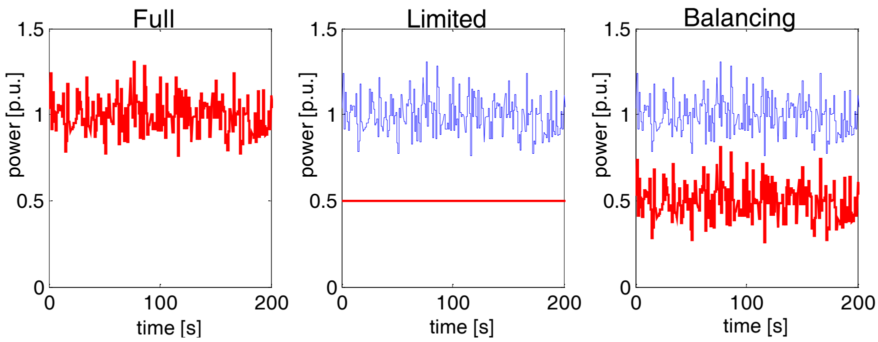

Figure 53: Active Power Operation Modes

The applicable operation mode is maintained by controlling the pitch angles of the turbines. The transition speed between two operation modes is determined by the pitch variation rate. The model for the transition between the operation modes is shown in Figure 54.

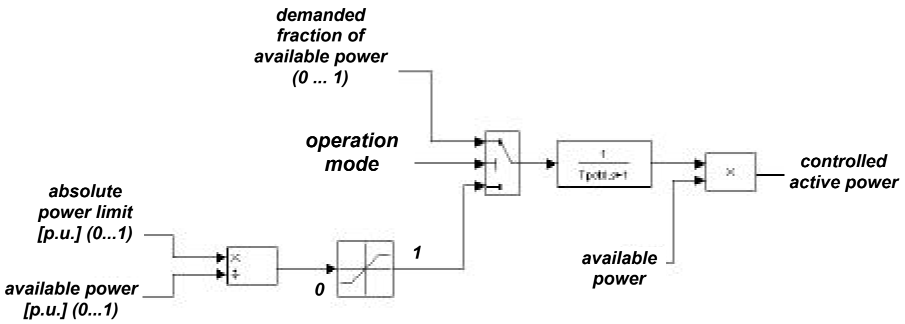

Figure 54: Model for Transition between Active Power Modes

The switch in Figure 54 is controlled by the 'operation mode'. The 'operation mode' determines whether the upper or lower input of the switch must be passed through as output. The switch output is the fraction (between 0 and 1) of the available active power that will actually be delivered to the grid. The upper switch input represents the 'Balancing' mode, in which a fraction of available active power can be chosen to be actually produced. The lower switch input represents the 'Limited' mode. From a given maximal value for the output power, the fraction of the available power that must be produced is calculated and is passed through the switch. The most common operation mode ('full power') can be reached either by setting the absolute power limit to '1' or by setting the demanded fraction to '1'.

The transition between the operation modes is modelled as a change of demanded fraction from the available power, through a first order delay. This delay time constant, Tpctrl, depends on the pitch variation rate, and is set in this model at 4 s. A maximum value for the delay time may be given by the grid connection requirements. For example, the power output at the 160 MW - offshore wind farm at Horns Rev must be able to be reduced from 100% to below 20% within 5 seconds [6].

Conclusion for the Active Power Model

A detailed turbine model is replaced with an equivalent transfer function, to calculate the available active power with satisfying accuracy for simulations of continuous operation. Much information about the turbine is lost (e.g. turbine speed, pitch angle) when the equivalent transfer function is used. On the other hand, the integration of this simplified turbine model in a power system model does not increase the computational efforts for power system simulations, and a good assessment of fluctuating generated power caused by wind turbines can be made.

The turbine model is extended to model the turbine yawing in a simplified way. An aggregate farm model is built up. Three operation modes are modelled, as well as the dynamic transition between these modes. The operation mode control is applied to the aggregated farm model, rather than to each turbine separately. This supports the idea that large wind farms can be regarded as single power plants, from the point of view of power system investigators.

The model parameters, such as the time constants of the equivalent transfer functions, and of the pitch and yaw control, reflect only approximately the turbine behaviour. These parameters are not given by manufacturers. However, they are strongly linked with fundamental turbine performance characteristics. They summarize the complicated turbine behaviour in a very dense way that is directly usable for grid operators, project developers or anyone who is involved in the assessment of wind energy potential in a given grid point.

The Active Power Model assumes variable speed operation of the turbines, but does not prescribe a certain generator type such as doubly-fed induction generators or synchronous generators. It has already been stated in literature that, for transient power system simulations, the differences between the generator types used in variable speed wind turbines can not be seen in their interaction with the grid anymore, because they are fully compensated for by the controllers [7]. However, the model developed here is not applicable for wind farms equipped with squirrel cage induction generators. These generator types are not expected to play a major role in the development of large wind farms, especially offshore.

3.3.2.2 Reactive power model

Most grid operators require that a wind farm is able to control its reactive power output, in order to provide voltage control as an ancillary service to the grid. This ancillary service also has a high economic value for the wind farm operator. Reactive power has to be controlled both during normal and during disturbed grid operation.

The modelling of the reactive power generation and the behaviour during grid disturbances does not start from a predefined detailed model from literature. It is believed that future large wind farms will always be able to control the reactive power output, either by control action on the generator itself or by additional devices (such as SVCs or STATCOMs) connected at the point of common coupling.

The speed of reactive power control and the maximum amount of reactive power that can be supported may however depend on the generator type or additional equipment. This will be discussed further in paragraph 3.3.2.4.

Two control modes for the reactive power generation are possible:

- operating at a constant power factor (e.g. one), or operating continuously between two extreme power factors (e.g. 0.975 inductive and 0.975 capacitive);
- controlling the reactive power output instantaneously to maintain the voltage at a given node at its reference value.

As stated by most grid connection requirements, a fast transition between the first and second operation mode must be possible, e.g. the EON connection requirements demand a transition towards the second operation mode as soon as the grid voltage drops below 60% of its rated value [1].

The reactive power supplied for the first operation mode is calculated from the required power factor and the supplied active power, obtained from the active power model.

For the second operation mode, the required reactive power is calculated by a P-controller or PI-controller with anti-windup, making sure that the reactive power that the wind farm must supply never exceeds a limit value. The implementation of a PI-controller is supported by most power system simulation software packages, and does not contain any particularities in its use for this model.

The dynamic transition between two reactive power modes is discussed below, where the interface between the farm model and the power system model is developed.

3.3.2.3 Wind Farm tripping

At extreme grid conditions, the wind farm is allowed to be disconnected from the grid in order to protect itself from overcurrents etc. The cases at which a farm is allowed or demanded to disconnect are mostly given by the grid operator.

Tripping requirements are characterized by threshold values for voltage or frequency deviations and their duration. An example for voltage tripping requirements is graphically represented in Figure 55.

Example threshold values are:

$u_{under,1}$,	= 0.3 p.u.	$u_{over,1}$,	= 1.8 p.u.
$u_{under,2}$,	= 0.5 p.u.	$u_{over,2}$,	= 1.3 p.u.
$u_{under,3}$,	= 0.8 p.u.	$u_{over,3}$,	= 1.1 p.u.
$t_{under,1}$,	= 0.02 s	$t_{over,1}$,	= 0.02 s
$t_{under,2}$,	= 0.15 s	$t_{over,2}$,	= 3 s

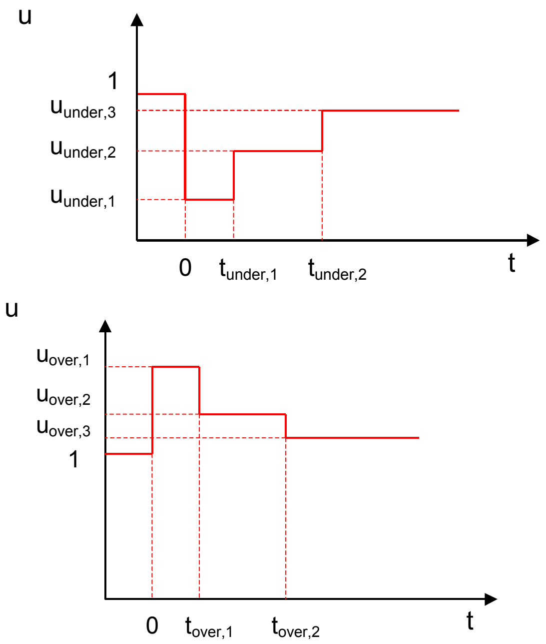

Figure 55: Voltage Thresholds for Tripping Actions

Most power system simulation software tools support the implementation of tripping relays included in a dynamic model. The threshold values are mostly given by the grid connection requirements and can be easily adapted in the model. Thus, the impact of more severe ride-through demands from the grid operator can be investigated using the model.

3.3.2.4 Interface of the dynamic model with power system model; current dynamic behaviour during grid disturbances

Transformation of Reference Frame

Up to this point, attention has been paid to describe the developed model as independent of the software. However, the construction of the interface between the wind farm model and the grid model requires some experience with the used software. The entire model as described above was implemented in the Macroblock Modelling Tool of the power system simulation tool Eurostag, as a current (IR,II)-injector [8, 9]. From here on, the model block figures are directly copied from the Eurostag Macroblock Model Editor. It would however be not too difficult to implement the same model in a different software tool, using the strategy described here.

IR and II represent the real and imaginary current component that is injected by the wind farm into the power grid. The two components of this current vector are obtained from a Park-transformation of the three-phase currents towards a reference (R,I)-frame, which is the same for the entire power system model. In this reference frame, the voltages and injected currents at each node are represented as vectors with components respectively (UR,UI) and (IR,II).

In order to easily compose the current, injected by the wind farm, from the calculated active and reactive power, a rotation of the reference frame is performed. All quantities are now referred to the (D,Q) frame, which is aligned with the voltage vector, in such a way that UQ = |**U**| and UD = 0. Hence it follows that IQ is the active current and ID is the reactive current (positive if inductive). The voltage and current vectors in both reference frames are shown in Figure 56. In this example, the phase shift between voltage and current is f, and the angular difference between the reference frames is q. After the wind farm current (ID,IQ) is calculated, (IR,II) is calculated by performing a back-transformation towards the original reference frame, which is actually the interface frame between the farm model and the grid model.

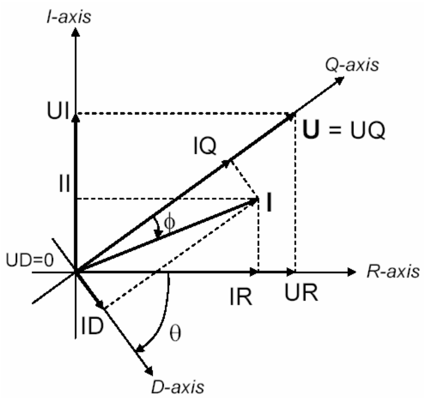

Figure 56: Voltage **U** and Current **I** in (R,I)- and (D,Q)-Reference Frame

The transformation towards the (D,Q)-reference frame is done through a rotation of the voltage and current vectors over *q* degrees, which is a well-known procedure and requires only some elementary trigonometric operations which can be easily done in the Eurostag Macroblock Modelling Tool.

Modelling of Current Dynamic Behaviour during Grid Voltage Disturbances

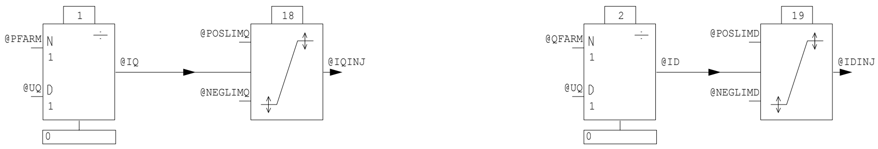

Figure 57: Calculation of Active and Reactive Current, to be injected in Grid Model

The calculation of @IQ en @ID is shown in Figure 57. Eurostag Macroblock I/O-variables are denoted with the prefix '@'. @PFARM is the active power of the farm, calculated in Figure 52. @QOUT is the reactive power calculated by the reactive power model described in paragraph 3.3.2.2. @IQ and @ID are calculated by dividing the active and reactive power by @UQ, which is a direct consequence of the used reference frame described above.

The impact of possible voltage disturbances at the point of common coupling (the grid node at which the wind farm is connected) are taken into account using the variables @POSLIMQ, @NEGLIMQ, @POSLIMD and @NEGLIMD. Those variables are no control parameters for the farm, but only mathematical aids, and part of a model strategy to take into account the dynamic behaviour during a voltage disturbance.

In case of a voltage disturbance, the wind farm needs to react in a double way:

- the reference reactive power @QFARM will change to deliver grid support. This is done by the reactive power model;
- in any case, the total current must be controlled in order not to exceed the rated current. However, in the first milliseconds of a voltage sag, the current will be, inevitably, very high. This is modelled in Figure 58 and Figure 59, in which @POSLIMD, @NEGLIMD, @POSLIMQ, @NEGLIMQ are calculated.

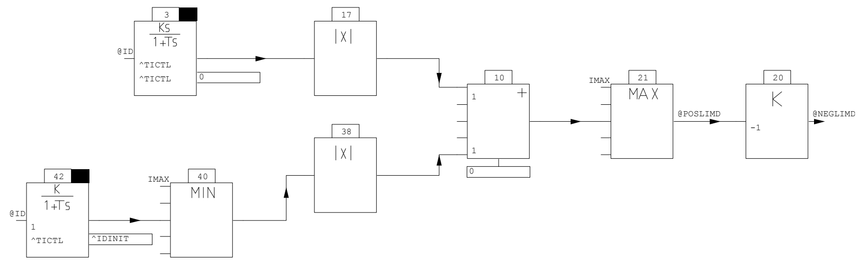

Figure 58: Calculation of @POSLIMD and @NEGLIMD

When the voltage undergoes a step change due to a disturbance, the currents @ID and @IQ will also undergo a step change, according to Figure 57.

The currents @ID and @IQ are split into their uncontrolled and controlled part. The uncontrolled part of @ID is fed into the upper entrance of the summator in Figure 58. It evolves from the height of the step change (at the moment of the disturbance) towards zero, with the time constant TICTL of the current controller.

The lower entrance of the summator in Figure 58 is fed by either the controlled part of @ID (which is @ID minus its uncontrolled part), or either IMAX, the rated current, i.e. the maximum allowable steady state current. IMAX is selected for the lower entrance of the summator in the case that the instantaneous value of @ID exceeds IMAX.

The final values for the variables @POSLIMD and @NEGLIMD are then calculated as shown in Figure 58. Those two variables are the extreme values that the current can have during the first tens of milliseconds after a voltage disturbance. Whether those limits are reached by the actual current depends on the reactive power – and thus current @ID - that is demanded. The actually injected reactive current @IDINJ is calculated in Figure 57: it is the originally calculated @ID, but limited by the values @POSLIMD and @NEGLIMD.

The time constant TICTL represents the speed with which the fast current increase due to a voltage dip can be annihilated by the current controller of the wind farm. The use of this time constant implies that the internal farm current control system may be approximated as a first-order delay. Its value depends on the specific technology of the wind farm. Thus, although the specific turbine technology is not visible in the model structure, the time constant associated with the current control loops are strongly affected by the choice between e.g. a doubly fed induction generator or a synchronous generator. Suggested values are:

- TICTL = 20 ms for a synchronous generator, connected to the grid through a fully dimensioned PWM-converter. The current can be controlled by power electronics devices only;
- TICTL = 200 ms for a doubly fed induction generator. In this generator type, the power and current is divided between the stator and the rotor, the larger part is however supplied by the stator. This stator current is controlled through the magnetic interaction with the rotor current, which is on its turn controlled by a PWM-converter. Because of this magnetic interaction, the current control speed is lower, and thus TICTL is higher.

The model for calculating the limits for @IQ (@POSLIMQ and @NEGLIMQ) are analogous as in Figure 58 and is showed in Figure 59.

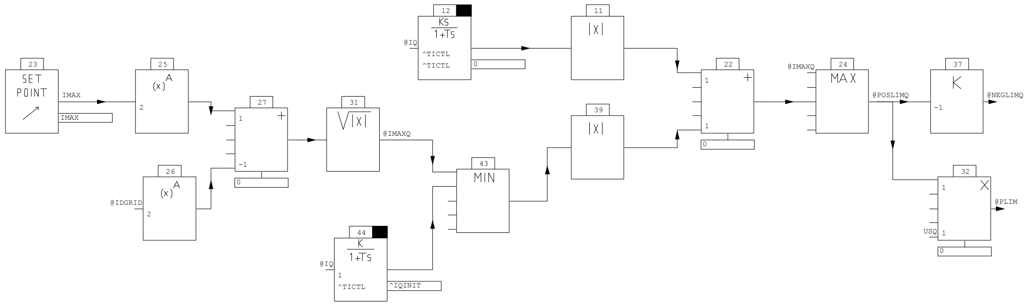

Figure 59: Calculation of @POSLIMQ and @NEGLIMQ

A difference with Figure 58 is that the upper limit for the controlled part of IMAX but @IMAXQ, which is calculated as SQRT(IMAX^2 - @IDLIM^2). This takes into account the fact that, in case the rated current value is reached due to a voltage sag, priority must be given to the reactive power support, rather than the continuing supply of active power. The amount of reactive power support is then as high as the rated current IMAX permits. If, during the support, there is any current margin left for supplying active power, this active power can be supplied.

Finally, a voltage dip, resulting in a reactive current demand for voltage support and hence the reduction of the delivered active current, will have its impact on the active power control of the farm. If the active current @IQ must be limited in order not to exceed the total rated current, the turbine blades must be pitched out of the wind in order to prevent the turbines from overspeed. This will occur if the mechanical power captured by the turbines is significantly larger than the electrical power delivered to the grid. In such a case, the farm active power control mode must switch to 'Limited'. The power limit value is called @PLIM, the fraction (0 … 1) of the farm rated active power that must be produced electrically. @PLIM is calculated as shown in Figure 59. @PLIM is then fed back from Figure 59 into the active power controller of Figure 54 (this is not shown on the figures, but straightforward to implement).

3.3.3 Simulation Results for Belgium

3.3.3.1 Simulation assumptions

Wind Farm Model

Turbines

The wind turbines and farm are modelled as described in the previous paragraph.

The GE 3.6 turbine type is considered as representative for a typical variable speed turbine. Therefore, the power curve from Figure 43 (in relative values), as well as the time constants for the active power transfer function that were found in the previous paragraph, are used:

T_{low} = 7 s	d = 0.3
T_0 = 0.52 s	K_{high} = 0.06

The time constant for the active power control in case of 'Limited' operation mode is 4 s, i.e. a possible reduction of active power from 100% to 37% in 4s.

Three values for TICTL are assumed.

1. TICTL = 20 ms
2. TICTL = 200 ms
3. TICTL = 2 s

As described in paragraph 2, TICTL represents the speed of the current control. Thus, a distinction is made between three levels of technological advance. As discussed in the previous paragraph, a value of 200ms for TICTL corresponds with a doubly fed induction generator, which, if well controlled, can be considered as 'advanced' technology. TICTL = 20 ms corresponds with a generator that is fully controlled by a power electronic IGBT –converter. This is considered as 'highly advanced' technology. Also the installation of static voltage controllers (such as SVCs) results in a better – i.e. lower - value for TICTL, in the order of magnitude of 20 ms.

Wind farm

The wind farm layout is assumed as five turbine rows behind each other, that are orthogonal to the wind speed direction.

Three values for the wind farm installed power are investigated: 250 MW, 500 MW and 1000 MW. Although an installed power of 1000 MW is presently not feasible in view of the limited grid availability that is found in Section 2, dynamic simulations can be made to see the impact of wind power on voltage fluctuations.

Grid connection

The grid connection is shown in Figure 60. The wind farm power is assumed to be collected at 30 kV, and transformed by an offshore transformer towards 150 kV. The grid connection is made by a submarine 150 kV cable. The cable characteristics have impact on the simulation results, especially its capacitance is not neglectible, the following typical cable parameters are used (taken from the ABB Cable N9445-16 data sheet of a 150 kV XLPE-insulated submarine power cable) :

- resistance per phase R = 0.0554 Ω / km
- inductive reactance per phase X = 0,145 Ω / km
- capacitance per phase C = 0.126 μf / km

As the cable consumes a lot of capacitive power, two inductors are assumed, each of them compensating half of the cable capacitive power in no-load condition. One is installed at Slijkens, the other at the 150 kV offshore substation. The inductors are not controlled and do not have an impact on the dynamic simulations.

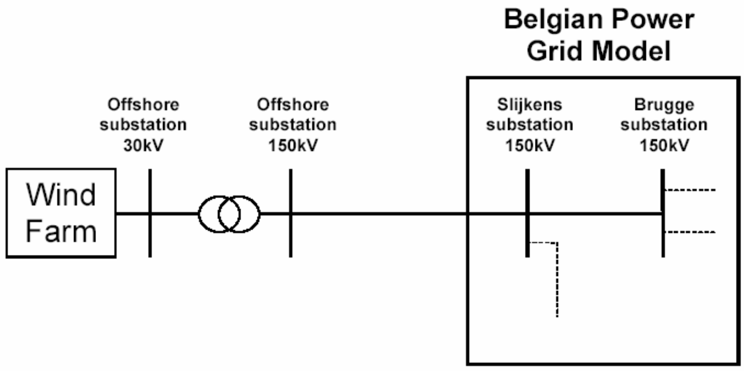

Figure 60: Assumed Grid Connection of Wind Farm to Belgian Power Grid

3.3.3.2 Model of Belgian Power Grid

A Eurostag model of the Belgian power grid has been used, containing:

- All 400 kV, 220 kV 150 kV and 70 kV substations and high voltage lines of Belgium, including the planned 150 kV cable between the coastal nodes Koksijde and Slijkens;
- All generation and load data for each substation, as they have been recorded on a representative winter day (19/01/1994);
- Dynamic models of the governors and voltage controllers of most generators in the Belgian Grid, including the power plant of Herdersbrug, which is the nearest power plant to the coast.

3.3.3.3 Wind Gust Simulation

The impact of wind speed changes on the voltage on the grid node at which the farm is connected is investigated. The wind farm has an assumed rated power of 500 MW and is connected at the 150 kV substation of Slijkens. The results for wind farms of 250 MW and 1000 MW are given in Annex 2.

Four scenarios are considered:

a) the wind farm produces nor consumes reactive power at the offshore 150 kV node; the transmission cable length is 10 km;

b) same as a), but with a cable length of 50 km;

c) the wind farm reactive power is dynamically controlled in such a way that the voltage at Slijkens remains at a fixed value. The transmission cable length is 10 km;

d) same as c), but with a cable length of 50 km.

