SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY

Intermediary report - January 2003

OPTIMAL OFFSHORE WIND DEVELOPMENT IN BELGIUM
CP-21

3E – KUL - RUG

SPSD II

PART 1
SUSTAINABLE PRODUCTION AND CONSUMPTION PATTERNS

- GENERAL ISSUES
- AGRO-FOOD
- ENERGY
- TRANSPORT

This research project is realised within the framework of the Scientific support plan for a sustainable development policy (SPSD II)

Part I "Sustainable production and consumption patterns"

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Optimal Offshore Wind Energy Developments in Belgium

First intermediary scientific report

Period 01/01/2002 – 31/12/2002

Optimal Offshore Wind Energy Developments in Belgium

First intermediary scientific report

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1 Introduction

1.1 Context and summary

The promotion of renewable energy is a means of decreasing the carbon content in the fuel mix. Beside its low to very low carbon content, it contributes to the security of supply and has net positive employment effect to the European Union. Therefore the European Union has published a White Paper in 1997, proposing to double the contribution from renewable sources to the primary energy consumption from 6% to 12% by 2010. Wind energy plays an essential role in this challenge, considering that its contribution should increase 19-fold in the next 10 years.

Belgium is at the forefront of implementation of offshore wind in its continental shelf, and – depending on the outcome of running administrative procedures - be among the first EU member states with large offshore wind farms in its part of the North Sea. Public studies on the potential of renewable energies in Belgium have not included as yet thorough investigations on the potential of off-shore wind, although the expected contribution of this technology is very important. On the other hand, a first offshore wind power plant is about to be constructed near the Belgian coast, 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 potential without indicating direct business opportunities, and 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 (marine environment, fisheries, military, shipping, military, tourism, etc.).

1.2 Objectives

1.2.1 Overall objectives

(A) Determing the resources for off-shore wind energy production in the Belgian continental shelf by

- Scanning the geological and geotechnical restrictions;
- Studying the wind resources for the envisaged region;
- Analysis of the options for grid-connection.

(B) Study on the technological evolutions and the economic viability of long-term options by studying:

- The off-shore wind turbine technology evolution scenario's
- The evolution in the electrotechnical schemes for interconnection and the grid-connection based on the expected technological evolutions and the likely evolutions of the grid architecture
- The long term options for support structures, installation procedures and O&M procedures

(C) Determining the physical, technical and economical potential for off-shore wind application in the Belgian continental shelf based on the indicated specific resources and expected technological evolutions.

1.2.2 Detailed objectives

1.2.2.1 Survey of the resources

A geological, geotechnical, sediment- and morphodynamical assessment study of the solid substrate and seabed sediments is made 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 the minimisation of environmental impacts on the seabed.

Using data from a complete network of measuring stations (meteo and oceanographic data) in the Belgian Northsea and at the shores, and using the latest offshore-versions of WAsP and additional software, the wind resource over the Belgian Continental Shelf will be calculated at several wind turbine hub heights. The latest insights in the relationship between wind speed and 'terrain roughness' for oceanographic climats will be applied in the analysis.

As for the grid connection, the objective is to make a detailed analysis of the required transmission capacity in order to estimate the grid costs involved in pushing towards larger offshore wind farms. The effects of the use of several types of marine electrical transmission systems will be studied (AC and HVDC).

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

To make a study of 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.

Starting from the possible energy conversion and transmission system to estimate the impact of the different options for the Belgian electrical system, both by steady-state and dynamic modelling.

1.2.2.3 Determining the potential

Based on the findings of the previous main tasks 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.

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.

1.3 Expected outcomes

The expected outcome is a quantification of the offshore wind energy potential (physical, technical and economical) of wind energy in the Belgian continental shelf. The format for the result will be such that the effects of policies and planological decisions on the offshore wind energy potential can be derived. Therefore, the result will be based on the subdivision into hard (physical) factors and policy dependent factors. Besides the decision matrix, the project will yield in detailed investigations and subsequent descriptive analyses, reports and maps on the topics mentioned below:

- Hierarchical classification and integrated mapping of sites based on geological, geotechnical, morpho-and sediment – dynamical criteria;
- Estimation of the spatial distribution of the wind resource at a number of altitudes relevant for wind farms. Maps indicating annual average wind speeds and wind power density over the BCP.
- Detailed parametrisation of the relevant grid-infrastructure options;
- Inventory and spatial definition of non-technical exclusive criteria;
- Projected technology figures for offshore wind energy technology in 2005 and 2015;
- Dedicated tool to perform static and dynamic calculations of grid interaction of offshore wind energy technology;
- Simulation results and analysis of the gird interaction of different electrotechnical options for interconnection and grid connection of offshore wind power plants;
- Evaluation of the local and global potential of wind energy in the Belgian BCP anno 2005 and 2015;
- Recommendations on policy measures for the optimal exploitation of Belgian offshore wind resources.

2 Detailed description of the scientific methodology

2.1 General

The project is divided into three main tasks which reflect the general methodology followed.

- Survey of resources (Task 1) consisting of a geotechnical study, a wind resources calculation, a study on the availability of HV connection options and a survey on non-technical barriers

- Calculation of technological options (Task 2) consisting of a prediction of technology figures for two time windows and a study of the impact of the connection of wind farms to the grid.

- Definition of the potential (Task 3) based upon the findings of the previous main tasks.

In the following paragraphs a more detailed description is given of methodology followed in the project tasks.

2.2 Task 1.1 Geotechnical study

The geotechnical study consisted in the following subtasks:

Subtask 1.1.1: Evaluation of the potential of the substratum of the Belgian continental shelf: A general review of the Belgian continental shelf is made on the basis of existing knowledge concerning the above-mentioned topics. Subsequently, knowledge gaps will be identified.

Subtask 1.1.2: Establishment of a hierarchical classification of suitable sites: An evaluation is made for the whole Belgian continental shelf with respect to its suitability for offshore wind farm implantation sites. The most suitable sites will be proposed on the basis of a classification of the relevant geological, geotechnical, morphodynamical and sediment dynamical criteria. Also less suitable sites will be indicated on same criteria.

The geotechnical study has been conducted in the following way:

- A European overview concerning the currently used stability and geo-environmental criteria has been realised. This state-of-the-art has allowed defining the parameters relevant for a geological investigation. The used 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, the geotechnics, the sediment- and morphodynamics 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.

The geotechnical study will result 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 environmental impacts. The main product will be a map with recommendations on the most suitable sites and also indicating less suitable sites.

2.3 Task 1.2 Wind resources

Using the data from a complete network of measuring stations (meteo and oceanographic data) in the Belgian North Sea and at the shores, and using the latest offshore versions of WAsP and additional software, the wind resource over the Belgian territorial waters will be calculated at several hub heights. This examination will be accompanied with new insights in the relationship between windspeed and roughness for marine sites. The analysis has been carried out according to the following main steps:

- Data check: A statistical analysis will be been carried out for every measuring station. Thereafter, the ratio between these measuring stations will be been studied in order to estimate the spatial distribution of the mean wind speed (distance to the coast, North-South gradient). Moreover, the statistical analysis is important to determine the ratio between the relative short-term measuring period to the long-term period.

- Selection of data sets: In order to estimate upper and lower limits of the potential, a division will be made of measuring stations, taking in account the calibration curve of the anemometers and the results of the cross check calculations after correction and filtering of the measuring data

- Calculation of the wind resource: The resource is expressed in terms of Weibull parameters and mean energy density (W/m^2 swept rotor area);

- In the end, the data have to be extrapolated as accurately as possible to relevant heights of 60, 80 and 100 m.

2.4 Task 1.3. Availability of a high-voltage grid connection

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

As input of the calculations, a model of the Belgian HV-grid is used. That model includes every Belgian node in the range from 380kV down to 70kV 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 in 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 sea-bed near Koksijde is not suited for constructing wind farms), 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.