A wind speed sequence as in Figure 61 is assumed. Starting from 10m/s, the wind speed rises at 14m/s, i.e. the turbine rated wind speed, and then further to 25 m/s, i.e. right below the cut-out wind speed. The wind speed direction undergoes a sudden change of 28 degrees at t = 5000s. The turbines must yaw towards the new wind direction. The mismatch angle between the wind direction and the turbines orientation, calculated according to the description in paragraph 3.3.2, is also shown in Figure 61.

The active power production is shown in Figure 62. The moments at which the wind gust at t = 1000 s reaches each of the five turbine rows can be clearly distinguished. A sudden wind speed increase results in a power increase towards rated power in approximately 150 s. The farm rated power is not fully achieved because of the farm losses, causing a reduction of wind speed for the turbines behind the first row.

The rated power is achieved when the wind speed increases further to 25 m/s. The turbines then have to change the blade pitch angle in order to control the power output and to keep the turbine within the design limits. The pitching action goes rather fast, and the farm is able to maintain its output power within a narrow range around its rated power. The moments at which the wind speed gust reaches each of the five turbine rows is again clearly seen.

The change in wind speed direction also causes a short drop in power production, which is quickly restored by the yawing action of the turbines.

For the active power production, no differences were noted between the four scenarios.

The produced reactive power for each of the four scenarios is shown in Figure 63. In the cases with voltage control, the reactive power production is negative: the farm behaves as an inductor. The resulting voltage in Slijkens and at the offshore 150 kV – substation are shown in Figure 64 and in Figure 65. It is seen that, without voltage control, the voltage at Slijkens fluctuates if the wind speed and farm active power production changes. In the cases with voltage control, the voltage can well be maintained at a fixed value.

The cable length has an impact on how the reactive power must be controlled in order to control the voltage at Slijkens. It is seen that the voltage at Slijkens either increases or decreases at the moment of increased active power production. This is because the cable capacitance, which has a large influence on the system's voltage behaviour, is proportional to the cable length, and thus much difference in the behaviour can occur with different cable lengths.

On Figure 63, it is seen that a longer transmission cable (50 km) requires a higher control range for the wind farm in order to provide voltage control at the coastal 150kV substation (Slijkens).

All four scenarios were investigated considering the three values for TICTL (20 ms, 200 ms, 2 s). However, the differences between scenarios with different TICTL-values were hardly visible. As the active power fluctuations in case of wind speed changes are very slow, (order of tens or hundreds of seconds), the advantages of a highly advanced generator control system were not noticed.

The voltage fluctuations at the 150 kV substation of Slijkens for the cases a) and b) are far less than 1% (Figure 64), and thus well within the normal voltage fluctuations that appear on a power system. A wind farm operation strategy at which the farm reactive power is controlled at a fixed value does not result in a gravely decreased grid power quality.

It is concluded that the impact assessment of wind speed fluctuations on the grid voltage does not provide an incentive for installing highly advanced generator types.

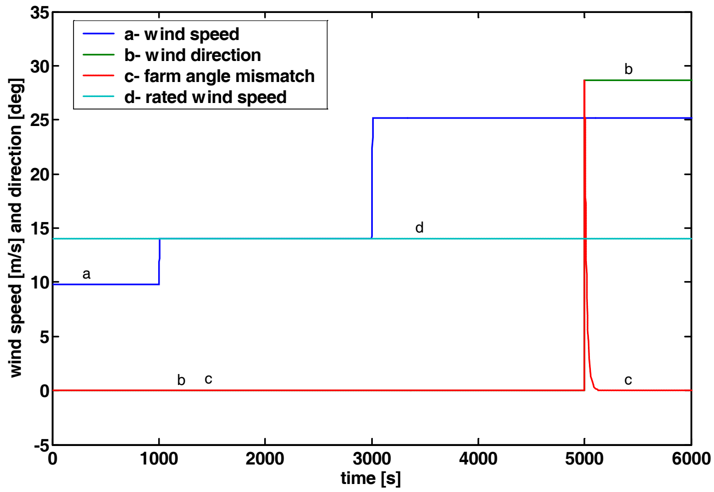

Figure 61: Assumed Wind Speed and Wind direction for Wind Gust Simulation

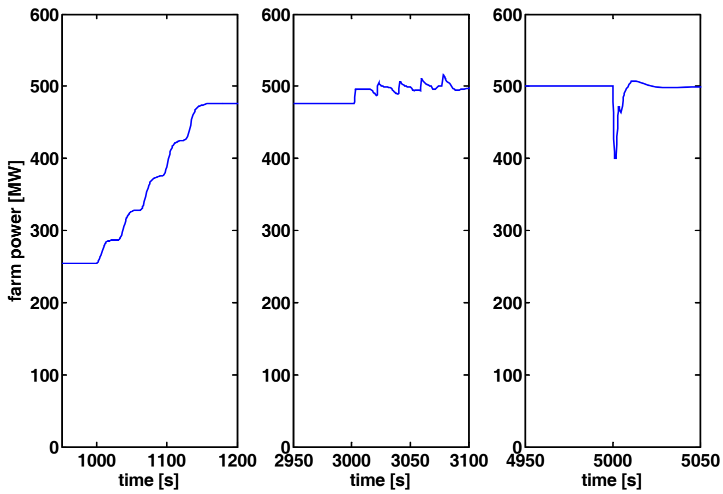

Figure 62: Active Power Production by a 500 MW Wind Farm

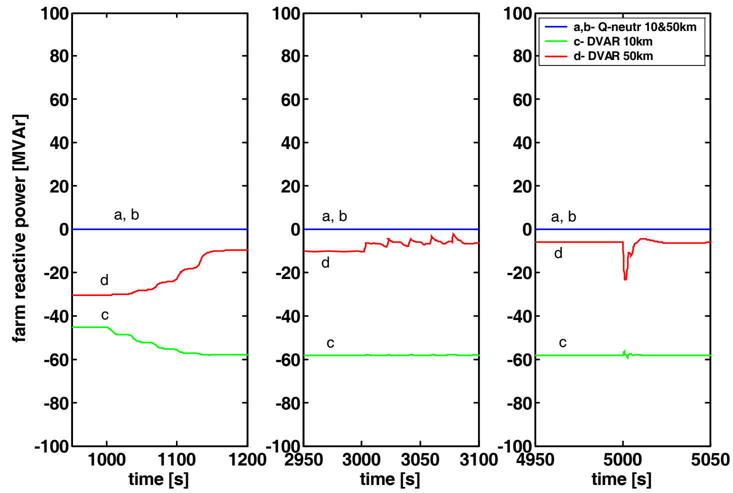

Figure 63: Reactive Power Production by a 500 MW Wind Farm

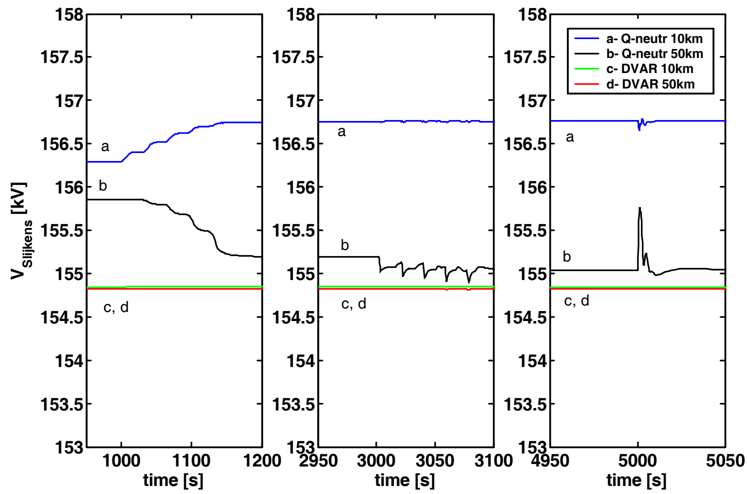

Figure 64: Voltage at Slijkens 150 kV substation

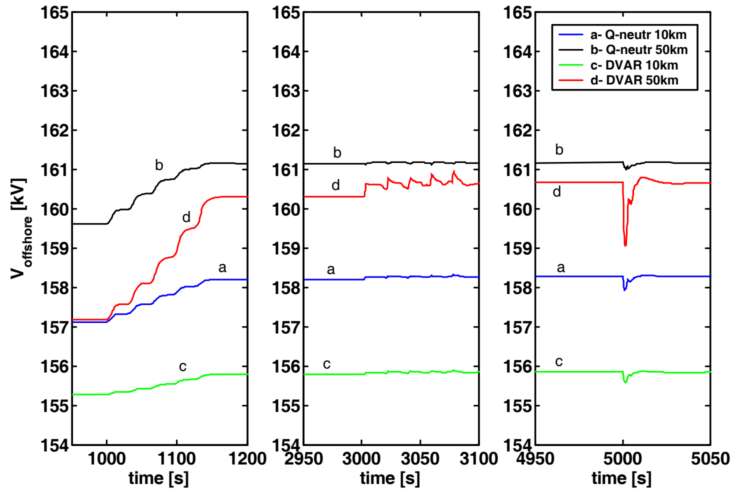

Figure 65: Voltage at offshore 150 kV node

3.3.3.4 Voltage Disturbance Simulation due to Grid Fault

A grid fault is simulated at t = 1s, by applying a short circuit in the substation of Brugge, which is located further inland and connected by a 150kV line to Slijkens. The fault is cleared after 300 ms. This results in a 300 ms voltage dip at Slijkens. The depth of the voltage dip depends on the wind farm reaction.

For the following simulations, the following assumptions were made:

- the rated wind farm power is 500 MW, the results for a wind farms of 250 MW are given in appendix;
- the wind speed is constant and equal to 12 m/s (below rated wind speed);
- calculations were made with transmission cable lengths of 1, 10, 20, 30, 40 and 50 km;
- in one scenario the wind farm keeps its reactive power output at zero;
- in the other scenario, the voltage at Slijkens is monitored and the wind farm provides dynamic support to control this voltage. The time constant of the farm current controller TICTL is either 20 ms (Figure 67), 200 ms (Figure 68) or 2 s (Figure 69).

The voltage at Slijkens for each of the scenarios is shown in Figure 66, Figure 67, Figure 68 and Figure 69. The scenario with a cable length of 1 km (in fact not offshore) is also representative for the case in which a dynamic voltage controller, such as a static var compensator, is installed onshore, near the point of common coupling (Slijkens).

The conclusions from the figures are:

- The voltage at the initial moment of the dip is the same for all cases. However, the voltage can be better maintained if fast voltage support is delivered by the wind farm generators.
- The duration of typical voltages dips is some hundreds of milliseconds, and thus the dynamic voltage support by the wind farm must be fast enough. There is nearly no difference between the voltages at Slijkens for the case where the wind farm does not provide voltage support (Figure 66) and where it provides voltage support very slowly (Figure 69).
- The cable length limits the voltage support that a wind farm can deliver. In each of the cases of Figure 67, the wind farm supplies the maximum available reactive power (this was set in the simulation model to 1 p.u., i.e. 500 MVAr). The effect on the voltage restoration is much less for a 50 km cable than for a 10 km cable. This effect was not yet visible on the curves of Figure 68 and Figure 69 because the maximum reactive power was not yet obtained, due to the slower control systems.

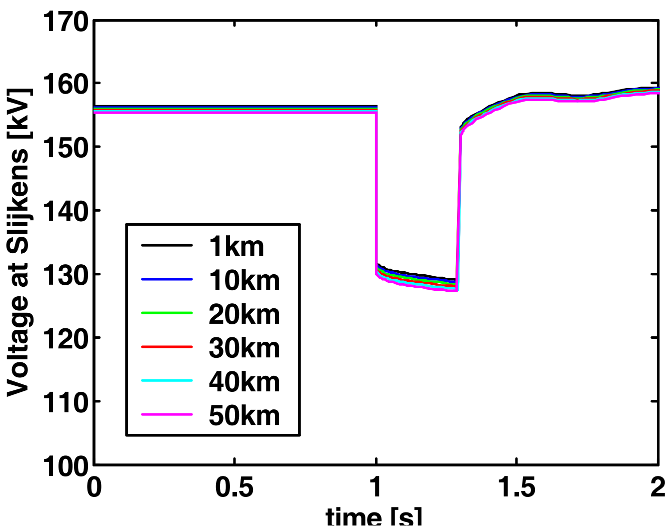

Figure 66: Voltage at Slijkens, wind farm keeps reactive power output at zero

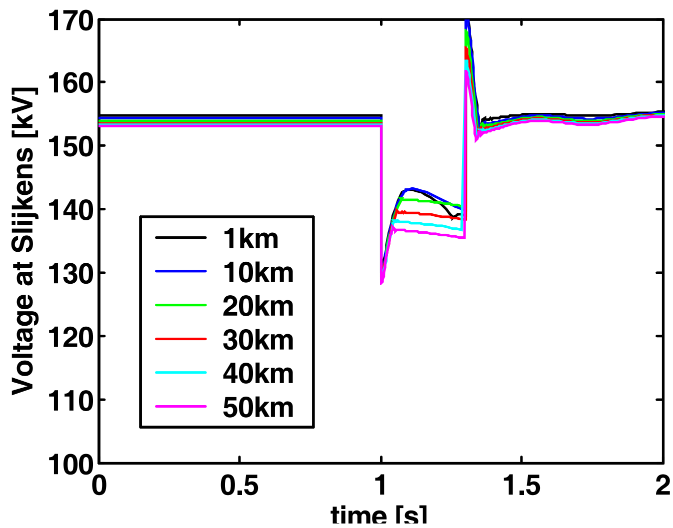

Figure 67: Voltage at Slijkens, wind farm provides dynamic voltage support, TICTL = 20 ms

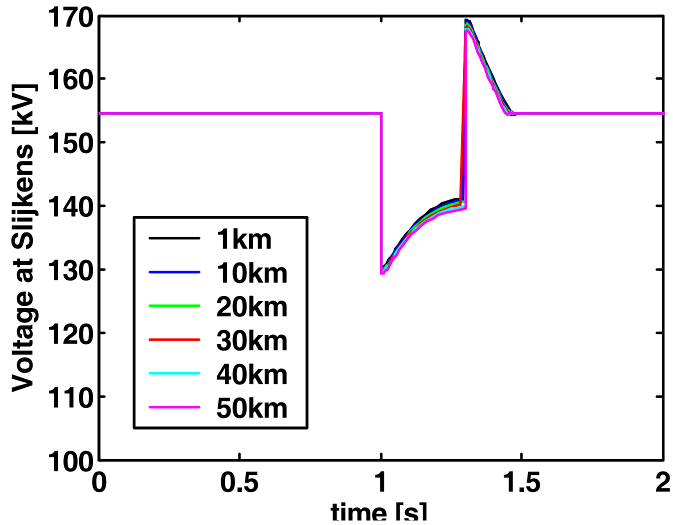

Figure 68: Voltage at Slijkens, wind farm provides dynamic voltage support, TICTL = 200 ms

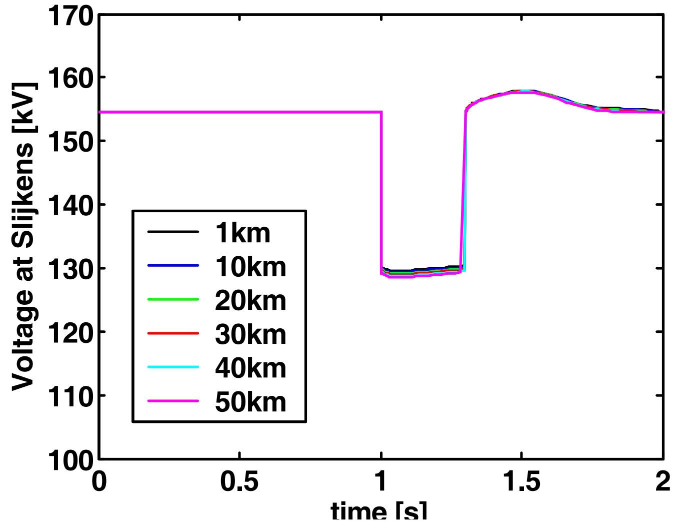

Figure 69: Voltage at Slijkens, wind farm provides dynamic voltage support, TICTL = 2 s

3.3.4 Conclusions

A simplified generic dynamic model for a wind farm has been developed. The model parameters have not been provided by wind turbine manufacturers, but they describe the wind farm electrical behaviour in a very dense way. The impact of the parameters (time constants for the transient responses to different kinds of disturbances) is directly visible in the different simulated scenarios. It must be noted that the followed generic modelling approach is not specific for wind farms, but can also be used for other kinds of generating units that are fully or partially controlled by power electronics.

A wind gust and a grid fault have been simulated.

Wind gusts do not result in considerable voltage fluctuations at the power substations nearby the wind farm. A sudden wind gust results in an increase of power production with a slope of approximately 1% per second. The voltage fluctuations that are seen at Slijkens, i.e. the assumed farm connection point on shore, are well within the normal margins even if the wind farm does not provide dynamic voltage control.

The simulation of grid faults demonstrates the benefits of highly advanced generator types, which can provide very fast voltage support, with a time constant of approximately 20 ms.

However, this voltage support action becomes less effective if longer cable lengths are used. With longer cables, the reactive power range in which a turbine must be able to operate becomes too high. For cable lengths from approximately 30 km on, the choice between an advanced or highly advanced generator type does not influence their dynamic voltage restoration capabilities. Instead, this voltage restoration task must then be taken over by an installation on-shore, such as a Static Var Compensator.

The use of HV DC (with voltage source converters) is, apart from the benefit of avoiding the capacitive cable currents, also able to provide voltage control at the shore, because it already requires a power electronic converter station at the shore for the DC-AC conversion. Thus, HV DC would alleviate the problems concerning dynamic voltage stability to a high extent, but is probably not an economic solution for cable lengths below 80 km.

Summarizing:

For cable lengths up to 30 km, the choice for a highly advanced generator type can improve the dynamic voltage stability at the point of common coupling.

For cable lengths between approximately 30 km and 50 km on, a dynamic voltage controller (such as Static Var Compensator) on shore is the best solution to ensure dynamic voltage stability at the point of common coupling.

HV DC, equipped with voltage source converters, can provide the same voltage control support as a highly rated SVC. The choice for HV DC depends on the cable lengths. For very large cable lengths, the cost of an HVDC installation becomes lower than the costs of the power losses due to the capacitive charging current in the cable. HV DC is however not expected to be the most economic solution for cable lengths smaller than 80 km, and is thus not relevant for the Belgian case.

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4 The offshore wind energy potential in the Belgian Continental Shelf

4.1 Introduction

This section discusses the estimation of the wind energy potential of the BCS.

Based on the resources, physical boundary conditions, technologies and cost assumptions the potential of offshore wind is evaluated with respect to the following aspects:

- Installed wind power capacity;
- Estimated energy generation potential for different wind turbine sizes and technology levels (2005–2015);
- The economic potential, presented as a mapping of the estimated investment cost and levelised production costs for different wind turbine sizes and technology levels (2005 – 2015).

The estimation of the potential starts from the assumed available area of the BCS, taking into account exclusion zones as discussed in par.2.5. The evaluation of the offshore wind energy potential in European seas has been undertaken and published in previous studies (for example in the references 1, 2, 3). Some of the studies also mention explicitly numbers for Belgium.

4.2 Offshore wind power capacity potential of the BCS

The wind energy potential in terms of installed capacity is proportional to the available sea surface area and to the assumed wind power density. In paragraph 2.5 it has been shown that the available area amounts to 2101 km², after excluding the 3 miles zone and all hard exclusion zones[24]. In paragraph 3.2.5.4 it has been demonstrated that for purposes of potential estimation, the power density for near future and far future can be reasonably assumed to be constant, and equal to 10 MW per km².

The distribution of the (available) potential as a function of distance to the shore and of the water depth is illustrated in Figure 70. It is clear from this figure that going beyond 30 m water depth does not make sense in terms of adding to the potential.

Turning the total available BCS area (after subtracting the exclusion zones, 2101 km2) into a giant wind farm would result in 21 GW of installed wind power capacity, sufficient to produce an amount of energy needed to cover a major part of the annual electricity consumption of the country.

Optimisation of the siting is strongly determined by the project investment cost, which is mainly driven by water depth and distance to the shore. The presentation in Figure 70 can be of assistance in the decision making (in connection to the cost analysis further presented in this section). Putting for example a limitation of 40 km to the distance and 20 m to the water depth, and assuming that 15 % of the area would be available for wind farming, yields a wind power capacity potential of 2.1 GW (10 % of the maximum potential). The percentage available area mentioned is arbitrarily chosen.

The installed wind power capacity is furthermore limited due to the limited power evacuation possibilities, in other words by the limitations posed by the electrical grid. The present Belgian HV grid configurations do not allow more than 0.5 GW wind power to be evacuated from offshore. Expansion of wind power beyond this capacity would involve additional measures in the electrical power network.

[24] The present estimation does not take into account unpublished short term political zoning decisions.

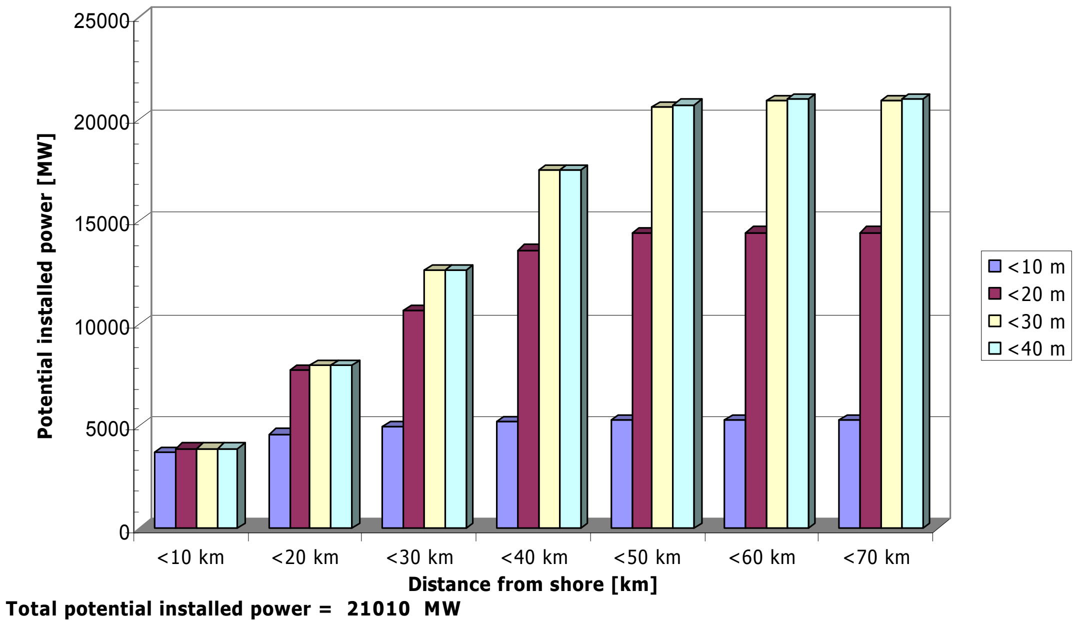


Figure 70: Cumulative distribution of the potential installed offshore wind power of the BCS as function of distance to the shore and water depth taking account of hard exclusion zones.

4.3 Offshore wind power generation potential (annual energy output)

4.3.1 Approach and method

The potential energy production from offshore wind farms in the BCS is calculated with the assumptions given in the sections 2 and 3. The characteristic value for the energy generation is the long-term average annual energy output.

The steps are summarised here:

- The BCS is divided into a grid of 1x1 km, each square represented by its centre point (3509 grid points) and position co-ordinates according to UTM zone 31.
- For every grid point, the perpendicular distance to the coast is determined. The water depth for each grid point is assumed constant and is taken from 2.5.3.
- The wind resources for every grid point are taken from the analyses of paragraph 2.2.
- The synthetic wind farm power curve is taken from paragraph 3.2.5.4.
- Energy output calculations for every grid point are performed for two representative hub heights (70 m/ 110 m) and two technology levels with corresponding values of availability (88% for improved technology 2005; 98 % for highly improved technology 2015). Array losses are included in the synthetic power curve. The electrical grid losses are calculated according to the models described in section 3.
- The net annual energy outputs (at the primary side of onshore transformer) are given in Figures 71 to 75. The numbers are expressed in equivalent full load hours. The energy output for every grid point (square kilometre) is obtained by multiplying this number with 10 MW.
- The total potential energy output of the BCS is obtained by summation of all individual grid points.

4.3.2 Discussion of the results

The results of the energy potential calculation are presented in Figure 71 to Figure 75, which show the geographical distribution of the energy production potential, for the various assumptions on hub height and technology level. The values presented are the calculated equivalent full load hours, to be multiplied with 10 MW in order to obtain the energy output per square kilometre.

A few characteristic numbers are summarised in Table 23. The lowest AEO is corresponding to the near shore location, the highest at the far end of the BCS.

The values for total AEO of the BCS are obtained by adding all the individual grid points. The total net AEO gives the sum of all grid points of the BCS where wind power is not excluded by other users or rules. The gross AEO represents the total potential, if abstraction is made of all exclusion zones. It is obvious that the last values are highly theoretical. They are only presented for reference.

The maps presented in Figure 71 to Figure 75 can be used to make a first assessment of the generation potential of zones selected for wind farming.

	Hub height	Lowest AEO per grid point	Highest AEO per grid point	Total Net AEO	Total Gross AEO
Time frame	(m)	(H/year)	H/year	TWh	TWh
2005	70	2800	3200	65.6	108.7
	110	3200	3400	71.1	116.5
2015	70	3200	3600	73.8	122.3
	110	3500	3800	78.9	131.3

Table 23: Characteristic numbers of potential annual energy generation in the BCS. Values for total AEO in TWh indicate the physical potential.

The variations in the numbers are mainly determined by the wind speed and the wind farm 'efficiency'. The wind speed is function of distance to the shore and of the height above sea level. The efficiency is assumed to be dependent on technology level i.e. improves in the future mainly due to higher availability.

Improving the technology (time frame 2005 versus 2015) can increase the energy production by 12.5%, mainly because of higher availability. On the other hand, increasing the hub height can only increase the annual energy production by 6.8%. From the energy generation point of view, it's better to invest in technology improvements (read: higher reliability) than in higher hub heights.

It is also relevant to look at the potential energy generation as a function of the distance to the shore and as a function of the water depth. This is illustrated in Figure 76 to Figure 79.

An example calculation illustrates the use of these numbers. Applying the same boundary conditions as in par 4.2 (limitation of 40 km distance, 20 m water depth) results in a total annual generation potential of around 42 TWh (from around 14 GW installed). Assuming adequate siting and using 15% of the surface of the available area, the potential generation amounts to around 6.5 TWh (from around 2.1 GW installed), which corresponds to approximately 6 % of the projected gross domestic electricity consumption in 2015.

The electrical grid absorption capacity is at present one of the strongest limiting factors. Taking into account the actual limitation of 500 MW, the potential annual energy generation would be limited to a fraction of the above number and would amount, depending on the siting of this 'small' wind farm to 1.5 - 1.6 TWh.

The calculated numbers are indicative. Because of the generalisations used in the wind climate, the shortcomings in the models and in the technology descriptions, they do not intend to be a basis for detailed feasibility calculations of wind farms on a specific site in the BCS. The effect of different values of the Weibull shape parameter k can be estimated with help of the graphs given in Appendix 2.

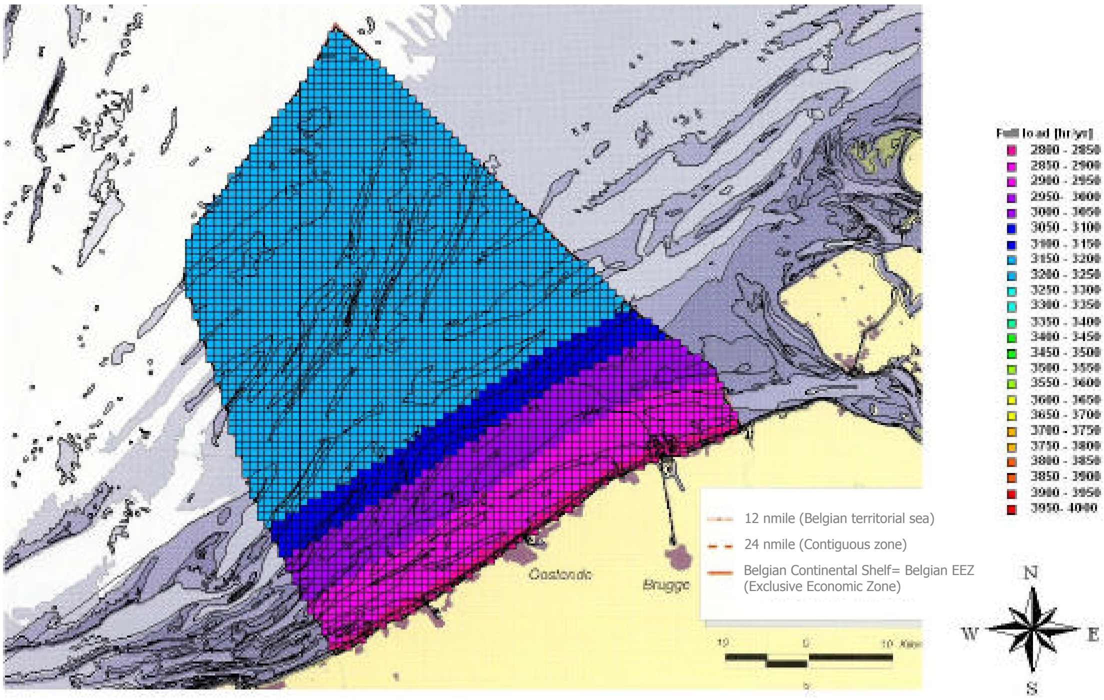


Figure 71: Equivalent full load hours per km², hub height 70 m, improved technology.

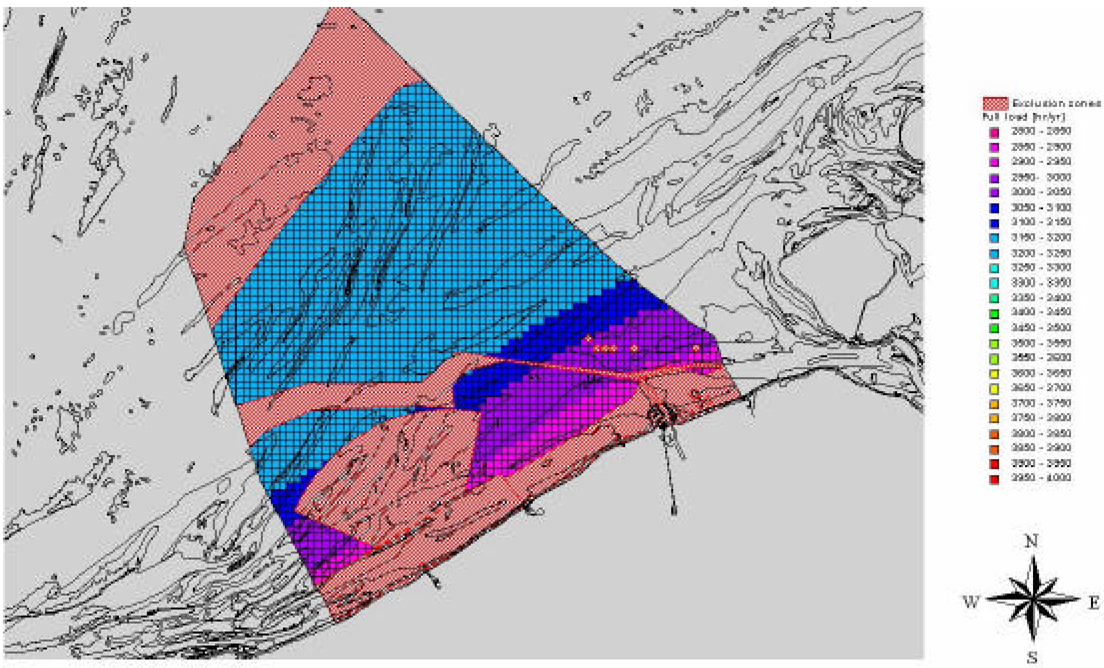


Figure 72: Equivalent full load hours per km², hub height 70 m, improved technology taking into account the exclusion zones.

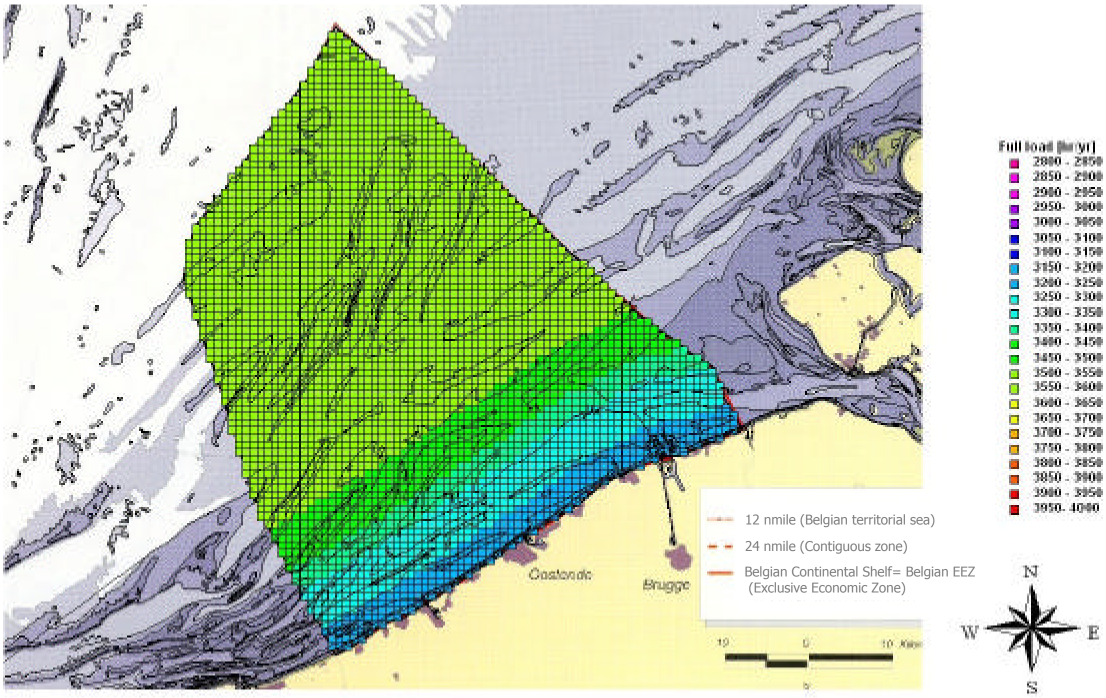


Figure 73: Equivalent full load hours per km², hub height 70 m, highly improved technology.

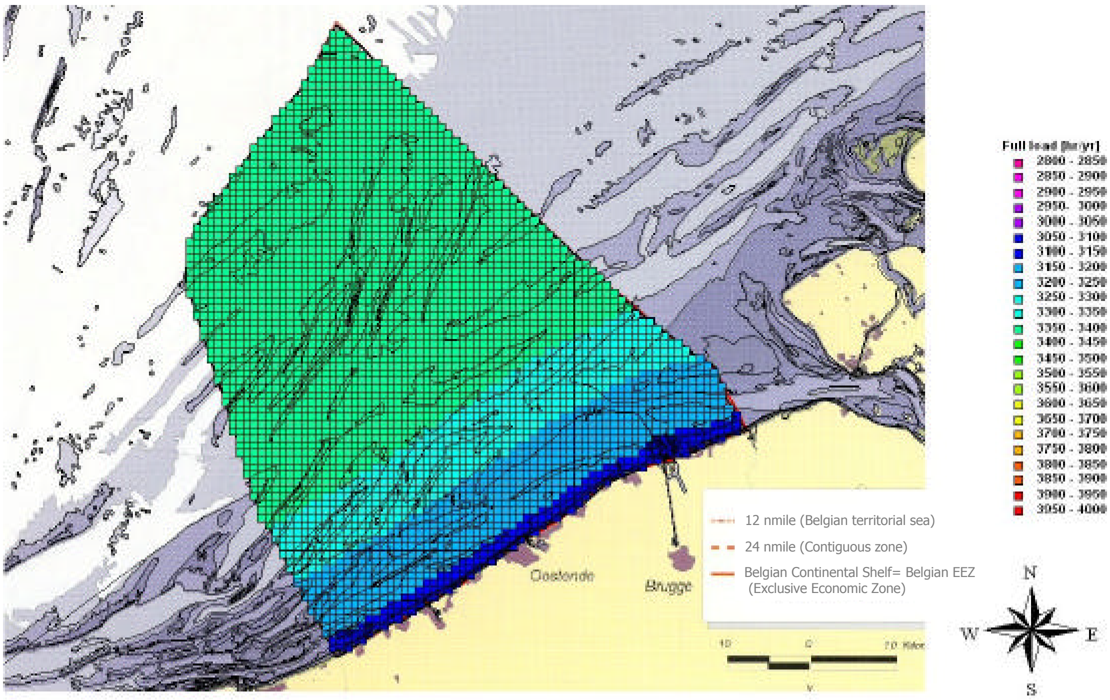


Figure 74: Equivalent full load hours per km², hub height 110 m, improved technology.

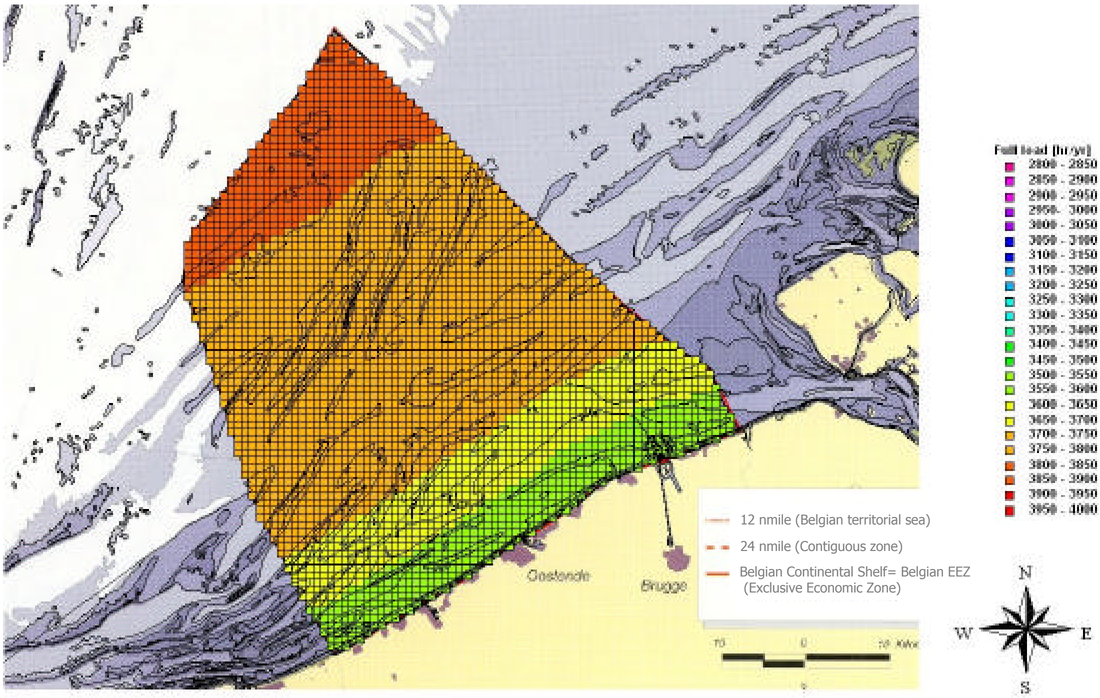
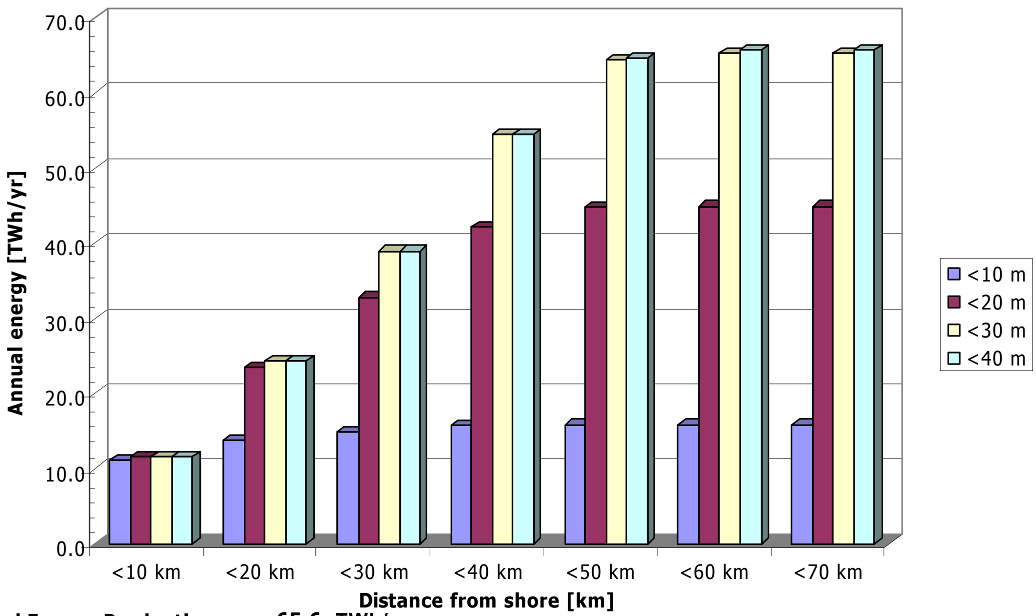


Figure 75: Equivalent full load hours per km², hub height 110 m, highly improved technology.



Total Energy Production = 65.6 TWh/yr

Figure 76: Distribution of the offshore wind energy potential of the BCS, hub height 70 m, improved technology.

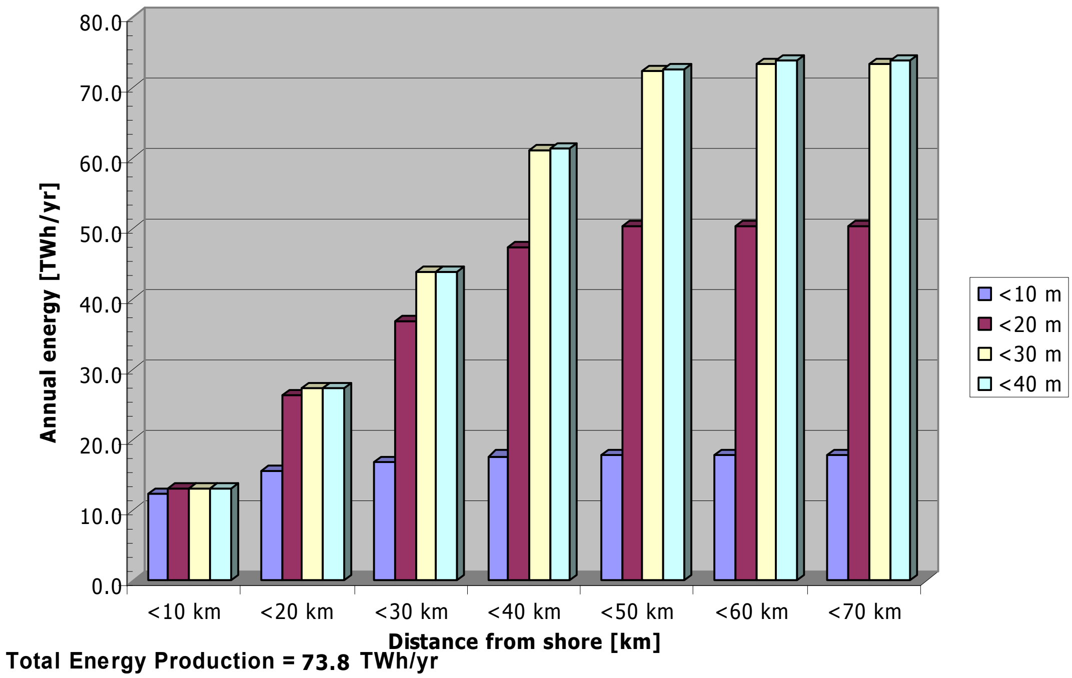


Figure 77: Distribution of the offshore wind energy potential of the BCS, hub height 70 m, highly improved technology.

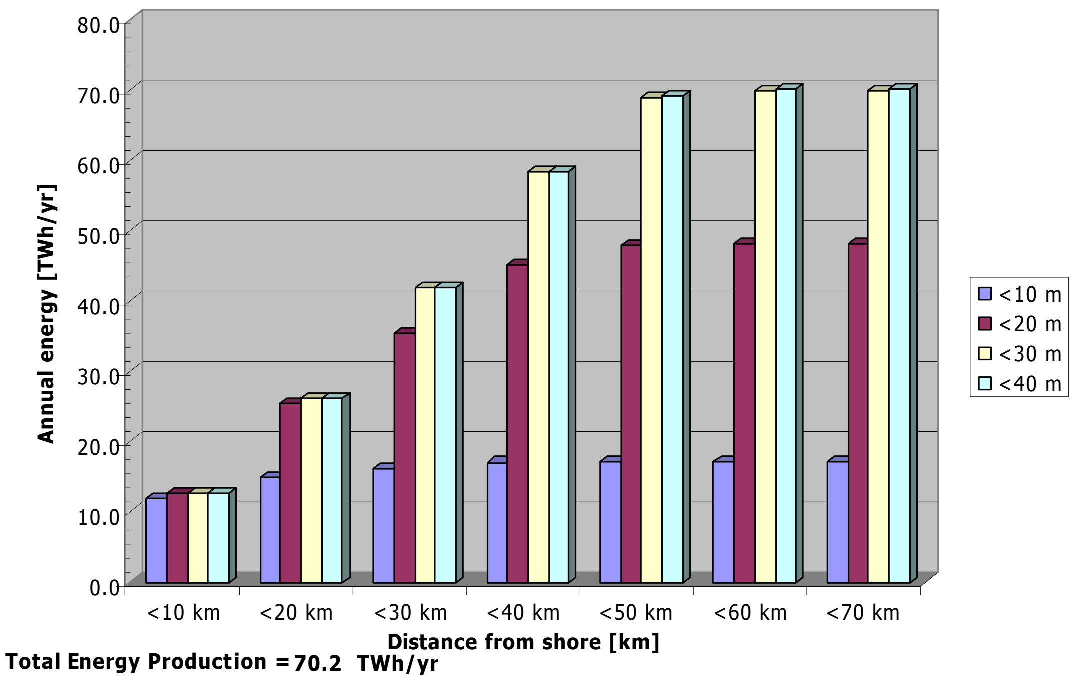


Figure 78: Distribution of the offshore wind energy potential of the BCS, hub height 110 m, improved technology.