2.5 Task 1.4. Investigation of all static and dynamic factors limiting the potential in practice

Factors determining the technically exploitable potential are: Visual impact (distance from the shores and coastal activity), Shipping lanes, Military zones ; deposits of munition from World War I, Civil and military aviation, Marine environmental protection (see VLIZ recommendation letter), Bird migration routes

Based on these non-technical barriers, a list of areas excluded for wind energy exploitation, is defined.

2.6 Task 2.1. : Wind farm technology

In this task, the expected technological evolutions are studied based on an international research overview. This results in technology figures that will be predicted for 2 different time stamps: 2005 and 2015. The figures are related to Optimal turbine dimensions, wind turbine costs, optimal park layout, costs of foundations, power curves, cost of grid-connection, interconnection electrotechnical parameters, operation and maintenance costs, grid-connection electrotechnical parameters, geotechnical parameters of underseas cabling

Based on this data, wind energy production simulations are performed for the identified wind regimes of task 1.2.

2.7 Task 2.2. Electric interconnection and grid-connection schemes

Starting from the possible energy conversion and transmission system identified under task 1.4. The impact of the different options for the Belgian electrical system are estimated on different levels:

- At first, a static model will be developed to study the balance of the active and reactive power household on a relatively long time horizon. The developed program allows to investigate and evaluate the various operating conditions with respect to the steady-state performance.
- Secondly, this will be extended to a short-term dynamic model, capable to study the different transient interactions due to, for instance, wind gusts, generator on/off-switching and harmonic injection. Grid-induced transients such as voltage dips can be studied as well. With the developed program, a set of simulations covering most typical dynamic phenomena for the different technological possibilities will be conducted.

The development of the simulation models will consist of the further extension of existing load-flow programs with appropriate turbine, generator, control and power electronic models. These models should be able represent all of the different technological options to couple the wind turbine to the grid. Possibly, different simulation algorithms will have to be coupled to study the global effect, as the nature of the different components is sincerely different.

Using these computations, it will be possible to study the impact on the grid of the different technologies, taking into account the different locations for connections. Hence, on-shore substation design can be optimised, for instance regarding dynamic reactive power compensating elements and filters. The results will allow the definition of a planning strategy for the electrical connections of offshore wind energy technologies.

2.8 Task 3 : Definition of the potential

The Belgian Continental shelf has been split up into a network of mazes as defined in tasks 1.1 and 1.2. Per maze the potential is calculated *in physical potential* (defined by wind resource characteristics and hard criteria as defined in task 1.4), *technical potential* (defined by exclusions based on geo-technical and grid issues and wind turbine power curves) and *economical potential* (defined by impact of geo-technical issues on foundation, installation and O&M costs, impact of electro-technical issues on installation and transmission costs and wind turbine cost)

Calculation of the technical and economical potential is performed for expected state-of-the-art of technology in 2005 and 2015.

The mazes are classified into ranges of physical technical and economical potential.

This classification is summed up and visualised for the Belgian Continental Shelf.

2.9 Task 4 : Recommendations on policy measures and dissemination of the results

Insights in the exploitation of the off-shore wind resources, gained during the course of the research, can serve as input on policy measures. Some evident examples are:

- Long term strategy on exploitation of the transmission grid
- Strategy on the exploitation of the natural reserves of the territorial sea
- Strategy on the concession of the off-shore wind exploitation

A workshop is organised to disseminate the project results.

3 Detailed description of the intermediary results, preliminary conclusions and recommendations

3.1 General

The intermediary project results are discussed in the following paragraphs. A division is made according to the projects main tasks.

The emphasis of the work in this period has been on the tasks 1.1, 1.2 and 1.3. This is reflected in the report by giving these issues the most attention.

3.2 Geological and geotechnical study of the Belgian continental shelf (Task 1.1)

3.2.1 Overview of stability and environmental criteria

Contacted people and consulted references are mentioned in Annex (in 5.1.2).