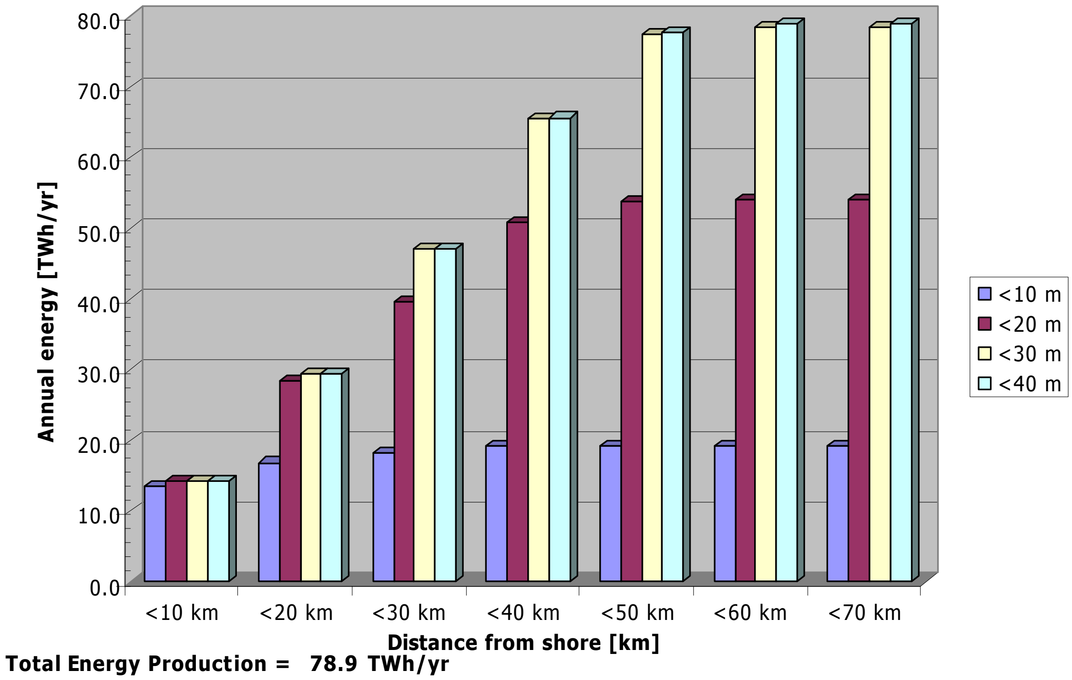


Figure 79: Distribution of the offshore wind energy potential of the BCS, hub height 110 m, highly improved technology.

4.4 Economical potential: projected investment and generation costs in 2005 and 2015

4.4.1 General

The economical potential is derived from the projected investment and generation costs. The assumptions and economic model are described in paragraph 3.2.6.

Similarly as the analysis of the previous paragraph, the calculated investments and generation costs are set up to make a global analysis. The evaluation of these numbers should be done with the necessary care. Whereas the authors believe that the basic assumptions are reasonably well chosen, the method followed in view of the limitations in the modelling, does not allow achieving a high precision. The usefulness of this analysis should be considered mainly in a demonstration of the effects of the most important parameters and in the relative values of the results, especially the calculated kWh costs, which should be used mainly in comparative evaluations.

It was not possible to take into account the geological characteristics into the cost model, because of the complexity of the relationship between soil characteristics and foundation structures.

Furthermore a number of essential costs are not taken into account in this analysis, mainly related to the accompanying economic measures needed to effectuate a large scale offshore wind energy deployment. Grid connection costs have been taken into account up to the onshore grid connection point, but necessary grid costs onshore have not been included. Other essential aspects include harbour facilities, capacity building, supporting research and development etc.

4.4.2 Investment cost

The total investment costs have been calculated for every grid point. They correspond to costs taking account water depth, distance to the grid connection point and to the shore for a 10 MW wind farm on the specific square kilometre in the BCS. The costs have been normalised per installed kW. Some costs such as grid connection have been aggregated to larger units (300 MW). The details of the investment costs are described in Section 3.

It has been assumed that the wind loading on the structure is uniform over the BCS, and that the construction costs are not varying with the wind speed. This should be a safe assumption in view of the weak variation of the wind speed over the area considered (although little is known about extreme wind speeds offshore). It also has been assumed that the wave loading is not varying over the BCS.

Given these assumptions, for a given hub height and technology level, the major cost drivers are the water depth and the distance to the shore. This is illustrated by the figures below, where the influence of water depth is clearly visible. On every sandbank, the investment cost decreases because of the cheaper foundations. For instance, on the Thornton Bank, 28 km from the coast, with an average water depth of 16 m, the investment cost is ± 1800 €/kW (2005 level technology).

The main values are summarised in Table 24.

Time frame	Hub height (m)	Lowest value (€/kW)	Highest value (€/kW)
2005	70	1500	2200
	110	1600	2400
2015	70	900	1500
	110	1000	1600

Table 24: Range of specific total investment costs

For a given hub height and technology level, the lower values correspond to near shore locations, the higher values to sites at the far end of the BCS. These values compare well with numbers found in literature.

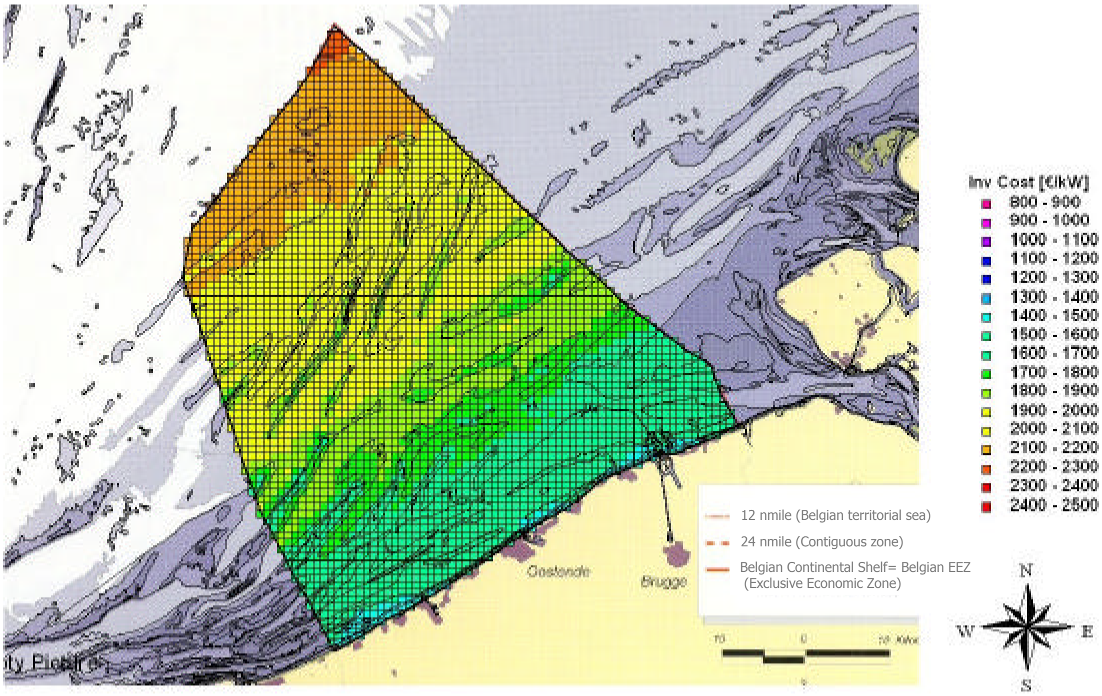


Figure 80: Investment costs per kW, hub height 70 m, improved technology.

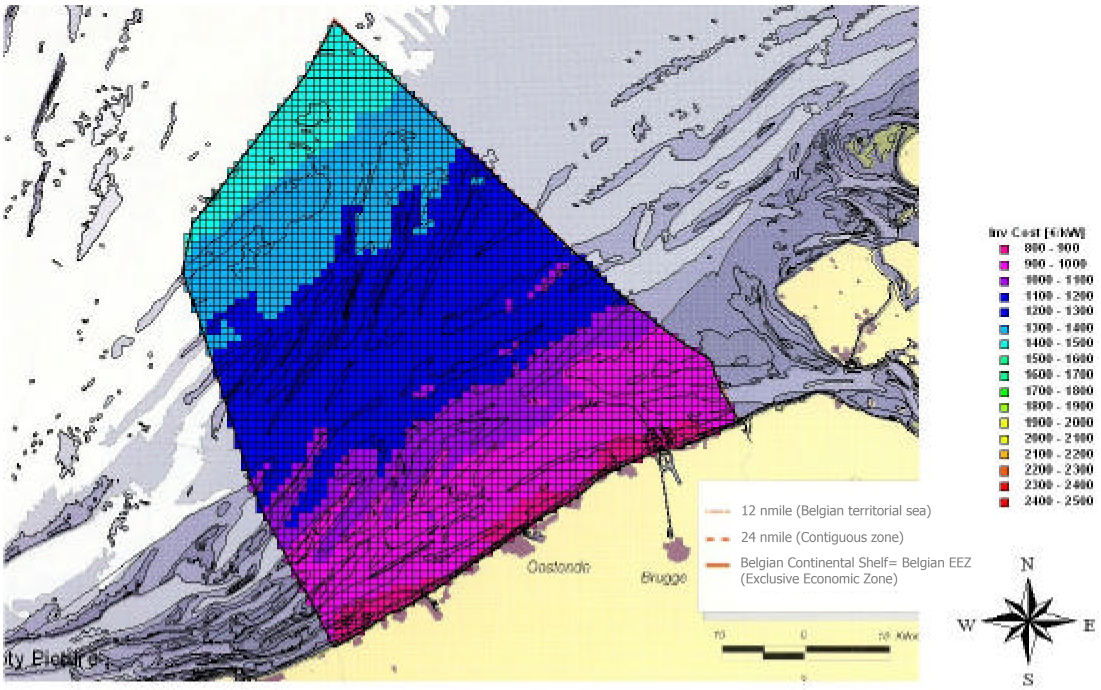


Figure 81: Specific Investment cost, hub height 70 m, highly improved technology.

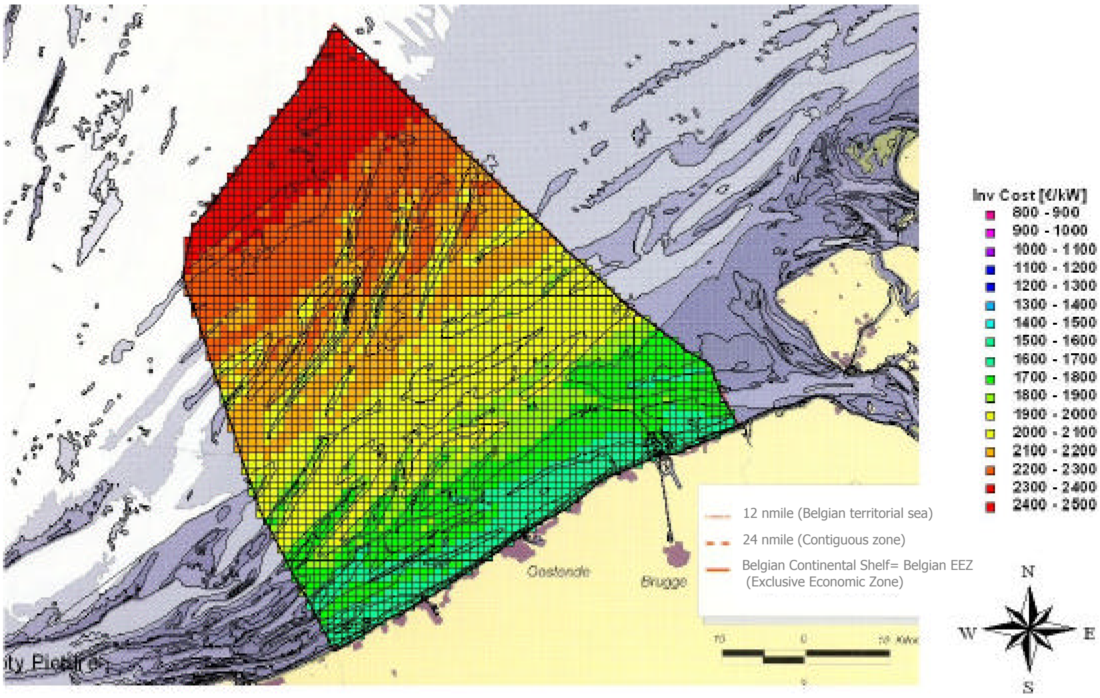


Figure 82: Investment cost for 10 MW/km², hub height 110 m, improved technology

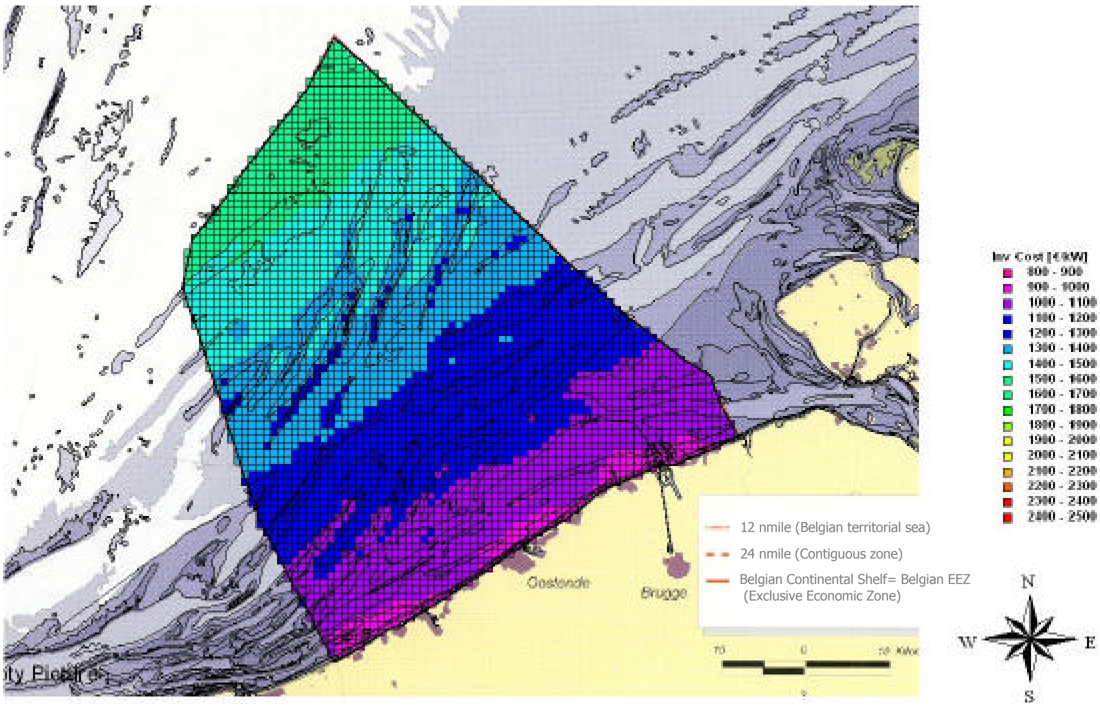


Figure 83: Specific Investment cost, hub height 110 m, highly improved technology

Figure 84 shows the relative influence of the major components (wind turbine, foundation and electrical system) in the total investment cost.

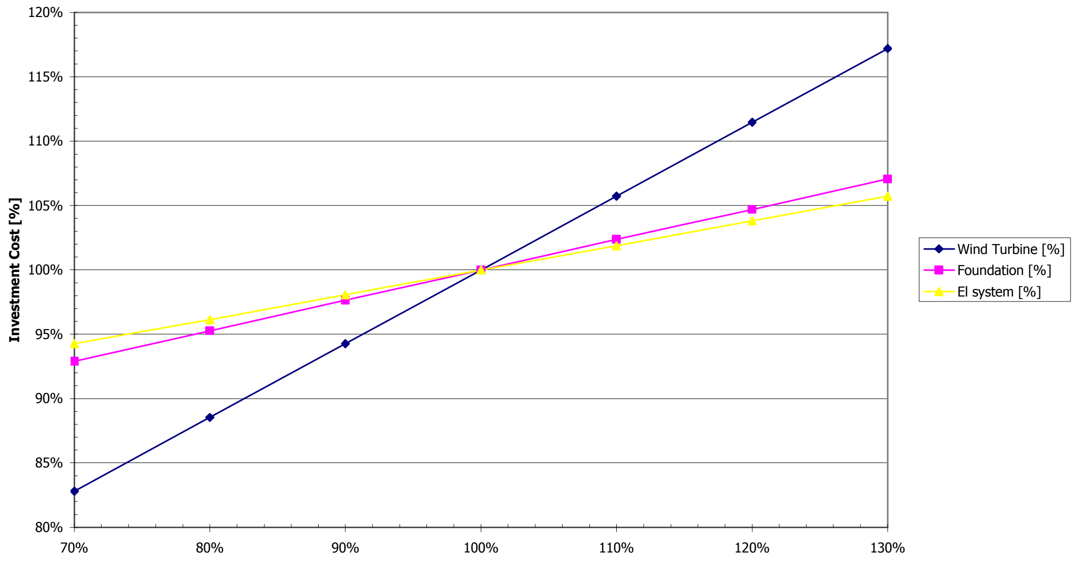


Figure 84: Sensitivity analysis of investment cost (Hub 70 m, Improved Technology)

For the 2005 level technology, the cost of the wind turbines has the strongest influence on the total investment cost. A 30% negative variation in wind turbine investment cost results in a 17% decrease in total investment. The influence of foundation and electrical system on the cost is almost identical.

The situation in 2015 is shown in Figure 85. A dramatic cost reduction for wind turbines is expected in 2015 with respect to 2005. The relative contribution of the foundation and the electrical system becomes more important (see Figure 42). A 30% negative variation of the wind turbine investment cost results in a decrease in total investment of 14%. A similar variation in foundation and electrical system cost results in a drop in total investment of respectively 7 % and 9%.

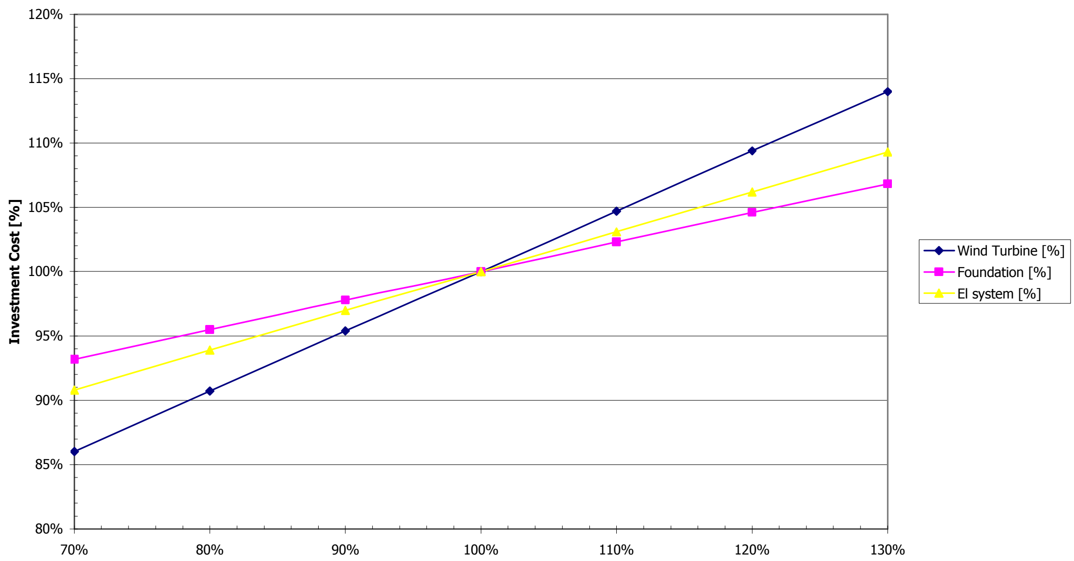


Figure 85: Sensitivity analysis of investment costs (Hub 70 m, Highly Improved Technology)

4.4.3 Production cost

The estimated generation costs are analysed based on the cost development assumptions described in 3.2.6. The production cost is calculated from capital costs and other annual returning costs.

The following assumption have been made to determine the capital costs:

Debt / equity ratio	100% / 0%
Project lifetime	20 years
Inflation:	2.0 %/yr
Interest rate:	8.50%
Term of loan:	12 years

The annual returning costs consist of:

- Operation and maintenance cost;
- Overhaul cost;
- Previsions for decommissioning;
- Cost for balancing power (not accounted for in the present study because hard to quantify).

Operation and maintenance

The operation and maintenance costs (including insurance cost) are assumed to be 2.0 % of the initial investment cost. This annual cost varies with the inflation. From production year 11 until the last production year of the wind farm, an increase of operation and maintenance of 10% per year has been taken into account, in order to ensure keeping the annual energy output at the constant high level.

Overhaul costs

Overhaul costs are foreseen for repair of damage not covered by the standard operation and maintenance costs. This includes the replacement of gearboxes, blades, etc. The estimated overhaul costs are 0.50 percent of initial investment cost.

Previsions for decommissioning costs

These annual costs for the decommissioning have been based on a Royal Decree of the Belgian Ministry of Economic Affairs for the 100 MW project of C-Power on the Wenduinebank (source BMM). According to this Decree, the project developer had to pay a yearly contribution to the authority in order to assure the dismantling of the wind turbines and there structures at the end of the project life time. This contribution was fixed at 0.6 M€ per year from year 3 to year 10. From year 11 to the end of the project lifetime, the contribution is raised to 1.35 M€.
Since these figures are applicable for a 100 MW scale project, they have been divided by 10 for the economic analysis of an installed power of 10 MW/km².