3.2.1.1 Offshore wind farm structures

An offshore wind farm is an array of wind turbines with support structures consisting of piles anchored in the seabed, stabilised by foundations and electrically interconnected to the onshore substation by submarine cables. Piles and cables are the only structures concerned with the soil and sub-soil.

Two main types of foundations can be distinguished:

(1) foundations driven 10 to 20 m into the seabed and the solid substratum, such as monopiles (3-3.5 m in diameter), tripods, suction buckets, guyed support structures. Monopiles are currently used in water depths up to 20 m (CA-OWEE, 2002).

(2) foundations put on the seabed, such as gravity based structures (e.g. concrete or steel caissons of 12-15 m in diameter). They are currently used in shallow waters (less than 10 m depth).

Submarine cables are generally about 10 cm in diameter and buried in the seabed.

3.2.1.2 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 turbine and the equipment, and (2) horizontal loads, mainly dynamic, coming from waves, tidal currents and winds, 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 bedform 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 comprised 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).

3.2.1.3 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).

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

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,…
	loading (exploitation phase)	sediment dynamics: transport rates, scouring, bedform migration
Foundation driven in the solid substrate	drivability of pile (construction phase) settlement (exploitation phase)	solid substrate geology: nature, depth, thickness, homogeneity,… of geological layers solid substrate geotechnics: shear strength, local friction, point resistance, undrained cohesion, determination of an adequate bearing layer,…
Foundation put on the seabed	smoothing of the seabed (construction phase)	seabed sediments: nature and grain-size, seabed morphology: slope, bedforms, rock outcrops
Submarine cables	trench construction and infilling problems (construction phase)	seabed sediments: thickness, nature, grain-size sediment dynamics: transport rates

3.2.1.4 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 are changes which may affect: (1) sediment patterns, especially important towards habitats, and (2) sediment storages 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).

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

Topics	Impacts	Parameter variation needed
seafloor characteristics	construction: sediment resuspension exploitation: scouring	seabed morphology and nature
sediment budget	exploitation: hydrodynamic and sedimentary changes, scouring, modification of wave pattern ?	sediment transport: erosion and accretion

3.2.2 Qualification of the substratum: data synthesis

3.2.2.1 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 can be rapidly altered by foundations, and (2) a non-consolidated level (surficial sediments) submitted to currents and wave action.

Available data (Figure 1, in Annex 1)

The data used to investigate the geological characteristics of the seabed and substratum consist essentially of seismic profiles (about 16,000 km, RCMG [1]) and cores (79, RGD [2] and BGD [3]). 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 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 1 in Annex 1) 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 2, in Annex 1). 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, in Annex 1). 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 sandstones have been observed in some onshore geological units and are probably present in equivalent offshore units (L1, Y5, Y4, Table 1).

- **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, direction in which they subcrop successively (Figures 3 and 4, in Annex 1). Thicknesses are highly variable from one unit to another, but quite constant within each unit (Figure 5-a, -b and -c, in Annex 1). Maximum unit thicknesses are reported in Table 1 (in Annex 1). Distribution patterns vary, although some similarities can be drawn.

- **Deformations:** On the Belgian continental shelf, 2 different genetic types of deformations are encountered: (1) Basement induced deformations due to an external, regionally tension field and consisting of folds, faults and collapses. They are essentially concentrated in 2 large areas (Figure 6, in Annex 1), 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

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

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 7-a and -b, in Annex 1).

Non-consolidated deposits

They consist of sediments of Quaternary age. Some of them are relict, but others are currently mobile under the tidal current action.