The production cost has been analysed for hub heights of 70 m and 110 m and for the two technology levels. The distribution of those costs over the BCS is presented in Fig. 86 to 89 (expressed in € cents per kWh). Table 25 summarizes the calculated cost ranges in € per MWh.

For a given hub height and technology level, the lower values correspond to the near shore and shallower locations, the higher values to the far offshore sites. The numbers are mainly important for illustrating the approximate cost levels, influence of the physical and technical parameters and the expected developments. A few striking conclusions can be made:

- A 40 % drop in generation costs can be expected from 2005 to 2015.
- The economic gain by using higher towers is negligible (higher energy capture totally offset by higher investment costs).

- The range of costs for given hub height and technology is large, which shows the importance of clever siting.

Time frame	Hub height (m)	Lowest value (€/MWh)	Highest value (€/MWh)
2005	70	65	88
	110	66	90
2015	70	36	53
	110	36	54

Table 25: Summary of production costs of offshore wind energy in the BCS.

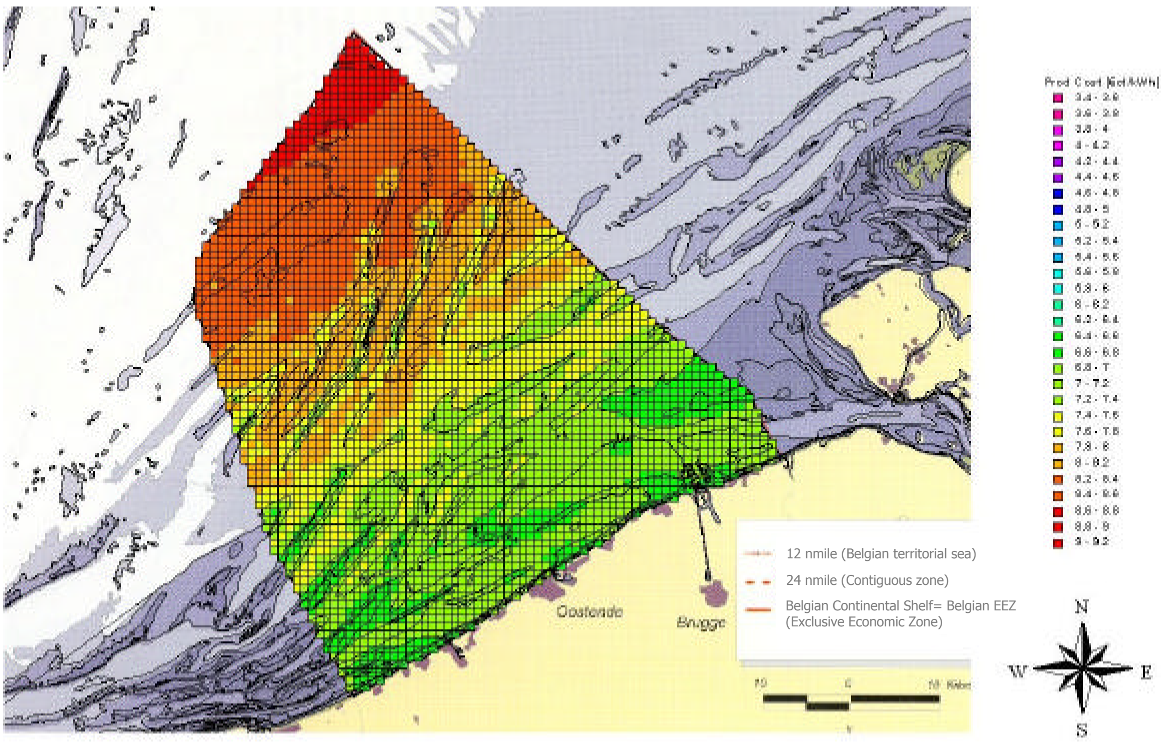


Figure 86: Production cost for 10 MW/km², hub height 70 m, improved technology

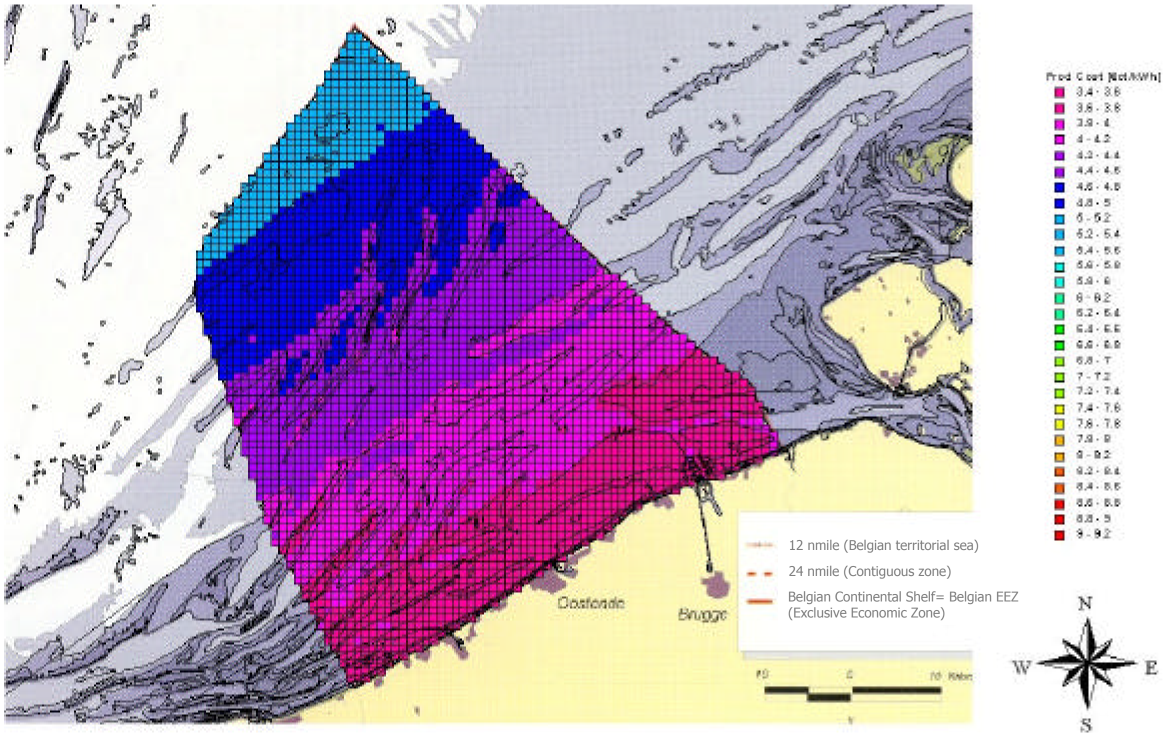


Figure 87: Production cost for 10 MW/km², hub height 70 m, highly improved technology.

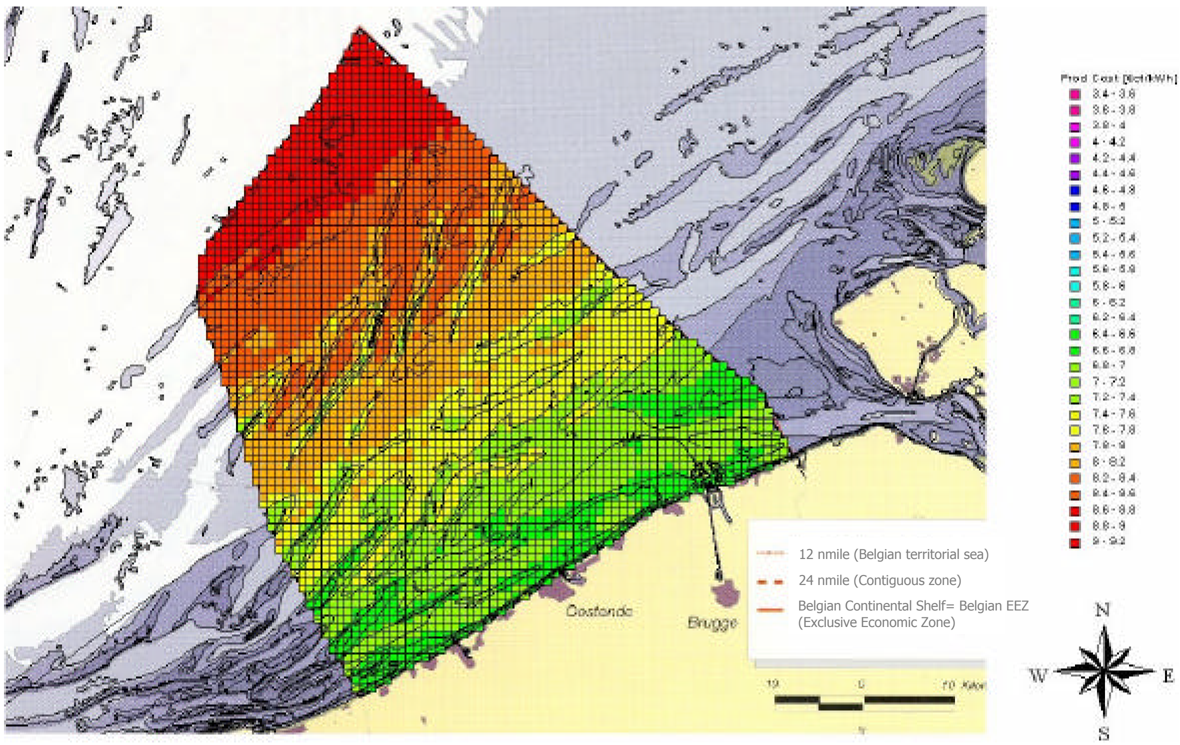


Figure 88: Production cost for 10 MW/km², hub height 110 m, improved technology.

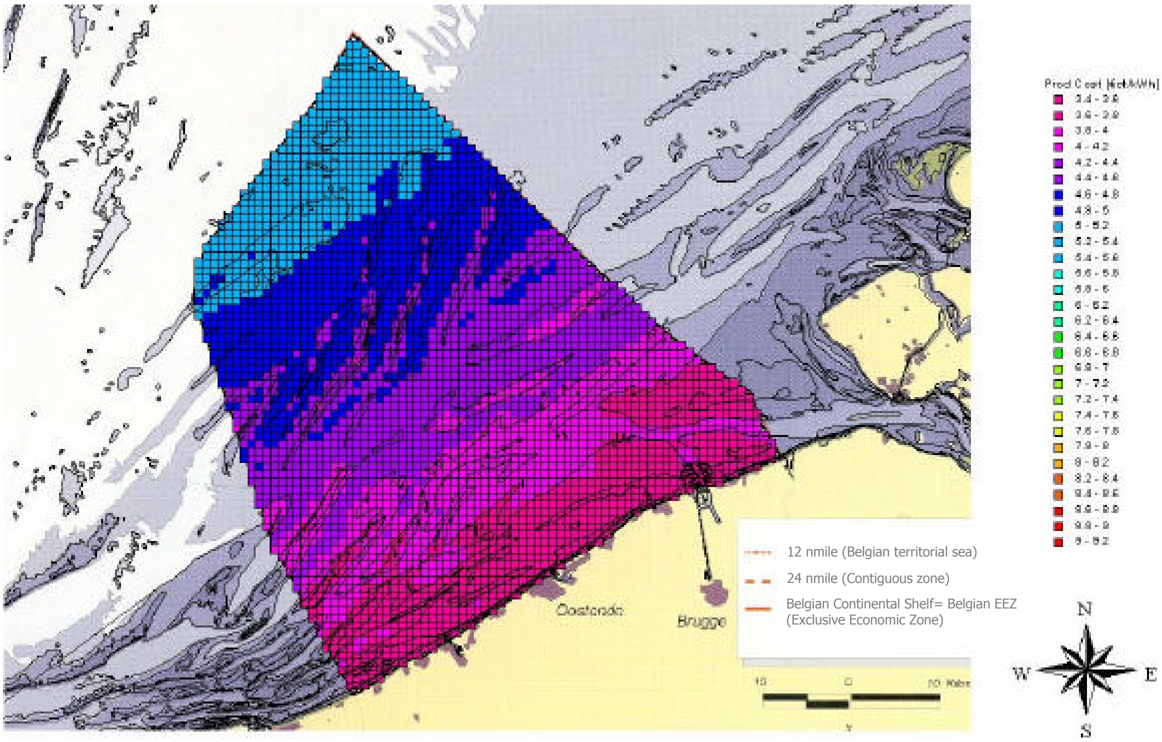


Figure 89: Production cost for 10 MW/km², hub height 110 m, highly improved technology.

4.4.4 Breakdown of offshore wind energy production costs in the BCS

Table 26 shows the breakdown of the production cost at a site 30 km in the sea, 70 m hub height, 2005 technology, at a distance of 40 km to the onshore grid connection point. The annual energy production for the particular grid point is 31.6 GWh/yr (for 10 MW). The local water depth is 16 m, the foundation is a monopile and the total installation cost is 1815 €/kW. The calculated generation cost is 7.3 cents per kWh.

Item	%
Investment costs	63
Operation and maintenance	28
Overhaul	5
Decommissioning	4

Table 26: Breakdown of generation cost for 10 MW/km², hub height 70 m, improved technology

The production cost for the same site with 2015 technology decreases to 4.2 € cents/kWh, but the relative contribution of the major cost items are the same as for 2005 technology. The cost breakdown is also identical assuming a 110 m hub height.

4.5 Conclusions

The analysis in this chapter has produced maps, which enable to estimate the potential installed capacity and energy generation for various assumptions on technology and boundary conditions such as geographical restrictions and water depth. Furthermore, the range of production costs has been calculated. A basic model used for the potential estimation is a generic wind farm of 10 MW/km².

The main numbers are summarised in Table 27 and Table 28.

	GW installed wind power	Restrictions
Maximum physical potential	21	Exclusion zones
Economic potential	2.1 – 4.2	15 % to 30 % of all areas with max water depth 20 m max distance to shore of 40 km
2004 status of grid integration absorption capacity	0.5	Based on static load flow calculations, available grid connection points in Zeebrugge en Slijkens.

Table 27: Main figures about the potential in terms of installed wind power capacity (GW).

Economically it makes a lot of sense to limit the water depth to 20 m and the distance to the coast to 40 km, as the relative contribution from far and deep sites (expensive sites) is not very substantial.

	TWh/year	Restrictions
Maximum physical potential	66 – 79	Exclusion zones as listed in 2.5
Economic potential	6.3 – 12.6	15 % to 30 % of all areas with max water depth 20 max distance to shore of 40 km

Table 28: Potential energy annual energy generation.

The investment costs range from 1500-2400 Euro/kW with 2005 technology and 900-1600 Euro/kW with 2015 technology. The ranges are depending on water depth, distance to coast, wind turbine hub height (70 m and 110 m), and assumptions on technology status.

The estimated generation costs range from 65-90 Euro/MWh with 2005 technology and 36-54 Euro/MWh with 2015 technology. Again, the ranges are depending on water depth, distance to coast, wind turbine hub height (70 m and 110 m), and assumptions on technology status. Increasing hub height is not really yielding better economics.

4.6 References

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5 Conclusions

5.1 Available resources: sea bed properties, wind resources, electrical grid and areas available in the BCS

Sea bed properties

The study of the geotechnical properties of the BCS revealed that a hierarchical classification of the seabed in view of suitability for offshore wind farm (bottom mounted structures) is difficult to establish. A classification will vary according to the type of structure (foundations, pile, cable), the type of foundation chosen (monopile or gravity based structure) and their further technological developments. Therefore, it was preferred to provide a sound knowledge base on the most relevant geo-parameters and provide maps on their spatial distribution. This allows a combination of various parameters in order to produce scenario’s for example according to the type of foundation selected. Maps have been generated indicating respectively the areas of the BCS with the most suitable subsoil characteristics and the areas where a more careful soil investigation is recommended because of potential hazards, especially in case of monopile structures. The maps have been obtained through a combination of the spatial distribution of: (1) the Tertiary stone layers (not suitable), (2) the most heterogeneous Quaternary deposits (scour hollows) (not suitable), and (3) the faults (not suitable). Thus, in general the sea bottom of the BCS is suitable for bottom mounted offshore wind turbine systems (mono pile type), however in a particular narrow area the soil structure could possibly include some hazards. These hazards and the possible consequences on foundation costs however are hard to quantify, and hence it is concluded that in principle there are no zones excluded.

Wind resources

An attempt has been made to derive the long-term wind climate distribution on the BCS from long term measurements at coastal stations. The resulting wind maps are not plausible mainly because of the low quality of the data sets in view of wind potential assessments. Thereupon it has been decided to base the wind mapping on the POWER method, which is a software tool for offshore wind mapping in the European seas developed within a European RTD project. The distribution over the BCS of the long-term average wind speed has been derived from seven data positions of the POWER database and linearly interpolated as function of the distance from the coastline. As opposed to POWER, the wind speed frequency of occurence is assumed to be Rayleigh distributed. Maps of the average wind speed have been constructed with a resolution of 1x1 km and for five relevant altitudes, from 70 to 150 m. The resulting long term average wind speed varies between 8.4 m/s at 70 m height near the coast to 10.1 m/s at 150 m height far offshore. In the areas where wind farm development can be expected in the near future, the values vary between 9.1 and 10.0 m/s, depending on altitude and distance from the coast. In the first 20 km from the coast, the average wind speed increases quite fast with distance, and from 20 km distance on the increase is very modest. In addition, the increase of wind speed with height is very moderate from 70 m altitude onwards. In this respect, it is recommended to try to exploit the resource not too far offshore and to be modest with tower heights. The numerical values about the wind resources are in reasonable agreement with wind data from measurement stations in the BCS and equally with the wind maps of the offshore areas of neighbour countries. The uncertainty of the data precludes them to be used for detailed feasibility analyses, which should be based upon on-site measurements.

Available grid capacity

Static electrical load flow calculations have been performed to identify potential problems in the electrical grid when injecting offshore wind power in the available connection points. During off-peak hours (weekends and weeknights), the limiting factor in the present grid is simply the power line capacity from Slijkens to Brugge (i.e. 300 MW) or from Zeebrugge to Brugge (i.e. ca. 400 MW). With local loads in Slijkens and Zeebrugge, injection capacity can become somewhat higher. With a connection Koksijde-Slijkens, power can be transported to Koksijde, increasing the injection limit, up to 500 MW in Slijkens (the highest value that was checked). The addition of extra transmission capacity further inland (i.e. Rodenhuize-Heimolen) does not influence this limit. The calculations also showed situations with lower limits. These are due to overloads further inland, in the Rodenhuize-Heimolen region, i.e. well beyond Brugge and even beyond Gent. This overload is only slightly alleviated by the

Koksijde-Slijkens link. Obviously, the Rodenhuize-Heimolen reinforcement does alleviate this overload. It must be stressed that the grid limitations encountered here are not due only to offshore wind power but also to the existing power flow from the region around Brugge towards Gent and beyond and to cross-border power transits. The static analysis – which does not take into account any controllability of offshore wind farms - shows that the amount of offshore wind power that the HV-grid can absorb may vary from 50 MW to 750 MW, depending on the load scenarios and the grid reinforcements. When the installed offshore wind power exceeds 500 MW, major grid reinforcements will be required to ensure grid availability for most load scenarios. These grid reinforcements include probably the extension of the 400 kV- grid towards the coastal substations of Slijkens or Zeebrugge, which is a major investment.

Areas excluded and available for wind energy

Various other activities on the sea, and environmental protection reasons limit the available sea area for offshore wind power. These other uses represent in total almost one third of the BCS, and consequently out of the total area of 3600 km², a net area of 2100 km² remains for wind power, which still is enormous. An inventory has been made of these different users, and maps have been prepared to allow the calculation of the wind energy potential. The most important exclusion areas are navigation routes, military exercise areas and special environmental protection areas near the coast.

5.2 Technological options

Offshore wind energy technology development

A review of the technological status and the observed developments has lead to the definition of the principal technical and economical characteristics of offshore wind energy technology, and their expected future trends. The factors determining a desirable future development of the technology are related to the wind turbine dimensions, the integrated design approach, the suitability for operation in offshore environment, the connection to and integration with the electrical grid, and last but not least the investment and operation costs.

Two types of technology have been defined and characterised for the calculation of the potential. For the near future, with reference year 2005, the technical solution is designated as 'improved technology' because it builds on the present best available onshore technology. The individual turbine size is typically around 3 MW. Further away in the future (reference year 2015) the technology is designated as 'highly improved', and is characterised by a very high reliability and substantially reduced investment cost. The corresponding turbine size is around 5 MW. For both types of technology, a model has been made to calculate the potential energy output. It has been found that an installed wind farm power density of 10 MW per km² is an appropriate figure for both types of technology. A generic 10 MW wind farm power curve has been defined for the calculation of the AEO per km².

A simplified cost model has been developed for the calculation of the investment and operation costs as a function of the position in the BCS, where distance to the coast and the water depth are the main cost drivers. The model takes account of all relevant costs in the entire life cycle of the wind farm, from site preparation to decommissioning. For a typical offshore site, 30 km from the coast and a water depth of 16 m the total wind farm investment cost with improved technology (2005) 70 m hub height are around 1800 €/kW, of which 54 % are taken up by the wind turbines, 22 % the offshore installation and foundations, 18 % by the power collection system and HV transmission cable. These costs at a similar site are expected to fall by 2015 (highly improved technology) to around 1100 €/kW of which 44 % are taken up by the wind turbines, 21 % the offshore installation and foundations and 29 % by the power collection system and HV transmission cable.

Developments in electrical interconnection schemes of offshore wind power plants

A simplified generic dynamic model for a wind farm has been developed in order to simulate the behaviour of the grid during wind gusts and grid faults. The simulations show that wind gusts do not result in considerable voltage fluctuations at the power substations nearby the wind farm. The voltage fluctuations that are seen at the assumed onshore connection are well within the normal margins even if the wind farm does not provide dynamic voltage control.

The simulation of grid faults demonstrates the benefits of highly advanced generator types, which can provide very fast voltage support, with a time constant of approximately 20 ms. However, this voltage support action becomes less effective if longer cable lengths are used. With longer cables, the reactive power range in which a turbine must be able to operate becomes too wide.

For cable lengths up to 30 km, the choice for a highly advanced electrical conversion system in the wind turbines can improve the dynamic voltage stability at the point of common coupling. For cable lengths between approximately 30 km and 50 km on, a dynamic voltage controller (such as Static Var Compensator) onshore is the best solution to ensure dynamic voltage stability at the point of common coupling.

HV DC, equipped with voltage source converters, can provide the same voltage control support as a highly rated SVC. The choice for HV DC depends on the cable lengths. For very long cable lengths, the cost of an HVD C installation becomes lower than the costs of the power losses due to the capacitive charging current in the cable. HV DC is however not expected to be the most economic solution for cable lengths under 80 km, and is thus not relevant for the Belgian case in the near future.

5.3 The offshore wind energy potential of the BCS

Maps have been constructed, which enable to estimate the potential installed capacity and energy generation for various assumptions on technology and boundary conditions such as geographical restrictions and water depth. Furthermore, the range of indicative production costs has been calculated. The model used for the potential estimation is the generic wind farm of 10 MW/km².

The maximum physical potential of the BCS after subtraction of exclusion zones amounts to 21 GW. The economic potential has been found as the wind power that can be installed in 15 % to 30 % of all areas with maximum water depth 20 m and within 40 km distance to shore, taking into account all hard exclusion zones such as the 3-miles zone, the navigation routes and the special conservation areas. The resulting potential varies between 2.1 GW and 4.2 GW, and should be put in perspective with the present maximum grid absorption capacity of 0.5 GW.

The potential annual energy generation corresponding to the maximum physical potential amounts to 66 – 79 TWh per year, the range being dependent on which type of technology is used. The economic potential corresponding to the above described zone delimitation varies between 6 and 13 TWh per year. These last figures represent contributions to the gross domestic electricity consumption allowing to meet the actual indicative Belgian Kyoto targets by large.

The estimated investment costs in the BCS range from 1500-2400 Euro/kW with 2005 technology and 900-1600 Euro/kW with 2015 technology. The estimated generation costs range from 65-90 Euro/MWh with 2005 technology and 36-54 Euro/MWh with 2015 technology. The ranges are mainly depending on water depth, distance to coast and wind turbine hub height (70 m and 110 m). It is found that increasing hub height above 70 m is not really profitable. A detailed geographical distribution of the calculated numbers is presented in this report. It should be stressed that these figures are only indicative because of the generalisations made, the shortcomings of the simplified model and of the uncertainties in the assumption of the wind resources.

The results can be very helpful in the development of a master plan to tap the huge offshore wind energy resources of the BCS. It is recommended to follow a careful approach in which the best available technology is used on sites where the technical, economical and environmental risk is minimised. This means to look for sites with moderate water depths (up to 20 m) and within a reasonable distance from the coast (up to 40 km).

6 Recommendations for future development of offshore wind power in Belgium

6.1 Introduction, the facts

This chapter gives recommendations for the future development of offshore wind power in Belgium based on the results of the investigations carried out. The recommendations should be assessed in view of the facts that can be summarised as follows:

- Belgium has committed itself to the Kyoto Protocol targets and to the indicative targets of the European Directive on the promotion of electricity from renewable energy sources. The contribution of renewable energy in the gross domestic consumption should be 6% in the year 2010.
- The physical, technical and economical offshore wind energy potential of Belgium is large. The estimated relevant hub height wind speeds vary between 8.4 and 10.1 m/s in the BCS. The area in the BCS where water depth is less than 20 m and in reasonable distance from the coast is vast (around 1300 km²). The economic potential on the short term – assuming maximum water depth of 20 m and maximum distance to the shore of 40 km in the entire BCS - is in the order of magnitude of 10 TWh of generated electricity per year. This corresponds to an installed wind power capacity of 3 GW. The economic potential on the longer term is at least twice that high.
- Estimated offshore wind energy generation costs in the BCS vary between 6.5 and 9.0 Euro cents/kWh (2005 technology). Future technological developments and learning curve effects may bring down the generation cost with 40 % to between 3.6 and 5.4 cents per kWh within 10 years from now. The estimated investment costs range from 1500-2400 Euro/kW with 2005 technology and 900-1600 Euro/kW with 2015 technology. The ranges are depending on water depth, distance to coast, wind turbine hub height (70 m and 110 m), and assumptions on cost developments within the various technologies involved including the grid connection. All these figures should be considered as indicative and the underlying assumptions are described in this report. The major uncertainties are related to the estimation of the wind speed, the costs for grid connection and to the future rate of increase in reliability and availability of the offshore wind power technology.
- The offshore wind power technology is maturing fast. It can build on a solid learning curve of wind energy technology onshore, which develops in a world market having been growing at 25 % a year for the last five years. The first large offshore farms have been realised (Denmark and UK), the total nearshore and offshore installed capacity 2003 reached around 0.5 GW. Industry and project developers expect a take-off of the European market for offshore wind in 2006. EWEA, the voice of the wind energy industry and corporate community foresees 10 GW installed offshore wind power by the year 2010 and 70 GW by 2020[25]. This realisation implies that wind power generation prices keep developing in a favourable way. In the meantime, it is a fact that industrial manufacturing capacity is building up allowing mass production of the wind turbines and the offshore installation technical services.
- Concrete offshore wind energy projects are being planned in the BCS. A large project, with a planned final size of at least 218 MW, is near take-off of its first stage (C-Power on Thornton Bank), with all necessary planning permits for the entire project in place. Besides, there exists experience in Belgium with planning procedures from various previously planned projects, which can be used for identifying administrative bottlenecks and environmental constraints.
- A major bottleneck is the integration of the wind power in the existing Belgian grid. The first estimations (static load flow) indicate an available power evacuation capacity of around 0.5 GW. Extending the amount of offshore wind power beyond this limit will require modification of HV-grid infrastructure and operation of the transmission system.
- A concerted action within EU is ongoing to identify and possibly remove non-technical barriers for the implementation of offshore wind power: legal, administrative, policy, environmental and grid infrastructure issues, by co-ordination between energy agencies of most sea-bordering countries in

[25] Wind Power Targets for Europe: 75000 MW by 2010, October 2003, EWEA, Brussels

the member states of the EU[26]. Belgium is participating in this concerted action, which in the end will yield in recommendations for improving the institutional and legal framework.

- High tech leading companies are present in Belgium in the fields of manufacturing gearboxes, electrical transformers, wind turbine towers and steel structures. Furthermore, leading companies are present in the field of offshore construction, offshore installation of wind turbine foundations, operation and maintenance. These companies have built up experience in several offshore wind energy projects abroad. Extensive know how is present in Belgium in a broad range of disciplines related to offshore wind energy: electrical grid aspects, wind turbine control, condition monitoring, vibration analysis, seabed geotechnical aspects, soil analysis, wind measurements and resource analysis, wind farm design, atmospheric modelling, short term forecasting of wind power, aerodynamics, wind turbine design, project certification and the marine environment. International links exist with initiatives such as the EAWE (European Academy for Wind Energy), which aims at building and maintaining a solid knowledge basis in the area of wind energy.
- According to a recent modification of the Royal Decree ruling the concessions for activities in the North Sea, the Belgian Government has the intention to assign an exclusive area within the BCS for offshore wind energy development. The area of this zone is approximately 270 km² and has a potential for average annual generation of 8 TWh of wind power corresponding with an installed wind power capacity of around 2.5 GW.

6.2 Recommendations

6.2.1 Amount of wind power to be installed versus time

The national gross electricity consumption is assumed to follow the pattern described by Planbureau[27], stepwise declining growth rate, reaching 90.6 TWh per year in 2010 and 103.1 TWh per year in 2020.

Two scenarios are considered in this study, notably a business as usual (BAU) and proactive scenario (PRO) scenario. Both scenarios are identical until 2015, the PRO scenario continues expansion of offshore wind power after 2015. The assumptions in the scenario's are:

- The wind energy based production in a particular year is estimated by defining the effective generating capacity as the average of the capacity of two subsequent years;
- There is a designated zone in the BCS for wind power of approximately 270 km² situated NW of Thornton Bank;
- The C-Power 218 MW offshore wind energy project is being constructed according to the announced schedule (6 wind turbines in 2005, 18 turbines in 2006 and 26 turbines in 2007). The plant is fully operational from the start of 2008.
- In addition to the C-Power project, additional capacity is added in the designated area up to a cumulative installed capacity of 500 MW.
- In the proactive scenario, after the year 2015 the designated zone in the BCS will be stepwise further developed, with an average growth rate of approximately 250 MW wind power per year, with technical and economic characteristics of "highly improved technology".

Under these assumptions, the following targets are reached:

- By 2010, the contribution of offshore wind energy from the BCS (approximately 300 MW installed capacity) is 0.87 TWh, which is 1.0 % of the gross national consumption.
- By 2016, BCS offshore wind energy produces 2.0 % of the electricity demand (750 MW installed capacity);
- By 2020 BCS offshore wind energy produces 5 % of the national electricity demand (1750 MW installed capacity).

These targets are modest in terms of contribution to the national consumption, but require a proactive policy in terms of zoning, and grid adjustments. The wind energy penetration level in the Belgian power system corresponding to the described scenario however is relatively low, and will only involve moderate power balancing costs.

[26] 'Concerted Action on Offshore Wind Developments, European Commission, Directorate General for Transport and Energy – contract nr NNE 2001 00633

[27] D. Gusbin, B. Hoornaert, Planning Paper 95, Energievooruitzichten voor België tegen 2030, Federaal Planning Bureau, Jan 2004

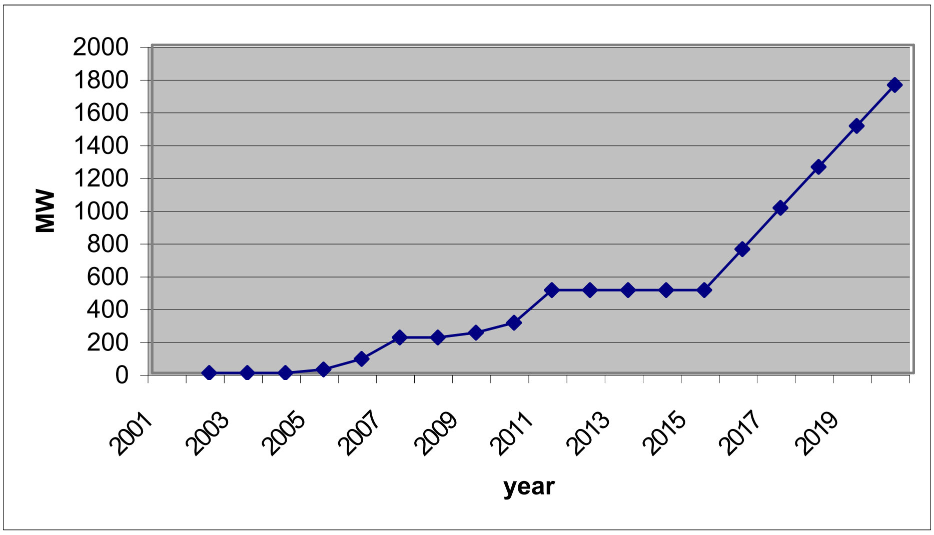

Figure 90: Scenario for development of offshore wind power capacity in the BCS, installed wind farm capacity (MW) versus time.

6.2.2 Siting

It is foreseen that the degree of freedom of future offshore siting will increasingly be based on zoning policies. It is recommended in the designation of zones for offshore wind power to take appropriately account of the factors favouring the reliable operation and economy of the wind power plants:

- Wind speed (as high as possible);
- Limit the water depth (e.g. put a limit to 20 m);
- Limit the distance to shore and harbours (for minimising cable costs and O&M costs, e.g. limit to 40 km);
- The siting should take appropriately take care of environmental factors and should make use of the best available knowledge on species present (especially birds) and if needed undertake dedicated study;
- With respect to soil geotechnical properties, siting should take into account findings reported in section 2.1.

Some of these mentioned limits are conflicting with the actual characteristics of the designated area. In this respect it is recommended to develop this zone gradually, starting with the lower risk sites (at the shortest distances and most favourable water depths). It should be stressed here that the present study has demonstrated that the economic potential (2.1 GW to 4.2 GW) can be realised in the area in the BCS comprised between the 3 miles border and up to 40 km from the coast, taking account of the other hard exclusion zones.

It is recommended to initiate as soon as possible a professional monitoring campaign in the designated area (with a purpose built meteorological mast or platform) to determine as accurately as possible the meteorological and environmental parameters necessary for the planning and the design of wind power plants. Where possible, relevant additional data from ongoing international studies – both from terrestrial observations and Earth Observation – should be considered.

6.2.3 Technology

It is recommended to take properly into account the site specific conditions and best available wind energy standards, into the offshore wind farm design for minimising production cost and maximising the reliability. This includes the following:

- Adopt the integrated design method in which the design solutions for individual parts and components are chosen in view of the maximum efficiency in the entire scope and life cycle of the project. This requires a maximum synergy between wind turbine suppliers and the offshore industry.

- Design the wind farm for optimal controllability on both wind turbine and wind farm level in order to maximise the possibilities for participation of the wind farms in grid management;
- Choose for hub heights as low as possible in order to minimise investment and O&M costs;
- Take properly account of wake effects in the array design, in order to minimise the array losses. For the same reason, it is recommended to optimise the location of different projects with respect to each other to minimise the flow disturbance from one wind farm to an adjacent wind farm.
- Monopile foundations are suitable for a major part of possible sites in the BCS. Avoid sites deeper than 20 m in order to minimise foundation costs.

6.2.4 Supporting measures

The development of a substantial amount of offshore wind power will only be possible in an efficient way if a proper and coherent set of supporting measures is taken on the national level. These should include:

- Improvement of institutional and legal framework
- Electrical grid measures
- Environmental control
- Capacity building
- International co-operation

6.2.4.1 Improving the institutional and legal framework

The present legal framework in Belgium needs some adjustments to be better prepared for a significant development of offshore wind power. The present licensing procedures (concessions, environmental permits) should be reviewed on their appropriateness for large-scale implementation of wind power.

The basic objective is to create a system of rules, which is clear, transparent and consistent for potential investors, and offers continuity and guarantees on the long term. This also involves measures to ensure continuity on the electricity market. It is recommended that the Federal Government will base its further policy on recommendations from projects like the COD project (see footnote 26) in which Belgium presently participates.

6.2.4.2 Grid infrastructure

It is obvious that major grid reinforcements are required to enable installed wind offshore wind power levels of more than 500 MW, probably including an extension of the 400kV grid towards the coast.

It is recommended to initiate an in depth study into the consequences of the integration of a substantial amount of wind power into the Belgian grid. Examples for such studies are the investigation in the Netherlands (Connect 6000). The study should result in recommendations both on required onshore and offshore aspects of the electrical connection of large amounts of wind power.

The onshore part includes a.o. the transmission system and the balancing requirements. Further research is recommended to estimate the consequences of high levels of offshore wind power on the need for balancing power[28] in the Belgian grid. In the present report, the dynamic power system simulations have been limited to the calculations of phenomena concerning grid faults and sudden wind speed variations, evaluating the instantaneous grid support that a wind farm can supply. On the other hand, the issues concerning balancing power constitute the subject of a complex multidisciplinary research, in which the technical barriers resulting from limited grid availability are a fundamental aspect. An in depth research should also take account of two other major aspects. The first is related to the problems of making accurate short-term predictions of wind power. The second one is related to the complexity of making predictions of the dynamics of a power system driven by a liberalised market.

[28] Balancing power: The instantaneously available backup power to ensure that the electrical generation is at every moment equal to the electricital load. This is needed to maintain stable grid behaviour.

The offshore part includes a.o. a study in possibilities for sea grid, sea HV sockets, and a further investigation into HV AC or HV DC taking into consideration the most recent state of the art and expected developments.

6.2.4.3 Environmental control

It is recommended to keep track of the experiences collected by ongoing (international) offshore wind energy projects with respect to the environmental impact in the design of environmental monitoring campaigns associated with offshore wind farms.

6.2.4.4 Capacity building

In order to by prepared to build and operate a substantial amount of offshore wind power it is recommended to develop a strategy for capacity building to strengthen the knowledge base in Belgium about the relevant aspects involved in offshore wind power development. The required human resources should be considered in the various stages of offshore wind development (planning, engineering, construction, operation and maintenance).

The major driving force for capacity building should be the intention to maximise the potential national employment in the sector.

The subjects primarily proposed for capacity building include: grid integration, offshore technologies and operations, wind farm installation, operation and maintenance, environmental monitoring, wind turbine and component testing, short term predictions of wind power.

6.2.4.5 International co-operation

Participation is recommended in international gremia to ensure exchange of experience, know-how and to tackle the themes where the joint effort on the international level is unavoidable.

Themes where international co-operation is required anyway are: electrical infrastructure, environmental aspects, international standardisation.

Annex 1: Grid study

Results for Slijkens

Maximum power injection in Slijkens, summer scenarios [MW]								
	Present grid							
Load level [GW]	6	7.25	8.5	8	8.5	9	10	10.5
T1	300	300	300	300	300	150	150	150
T2	300	300	300	250	300	100	100	100
T3	300	300	300	200	300	50	50	50
T4	300	300	250	200	250	-	-	-
T5	300	300	250	150	200	-	-	-
	Grid with connection Koksijde-Slijkens							
Load level [GW]	6	7.25	8.5	8	8.5	9	10	10.5
T1	400	450	450	450	450	300	250	250
T2	400	400	400	400	400	200	200	150
T3	350	400	400	300	400	100	100	100
T4	350	400	350	250	350	100	50	50
T5	350	400	300	200	300	50	-	-
	Grid with Koksijde-Slijkens and reinforcement Rodenhuize-Heimolen							
Load level [GW]	6	7.25	8.5	8	8.5	9	10	10.5
T1	400	400	400	450	400	450	450	450
T2	400	400	400	450	400	450	450	450
T3	350	400	400	400	400	450	450	450
T4	350	400	400	400	400	450	450	450
T5	350	400	400	400	400	450	400	400

Table 29: Maximum power injection in Slijkens, summer scenarios, before overload

Maximum power injection in Slijkens, intermediate scenarios [MW]								
	Present grid							
Load level [GW]	7	8	9	8	9	10	11	12
T1	300	300	150	300	100	200	200	50
T2	300	300	100	300	50	100	100	-
T3	300	300	50	300	-	50	50	-
T4	300	300	-	300	-	50	50	-
T5	300	300	-	300	-	-	-	-
	Grid with connection Koksijde-Slijkens							
Load level [GW]	7	8	9	8	9	10	11	12
T1	450	450	250	450	250	300	300	150
T2	450	450	150	450	150	250	200	50
T3	450	450	100	450	50	150	150	-
T4	450	450	50	450	-	100	100	-
T5	450	450	-	450	-	50	50	-
	Grid with Koksijde-Slijkens and reinforcement Rodenhuize-Heimolen							
Load level [GW]	7	8	9	8	9	10	11	12
T1	450	450	450	450	450	500	450	450
T2	450	450	450	450	450	500	450	450
T3	450	450	450	450	450	450	450	450
T4	450	450	450	450	450	450	450	450
T5	400	450	450	450	450	450	450	450

Table 30: Maximum power injection in Slijkens, intermediate scenarios, before overload

Maximum power injection in Slijkens, winter scenarios [MW]								
	Present grid							
Load level [GW]	8	9	10	9	10	11	12	13
T1	350	350	350	350	350	100	250	50
T2	350	350	350	350	350	50	200	-
T3	350	350	350	350	350	-	150	-
T4	350	350	350	350	350	-	100	-
T5	350	350	350	350	350	-	50	-
	Grid with connection Koksijde-Slijkens							
Load level [GW]	8	9	10	9	10	11	12	13
T1	500	500	500	500	500	200	400	150
T2	500	500	500	500	500	150	300	50
T3	500	500	500	500	500	50	250	-
T4	450	500	500	500	500	-	200	-
T5	450	500	500	500	500	-	150	-
	Grid with Koksijde-Slijkens and reinforcement Rodenhuize-Heimolen							
Load level [GW]	8	9	10	9	10	11	12	13
T1	500	500	500	500	500	550	500	550
T2	500	500	500	500	500	550	500	500
T3	450	500	500	500	500	500	500	500
T4	450	500	500	500	500	500	500	500
T5	450	500	500	500	500	500	500	500

Table 31: Maximum power injection in Slijkens, winter scenarios, before overload

Maximum power injection in Zeebrugge, summer scenarios [MW]								
	Present grid							
Load level [GW]	6	7.25	8.5	8	8.5	9	10	10.5
T1	300	350	350	350	350	150	150	150
T2	300	350	350	250	350	100	100	100
T3	300	350	300	200	300	50	50	50
T4	300	350	250	200	250	-	-	-
T5	300	350	250	150	200	-	-	-
	Grid with connection Koksijde-Slijkens							
Load level [GW]	6	7.25	8.5	8	8.5	9	10	10.5
T1	300	350	350	350	350	250	250	200
T2	300	350	350	350	350	200	150	150
T3	300	350	350	250	350	100	100	100
T4	300	350	350	250	300	50	50	50
T5	300	350	300	200	250	-	-	-
	Grid with Koksijde-Slijkens and reinforcement Rodenhuize-Heimolen							
Load level [GW]	6	7.25	8.5	8	8.5	9	10	10.5
T1	300	350	350	350	350	350	300	300
T2	300	350	350	350	350	350	300	300
T3	300	350	350	350	350	350	300	300
T4	300	350	350	350	350	350	300	300
T5	300	350	350	350	350	350	300	300

Table 32: Maximum power injection in Zeebrugge, summer scenarios, before overload

Maximum power injection in Zeebrugge, intermediate scenarios [MW]								
	Present grid							
Load level [GW]	7	8	9	8	9	10	11	12
T1	400	400	150	350	100	200	200	50
T2	400	400	100	350	50	500	100	-
T3	400	400	50	350	-	50	50	-
T4	400	400	-	350	-	50	50	-
T5	400	400	-	350	-	-	-	-
	Grid with connection Koksijde-Slijkens							
Load level [GW]	7	8	9	8	9	10	11	12
T1	400	400	250	350	200	300	250	150
T2	400	400	150	350	150	200	200	50
T3	400	400	100	350	50	150	750	-
T4	400	400	50	350	-	750	100	-
T5	400	400	-	350	-	50	50	-
	Grid with Koksijde-Slijkens and reinforcement Rodenhuize-Heimolen							
Load level [GW]	7	8	9	8	9	10	11	12
T1	400	400	350	300	350	300	300	300
T2	400	400	350	350	350	300	300	300
T3	400	400	350	350	350	300	300	300
T4	400	400	350	350	350	300	300	300
T5	400	400	350	350	350	300	300	300

Table 33: Maximum power injection in Zeebrugge, intermediate scenarios, before overload

Maximum power injection in Zeebrugge, winter scenarios [MW]								
	Present grid							
Load level [GW]	8	9	10	9	10	11	12	13
T1	400	400	400	400	400	100	250	50
T2	400	400	400	400	400	50	200	-
T3	400	400	400	400	400	-	150	-
T4	400	400	400	400	400	-	100	-
T5	400	400	400	400	400	-	50	-
	Grid with connection Koksijde-Slijkens							
Load level [GW]	8	9	10	9	10	11	12	13
T1	400	400	400	400	400	200	350	150
T2	400	400	400	400	400	100	300	50
T3	400	400	400	400	400	50	200	-
T4	400	400	400	400	400	-	200	-
T5	400	400	400	400	400	-	150	-
	Grid with Koksijde-Slijkens and reinforcement Rodenhuize-Heimolen							
Load level [GW]	8	9	10	9	10	11	12	13
T1	400	400	400	400	400	350	350	350
T2	400	400	400	400	400	350	350	350
T3	400	400	400	400	400	350	350	350
T4	400	400	400	400	400	350	350	350
T5	400	400	400	400	400	350	350	350