- **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 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 5-a, -b and -c, in Annex 1). The main deposits consist of (1) Holocene tidal sandbanks, and (2) Pleistocene scour hollow infillings (Figure 9, in Annex 1).
- The Quaternary assembly of some of the sandbanks has been characterised (Figure 11, in Annex 1), mainly from seismic investigations. As an example, the Middelkerke Bank (De Moor and Lanckneus, 1993; Heyse & De Moor, 1996) 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 12 and 13, Table 6, in Annex 1). 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 infilled 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) (Figures 14-a and 14-b, in Annex 1). The Quaternary deposits are generally thinner offshore: they range in thickness from a few metres to 50 metres (Figure 16, in Annex 1). The larger thicknesses are reached on 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 10, in Annex 1).

3.2.2.2 Geotechnical properties

Available data (Figure 1, in Annex 1)

The data used to investigate the geotechnical characteristics of the seabed and substratum consist of cone penetration tests (177 evaluated) and cores (79). 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 both types of 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 DOV4). 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).

[4] Databank Ondergrond Vlaanderen

Generalities

Typical CPT's are reported on Figures 17 and 19 (in Annex 1).

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 characterize.

The cone resistance allows to determine sandstone or calcareous layers (Tertiary), or pebble (Quaternary) thin layers. These thin hard layers correspond to positive peak values of the cone resistance. They occur both in Quaternary and 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 geological units composed of alternating layers of clay and sand: the Oedelem Member (in L1), Vlierzele Member, Pittem Member and Egem Member.

Quaternary deposits

Geotechnical properties of the Quaternary deposits are characterized 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 (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 7 and 8, Figure 18, in Annex 1).

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 trends can be determined as all CPT's information concerns a small extended area.

3.2.2.3 Morphodynamics and sediment dynamics

Available data

Results of the OSTC project 'BUDGET' are referred to (Lanckneus et al., 2001 ; Figures 20 and 21, in Annex 1). 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 9, in Annex 1). 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. Figure 22 (in Annex 1) 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 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 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. By the end of 2003, more detailed information will become available from the OSTC projects 'Marebasse' and 'GAUFRE' where a compartmentalisation will be made of the Belgian part of the North Sea a.o. based on physical and ecological criteria. This will be one of the base maps for the evaluation of the impact of human activities.

- 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 implantating offshore structures especially towards scouring.

3.2.3 Suitability of the Belgian continental shelf: recommendations for site selection

3.2.3.1 Parameters relevant for stability and geo-environmental impacts

Generalities

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 mechanism.

As far as seabed conditions are concerned, the most suitable places correspond to the less dynamic ones. 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 (e.g. sandbanks).
  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, such as sandbanks.
  - Layers affected by regional (faults) or internal (e.g. block-faulting, -tilting) deformations. Only some clayey units are concerned by 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 should be avoided.

- Seabed parameters:
  Belgian offshore sandbanks are stable except for their surficial summital 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 very small net migration rate would be considered as most suitable.

3.2.3.2 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 concerned (foundations, pile, cable), the type of foundation chosen (driven into the soil or put on the seabed) 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. A combination is possible of various parameters enabling to produce scenario's according, for example, to the type of foundation selected.

An example of the type of map that can be produced is presented in Figure 23 (in Annex 1). This map indicates some sites where wind farm implantation is not recommended, 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 thickest Quaternary layers (the thicker, the less suitable), and (3) the faults (not suitable).

Still, refinements can be made according to further discussions with the project group (e.g. technological aspect). Moreover, the final proposal of sites will be limited by the multi-user restrictions as defined in Task 3.1.4. The whole will serve as an input to Task 3.3.1. on the definition of the potential of the Belgian continental shelf regarding the implantation of windmill farms.

3.3 Wind resources (Task 1.2)

3.3.1 General

The wind resources are estimated from available long term data collected at several measuring stations in the BCP. The data are extrapolated using the programme WasP. The resource is calculated at a level of 60, 80 and 100 m.

3.3.2 Wind measuring stations

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

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

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	Paal	Paal	Paal	Paal	Paal op land
Coordinates geografical 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
Period	Maa 94– Sept 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%
Number of valid observations	365276	588345	131542	98032	83107
Number of observations per day	144	144	96	24	24
Gem. windsnelheid [m/s]	8.46	7.84	8.18	7.65	6.39
Weibull A [m/s]	9.606	8.933	9.298	8.752	7.208
Weibull k[-]	2.1756	2.0676	2.1546	2.2237	1.9172
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%)

The positions of these stations are depicted in Figure 5 in par. 5.3.2.1. These measuring stations are operated by the Flemish and Dutch national authorities. The aim of these stations was originally to be used for the ship traffic in the North Sea, and not explicitly to collect data for wind resource analyses. Therefore, the detailed analysis of these data is necessary to study the quality and consistency.

3.3.3 Analysis of data of measuring stations

3.3.3.1 Method

A statistical analysis has been carried out for every measuring station (see Table 3). Thereafter, the ratio between these measuring stations has been studied. This is necessary to estimate the spatial distribution of the mean wind speed (distance to the coast, North-South gradient). Moreover, the statistical analysis is important to determine the ratio between the relative short-term measuring period to the long-term period.

In the end, the data have to be extrapolated as accurately as possible to relevant heights of 60, 80 and 100 m.

Details about the reliability check and analysis of the data are given in 5.3.2.2.

3.3.3.2 Definition of data sources to be used in the calculation

Taking in account the calibration curve of the anemometers and the results of the cross check calculations after correction and filtering of the measuring data, it has been concluded to calculate an upper limit and a lower limit for the wind resource at the BPC.

The following division of the data sources has been made in order to calculate these values:

Upper limit:	MOW0: raw data after correction and filtering according to the analysis over the same statistics
	VR, CAWI: raw data
	MOW5, MOW7: raw data minus calibration range
Lower limit:	MOW0: raw data after correction and filtering according to the analysis over the same statistics, minus calibration range
	VR, CAWI: raw data minus calibration range

3.3.4 Calculation of the wind resource

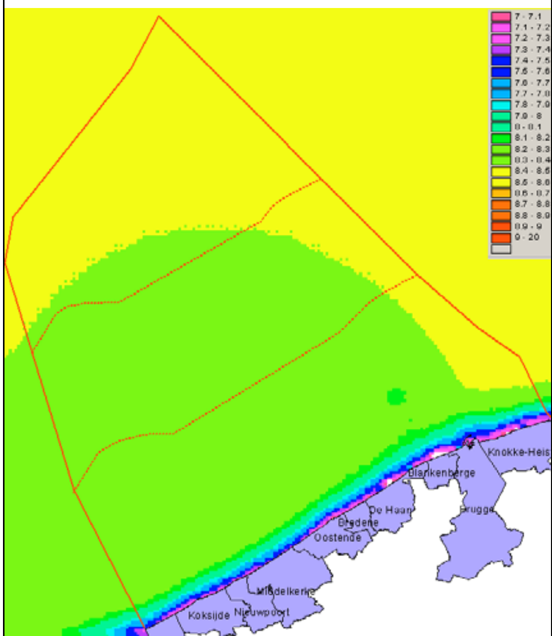
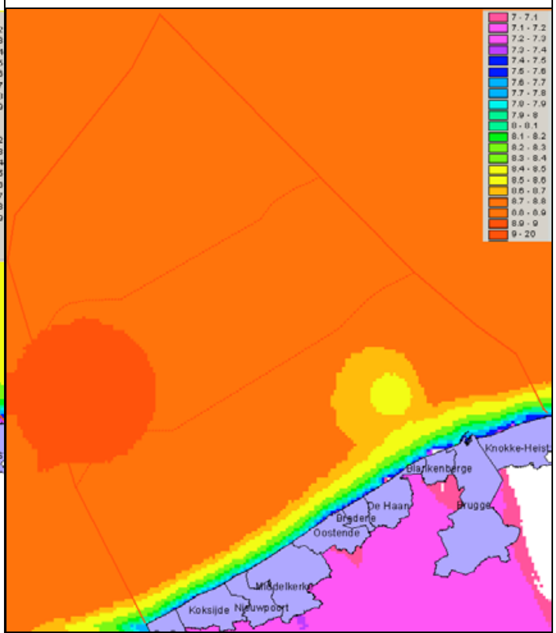
The wind resource map for the BPC has been calculated at a level of 60, 80 and 100 m. The selected grid size has mazes of 1 km x 1 km. The following values have been calculated for each altitude:

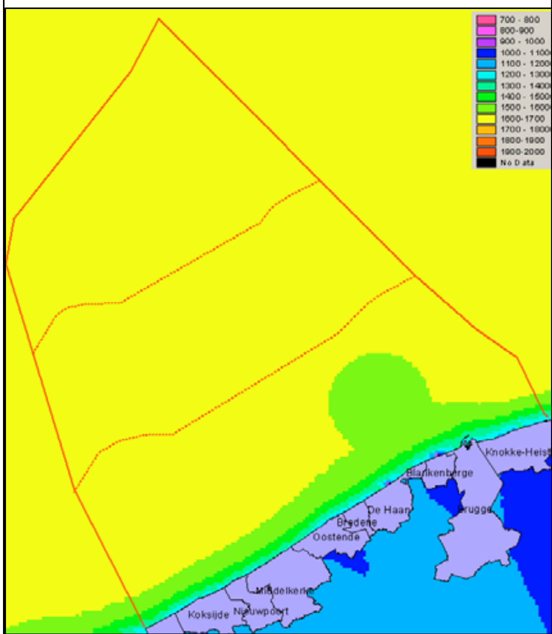
- Weibull parameters: A [m/s] and k
- Mean wind speed [m/s]
- Mean energy density [W/m²]
- Specific energy density [kWh/m²/jr]
- Sectoral distribution: Frequency [%] per sector of wind direction

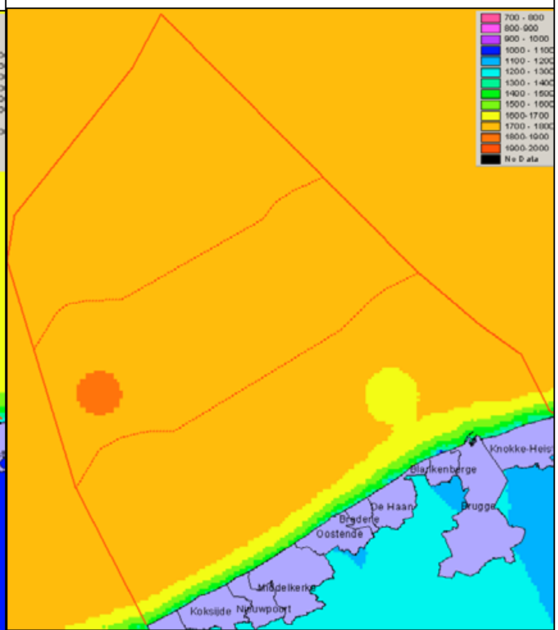
The values for each grid maze have been calculated taking into account their relative distance to the various measuring stations.

The preliminary results at the level of 60 m are depicted here below and in 5.3.2.5.

Figure 1 Wind resource at 60 m level.

Mean windspeed at 60 m [m/s], lower limit	Mean windspeed at 60 m [m/s], upper limit
	
Specific energy density [kWh/m²/jr] at 60 m, lower limit	Specific energy density [kWh/m²/jr] at 60 m, upper limit





3.3.5 Discussion and conclusions

The wind resource at the level of 60 m shows clearly the influence in the neighbourhood of the local measuring stations. There appears to be little variation in the wind resource over the entire surface of the BCP. Only in a narrow area close to the coast, the resource is lower.

In order to refine the calculations, the following actions will be taken in the next stage of the project:

- Input of new measuring stations from the Netherlands, France and UK
- Reduce the grid space (e.g. 250 m x 250 m)

3.4 Availability of High Voltage grid connection (Task 1.3)

3.4.1 Existing power system

Figure 2 shows the main existing power plants in Belgium. Figure 2 shows the 400kV, 220kV and 150kV high-voltage lines. There are three 150-kV nodes in the coastal region: Zeebrugge and Slijkens in the northeast and Koksijde in the southwest.