Table 34: Maximum power injection in Zeebrugge, winter scenarios, before overload

Results for Zeebrugge plus Slijkens

Maximum power injection in Slijkens and Zeebrugge, summer scenarios [MW]								
	Present grid							
Load level [GW]	6	7.25	8.5	8	8.5	9	10	10.5
T1	650	650	450	400	450	200	200	200
T2	650	650	400	300	400	150	150	150
T3	650	650	350	250	350	100	100	100
T4	650	650	300	250	300	50	50	50
T5	650	650	300	200	250	50	50	50
	Grid with connection Koksijde-Slijkens							
Load level [GW]	6	7.25	8.5	8	8.5	9	10	10.5
T1	650	700	600	500	600	300	300	300
T2	650	700	500	400	500	250	200	200
T3	650	700	450	350	450	150	150	150
T4	650	700	400	300	400	100	100	100
T5	650	700	350	250	350	100	50	50
	Grid with Koksijde-Slijkens and reinforcement Rodenhuize-Heimolen							
Load level [GW]	6	7.25	8.5	8	8.5	9	10	10.5
T1	650	700	700	700	700	650	600	600
T2	650	700	700	700	700	700	650	650
T3	650	700	700	700	700	700	650	650
T4	650	700	700	700	700	700	650	650
T5	650	700	700	700	700	700	650	50

Table 35: Maximum power injection in Slijkens and Zeebrugge, summer scenarios, before overload

Maximum power injection in Slijkens and Zeebrugge, intermediate scenarios [MW]								
	Present grid							
Load level [GW]	7	8	9	8	9	10	11	12
T1	650	700	200	550	150	250	250	100
T2	650	650	150	500	100	150	150	50
T3	650	600	100	450	50	100	100	50
T4	650	550	50	400	50	100	100	50
T5	650	550	50	400	50	50	50	50
	Grid with connection Koksijde-Slijkens							
Load level [GW]	7	8	9	8	9	10	11	12
T1	750	750	300	700	250	350	350	200
T2	750	750	200	650	200	250	250	100
T3	750	750	150	550	100	200	200	50
T4	750	750	100	500	50	150	150	50
T5	750	650	50	450	50	100	100	50
	Grid with Koksijde-Slijkens and reinforcement Rodenhuize-Heimolen							
Load level [GW]	7	8	9	8	9	10	11	12
T1	750	750	750	700	750	650	700	650
T2	750	750	750	700	750	650	700	650
T3	750	750	750	700	750	650	700	650
T4	750	750	750	700	750	650	700	650
T5	750	750	750	700	750	650	700	650

Table 36: Maximum power injection in Slijkens and Zeebrugge, intermediate scenarios, before overload

Maximum power injection in Slijkens and Zeebrugge, winter scenarios [MW]								
	Present grid							
Load level [GW]	8	9	10	9	10	11	12	13
T1	750	750	750	650	750	150	300	100
T2	750	700	700	600	650	100	250	50
T3	750	600	650	550	600	50	200	50
T4	750	600	600	500	600	50	150	50
T5	750	550	550	800	550	50	100	50
	Grid with connection Koksijde-Slijkens							
Load level [GW]	8	9	10	9	10	11	12	13
T1	750	750	750	750	750	250	450	200
T2	750	750	750	750	750	200	350	100
T3	750	750	750	650	750	100	300	50
T4	750	750	750	600	700	50	250	50
T5	750	700	700	550	650	50	200	50
	Grid with Koksijde-Slijkens and reinforcement Rodenhuize-Heimolen							
Load level [GW]	8	9	10	9	10	11	12	13
T1	750	750	750	750	750	700	750	750
T2	750	750	750	750	750	700	750	750
T3	750	750	750	750	750	700	750	750
T4	750	750	750	750	750	700	750	750
T5	750	750	750	750	750	700	750	750

Table 37: Maximum power injection in Slijkens and Zeebrugge, winter scenarios, before overload

Annex 2: Simulations of dynamic phenomena in the electrical grid

The figures from paragraph 3.2 and 3.3 (wind gust and voltage disturbance simulation due to a grid fault) are given for an installed wind power of 250 MW and 1000 MW.

Wind gust

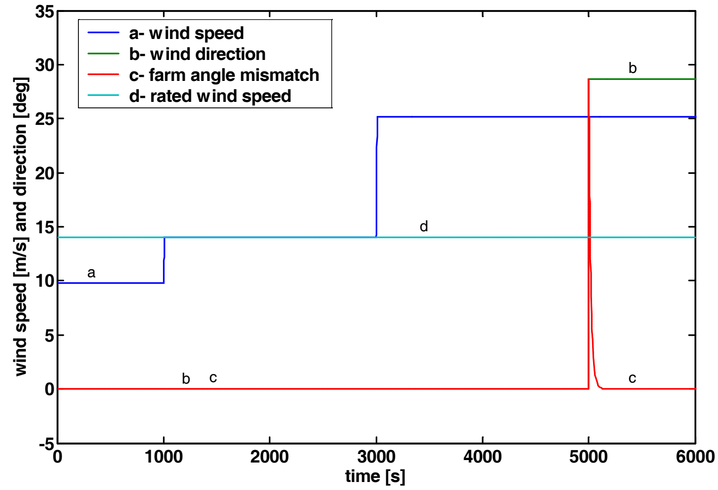

Figure 1: Assumed Wind Speed and Wind direction for Wind Gust Simulation

250MW

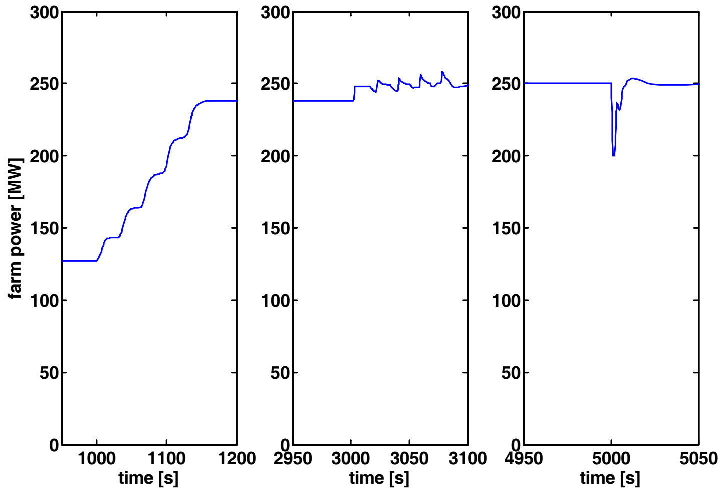

Figure 2: Active Power Production by a 250 MW Wind Farm

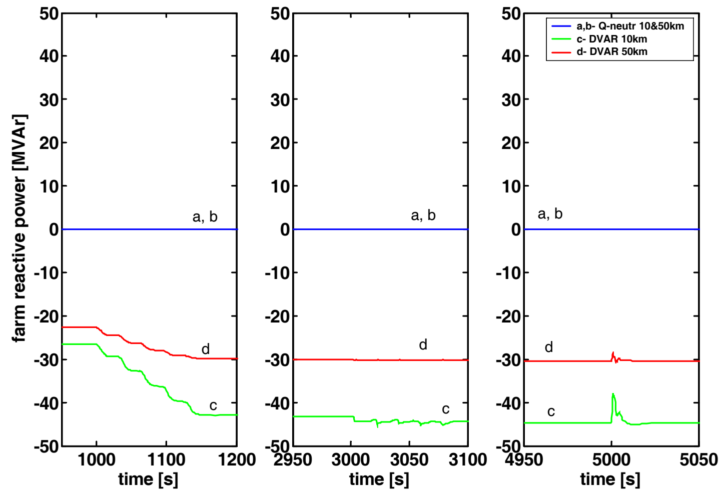

Figure 3: Reactive Power Production by a 250 MW Wind Farm

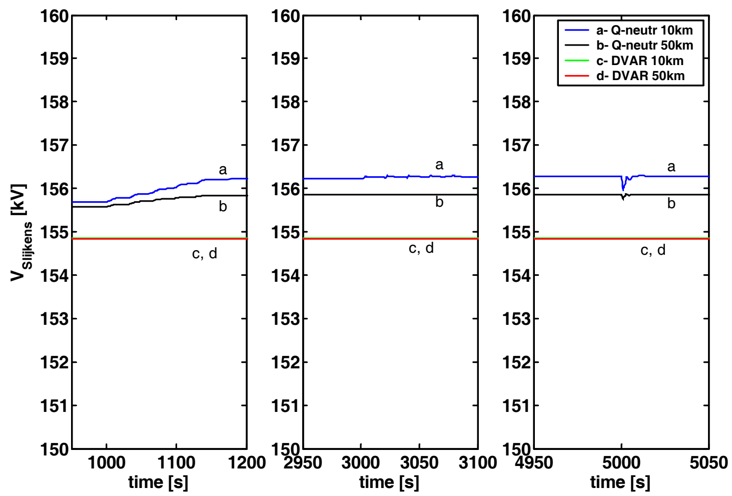

Figure 4: Voltage at Slijkens 150kV-substation

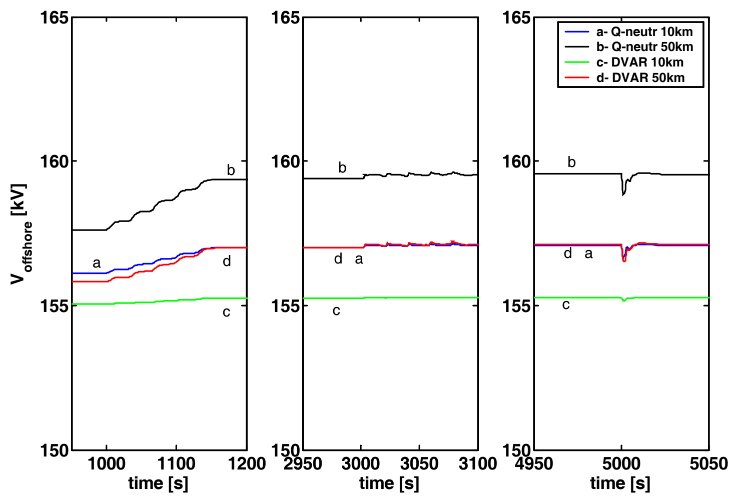

Figure 5: Voltage at offshore 150kV-node

1000 MW

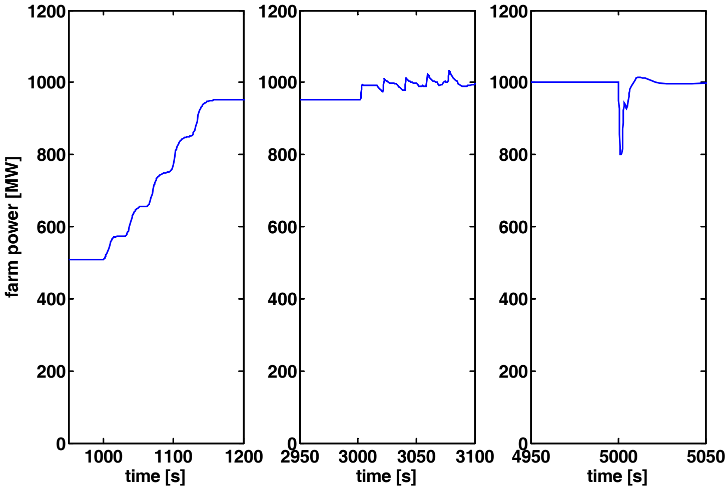

Figure 6: Active Power Production by a 1000 MW Wind Farm

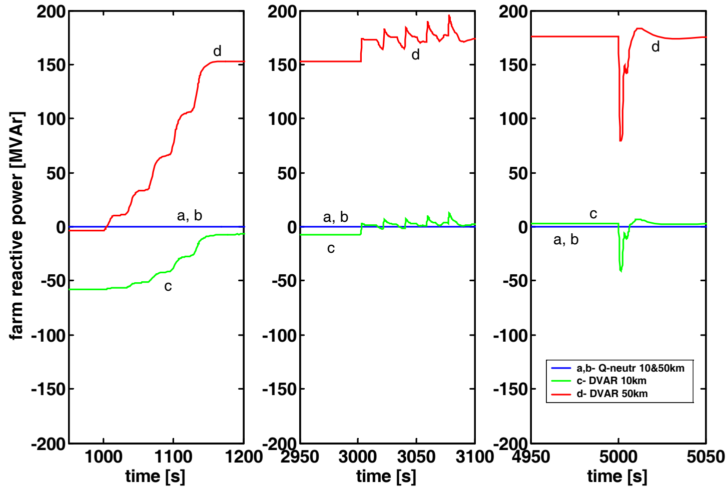

Figure 7: Reactive Power Production by a 1000 MW Wind Farm

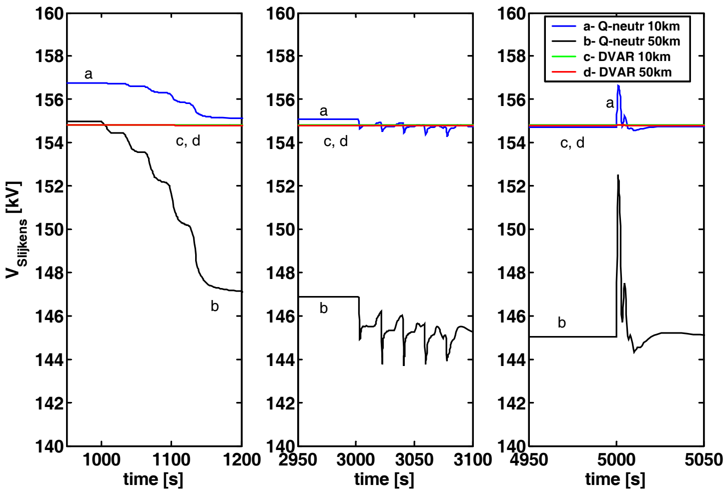

Figure 8: Voltage at Slijkens 150kV-substation

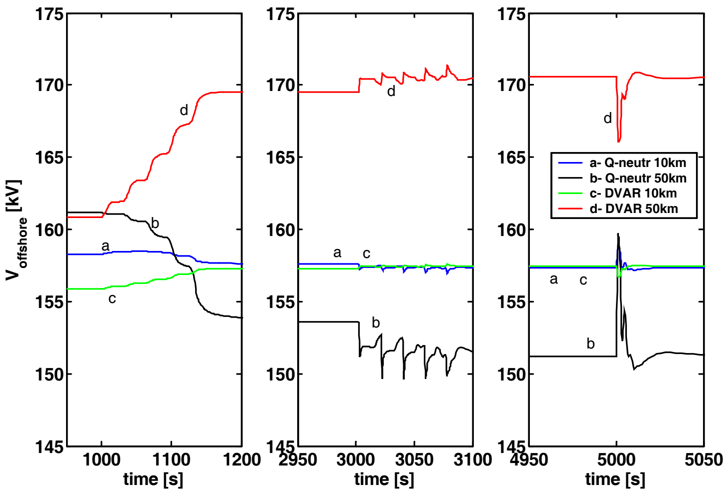

Figure 9: Voltage at offshore 150kV-node

Voltage disturbance simulation due to a grid fault

250 MW

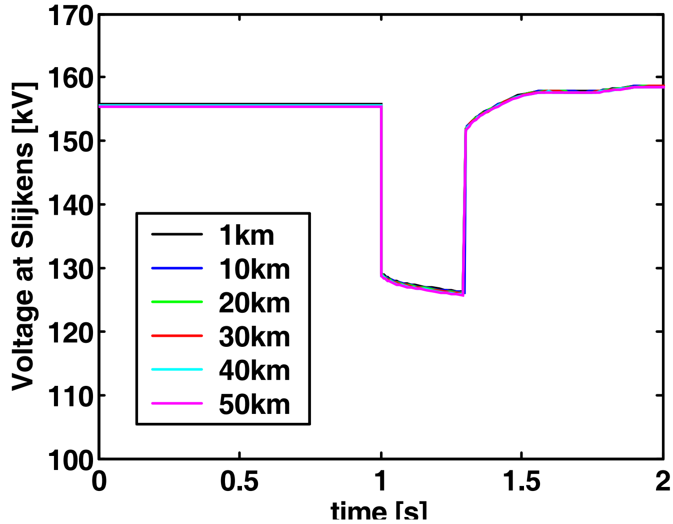

Figure 10: Voltage at Slijkens, wind farm keeps reactive power output at zero, installed wind power 250 MW

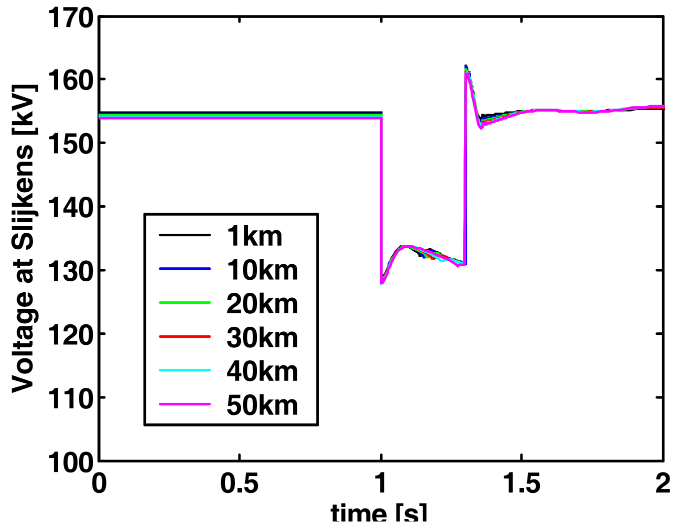

Figure 11: Voltage at Slijkens, wind farm provides dynamic voltage support, TICTL = 20 ms, installed wind power 250 MW

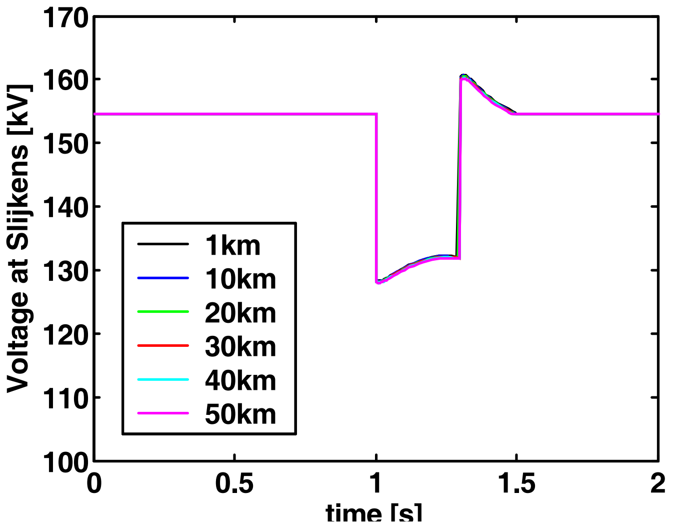

Figure 12: Voltage at Slijkens, wind farm provides dynamic voltage support, TICTL = 200 ms, installed wind power 250 MW

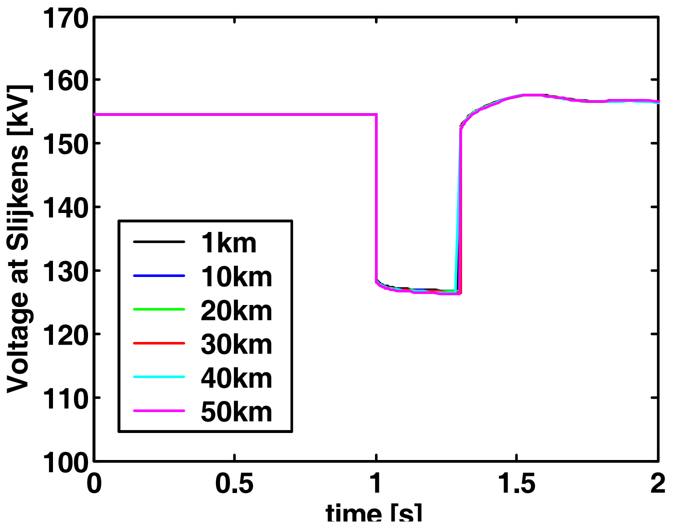

Figure 13: Voltage at Slijkens, wind farm provides dynamic voltage support, TICTL = 2 s, installed wind power 250 MW

1000 MW

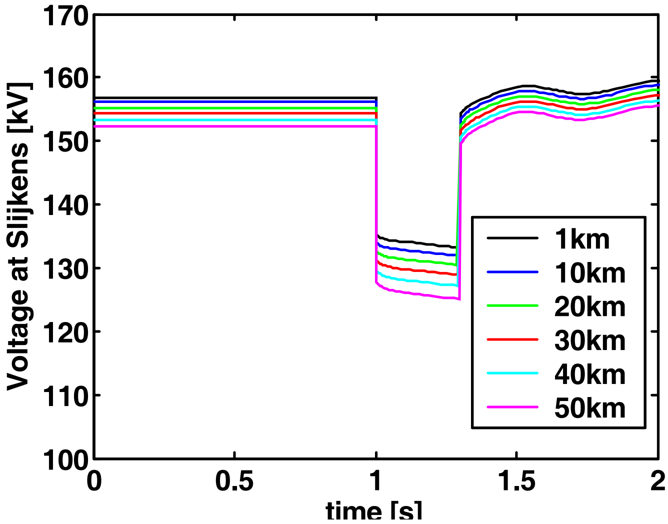

Figure 14: Voltage at Slijkens, wind farm keeps reactive power output at zero, installed wind power 1000 MW

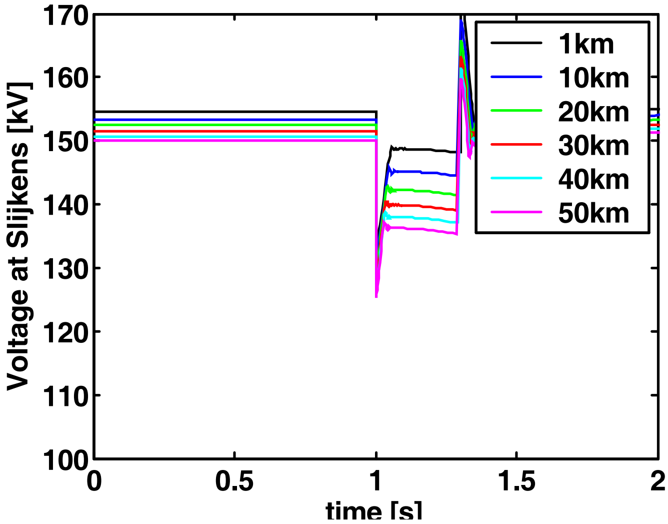

Figure 15: Voltage at Slijkens, wind farm provides dynamic voltage support, TICTL = 20 ms, installed wind power 1000 MW

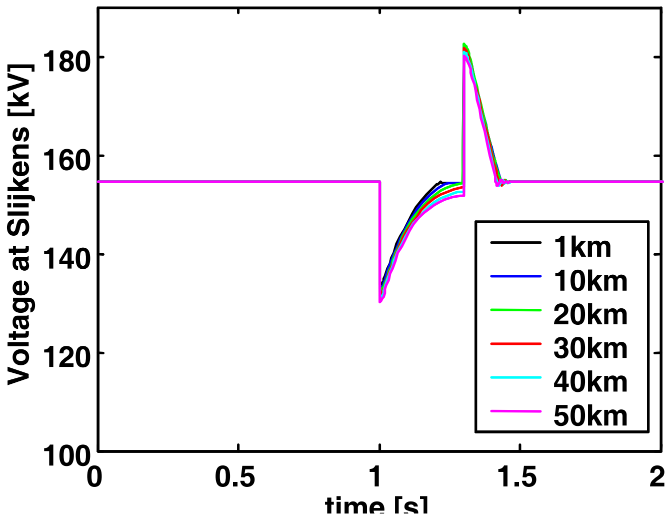

Figure 16: Voltage at Slijkens, wind farm provides dynamic voltage support, TICTL = 200 ms, installed wind power 1000 MW

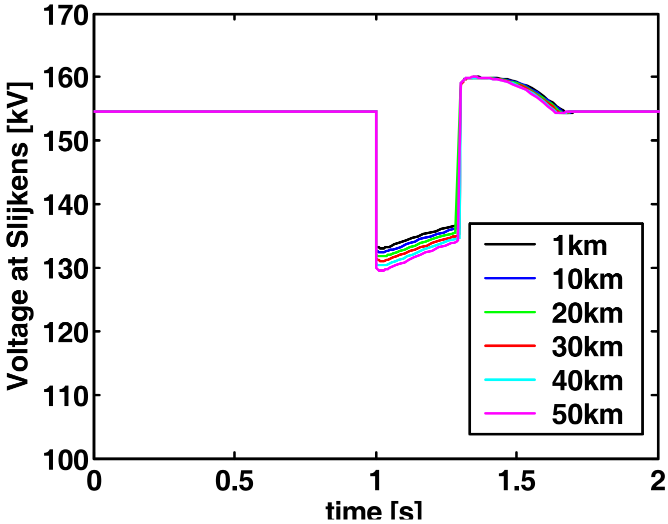

Figure 17: Voltage at Slijkens, wind farm provides dynamic voltage support, TICTL = 2 s, installed wind power 1000 MW

Annex 3: Sensitivity analysis of cost

Influence of the wind speed distribution shape (Weibull shape parameter)

As pointed out in 2.3, the Weibull shape parameter determined by the POWER method is too low (values around 1.7). Wind regimes measured offshore (Westhinder, Wandelaar, Droogte van het Schooneveld, Vlakte van de Raan) show Weibull shape factors of at least 2.1. The effect of varying the Weibull k parameter on the mean annual energy output is presented in Figure 91 and Figure 92.

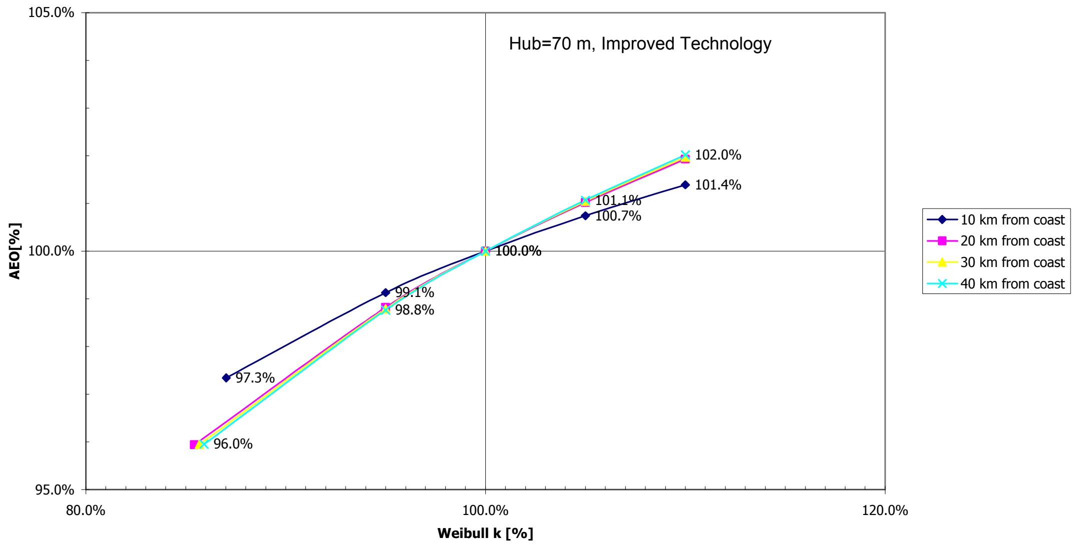

Figure 91: Influence of the Weibull shape factor on the annual energy production, hub height 70 m

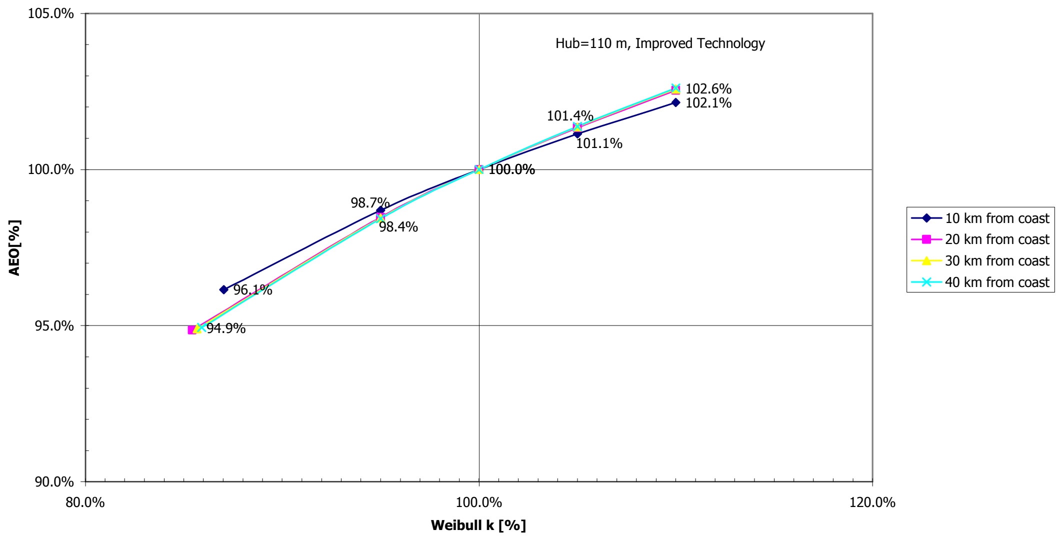

Figure 92: Influence of the Weibull shape factor on the annual energy production, hub height 110 m

The reference point in the diagrams corresponds to a Weibull k parameter equal to 2.0 (used in all presented calculation results). At 70 m, the annual energy output increases by 1.4% if k increases to 2.2 for a distance of 10 km from the coast. For a distance of 20 km from the coast and more, the annual energy output increases with 2.0% with a 10% increase of k. Decreasing k to 1.7 decreases the annual energy output by 2.7% for a distance of 10 km from the coast to 4% for a distance of 20 km or more from the coast. At 110 m, the variation of the energy output with k is a bit higher, because of the higher average wind speed.

Production cost sensitivity analysis

The relative influence of the variation in the main cost elements in the total production cost can be derived from Fig. 93. The investment cost (wind turbine, foundation, electrical system,…) has the strongest influence on the production cost. A negative variation of 30% in investment results in a 29% reduction of the production cost. A 30% negative variation of operation and maintenance cost results in a 8% decrease in production cost. The influences of possible overhaul cost and decommissioning costs are relatively low.

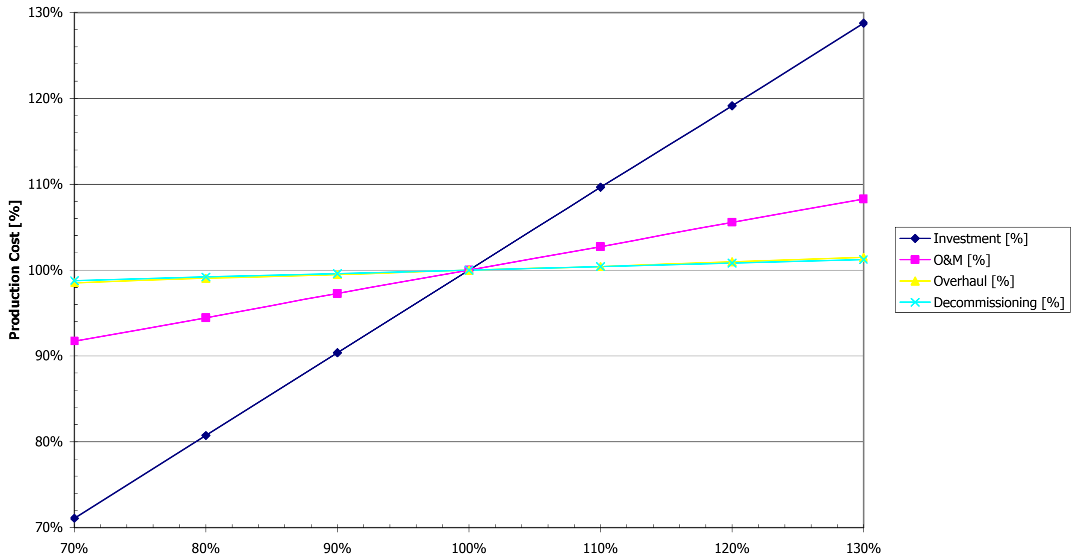

Figure 93: Relative influence on total production cost (Hub 70 m, Improved Technology)

Figure 94 shows the influence of the economic parameters: interest rate, term of loan, project life time, inflation.

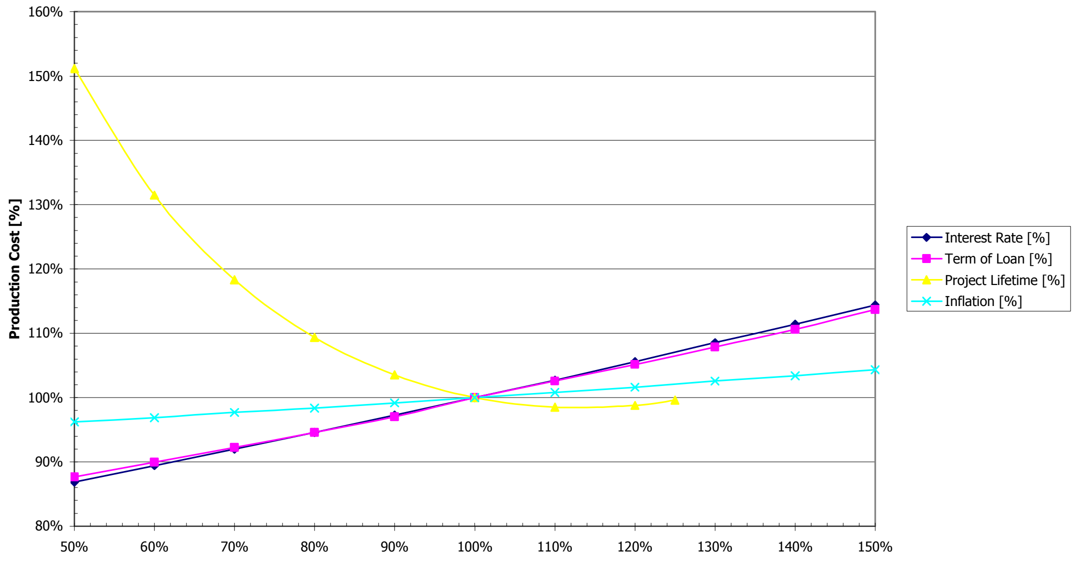

Figure 94: Relative influence on total production cost (Hub 70 m, Improved Technology)

Production costs decreases with increasing project lifetime. If the project lifetime is only 10 years instead of 20 years, the production cost increases with 50%. On the other hand, when the project life time exceeds 25 years, the production cost will increase again. Under the assumptions made, minimum production cost is found for a lifetime of 22 years.

The influence of inflation is quite low, but the interest rate and the term of loan have a strong influence. A drop in interest rate from 8.5% to 4.25% decreases the production cost with 13%. Decreasing the term of loan from 12 years to 6 years decreases the production cost with 12%.

All previous calculations have been made for a Weibull shape (k) parameter equal to 2.0. Figure 95 shows the variation of the production cost with varying Weibull shape parameter in the range between k = 1.7 and 2.2, (k reference = 2.0). The lower value of k (1.7) yields a 4% higher production cost compared to k = 2.0. The higher value results in a 2% lower production cost. This illustrates the importance of accurate wind assessment in view of the cost estimation.

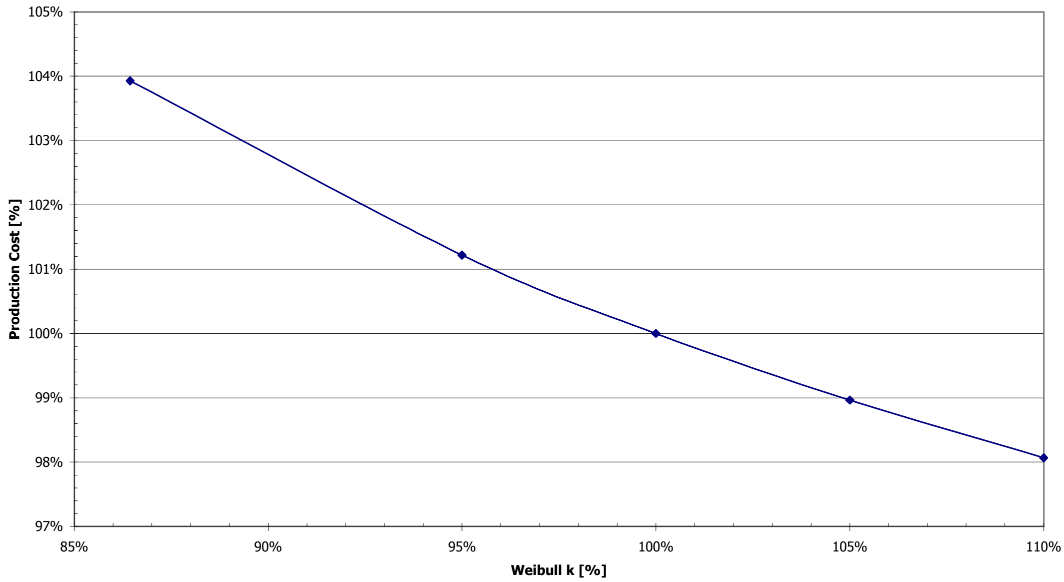

Figure 95: Relative influence on total production cost (Hub 70 m, Improved Technology) of the Weibull shape parameter (reference value of k is 2.0).

A relationship between generation costs and investment costs has been calculated based on the data calculated for the BCS for the different technology levels and hub heights. This is presented in Figure 96.

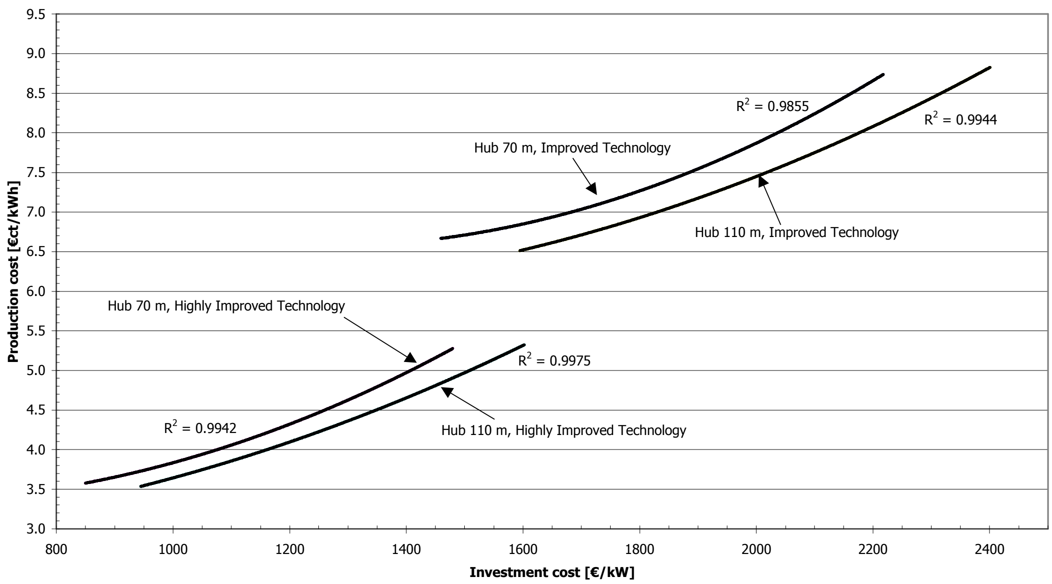

Figure 96: Production Cost versus Investment Cost

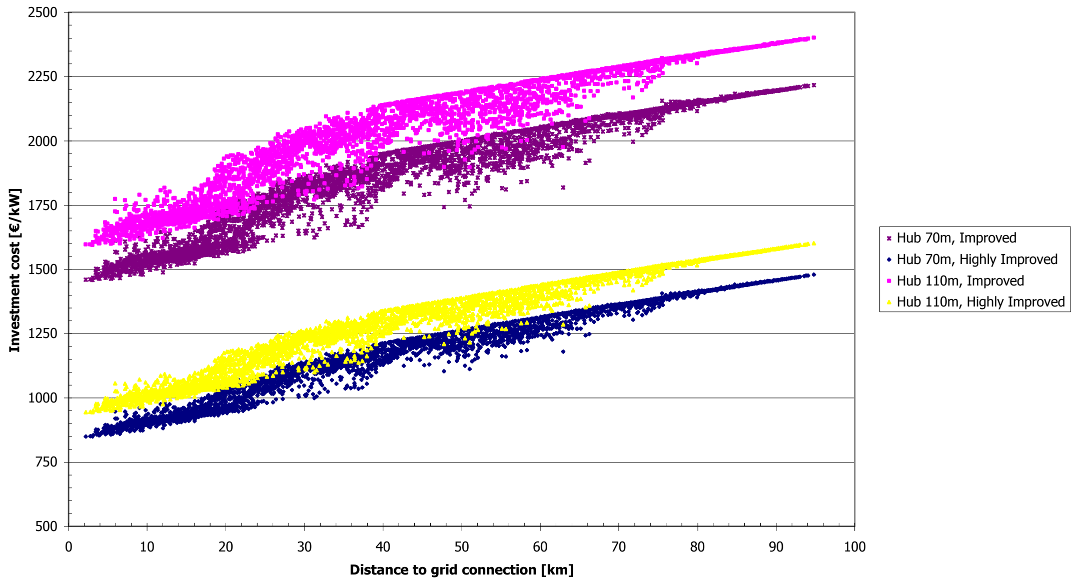

Figure 97: Investment cost versus distance to the grid connection

Figure 97 shows the calculated investment cost versus the distance to the grid connection point for the four options. The scatter of the individual points is due to the variation in water depth (decreasing far offshore, large in the area with many sandbanks). The variation of the generation costs with the distance to the grid connection point is shown in Figure 98. These figures clearly illustrate again the small to 'negative' benefit of using high towers.

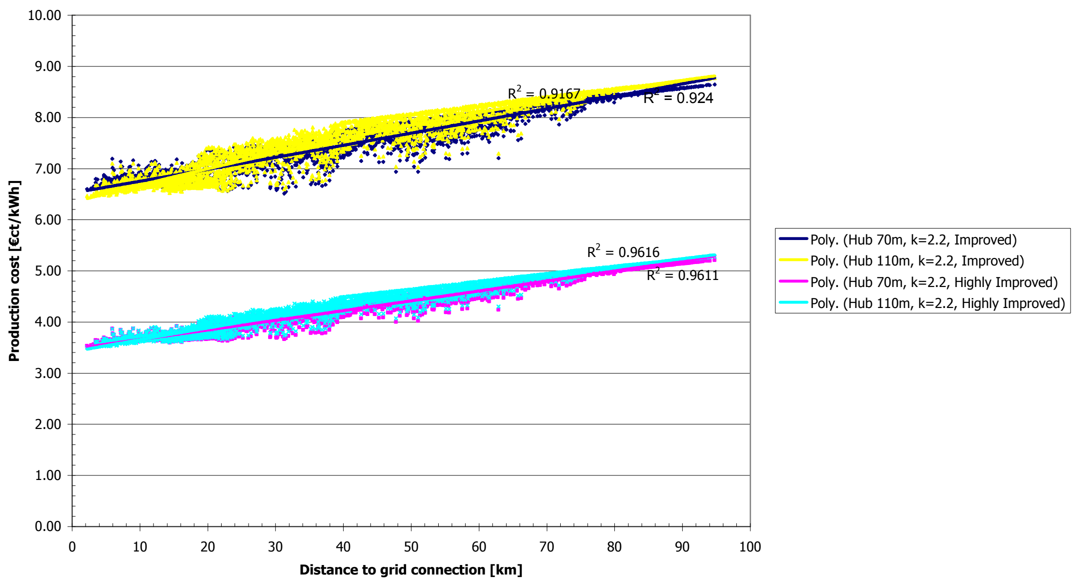

Figure 98: Production cost versus distance to the grid connection.

Annex 4: Literature, references and publications of the partners

RCMG

Contacted people and consulted references related to the overview on the stability and environmental criteria

Persons:	Organism:	Country:
Noemie LAUMONT, Marissa MERCANTONIO Dries VAN DEN EYNDE	BMM/UGMM	Belgium
Wim HAEGEMAN	University of Ghent, Geotechnics Department	
Peter DE POTTER	Haecon	
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Bernard LATTEUX	consultant in coastal and harbour engineering	
Patrick KLEINEIDAM	University of Hannover, Steel Construction Institute	Germany
Kerstin Lesny Jens WIEMANN	University of Hannover, Institute for Foundations and Soil Mechanics	
Andrew WHEELER	Dept of Geology and Environment Research Institute, University of College Cork	Ireland
Jimmy MURPHY	Hydraulics and Maritime Research Centre, University College Cork	
Saskia VAN GOOL	Ministerie van Verkeer en Waterstraat	The Netherlands
Ad STOLK	Ministry of Transport, Public Works and Water Mangement, North Sea Directorate	
Ceri JAMES Sally PHILPOTT	BGS (British Geological Survey)	United Kingdom
Huw POWELL Richard WHITEHOUSE	HR WALLINGFORD	

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