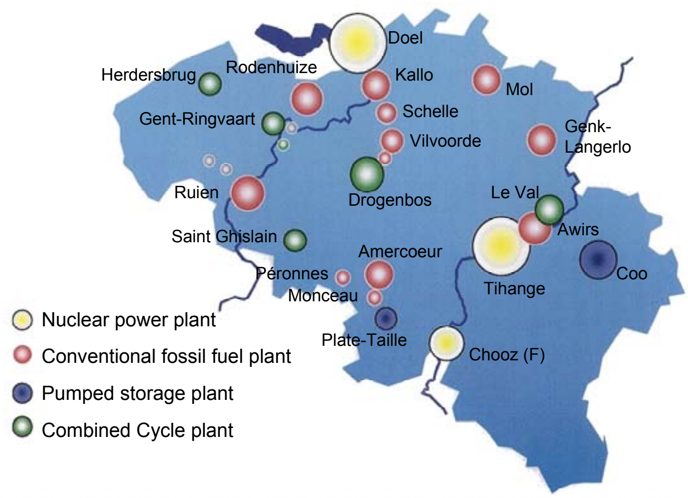


Figure 2 Main power plants of Belgium

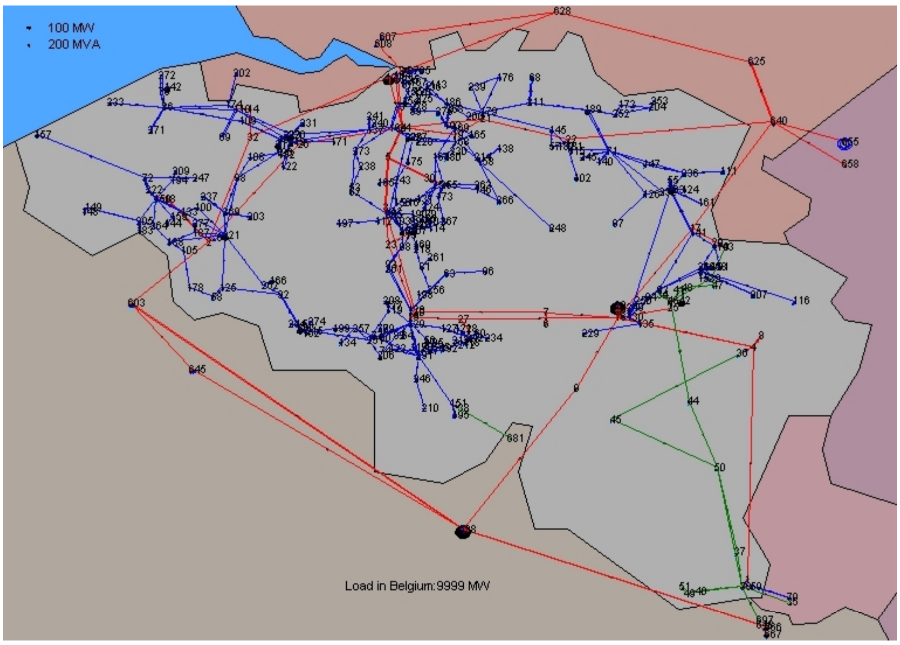


Figure 3 Belgian HV-grid (380, 220 and 150 kV)

With the power plants in Herdersbrug (460 MW), Gent-Ringvaart (460 MW), and Rodenhuize, there already is overcapacity in production in the northern part of Western Flanders, compared to the relatively light load. Also the largest Belgian wind farms until now are installed in Zeebrugge (7.4 MW) and Herdersbrug (8.4 MW). 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 4. Line overload problems are most likely to occur at the link between Rodenhuize and Heimolen, as will be explained in the calculation results.

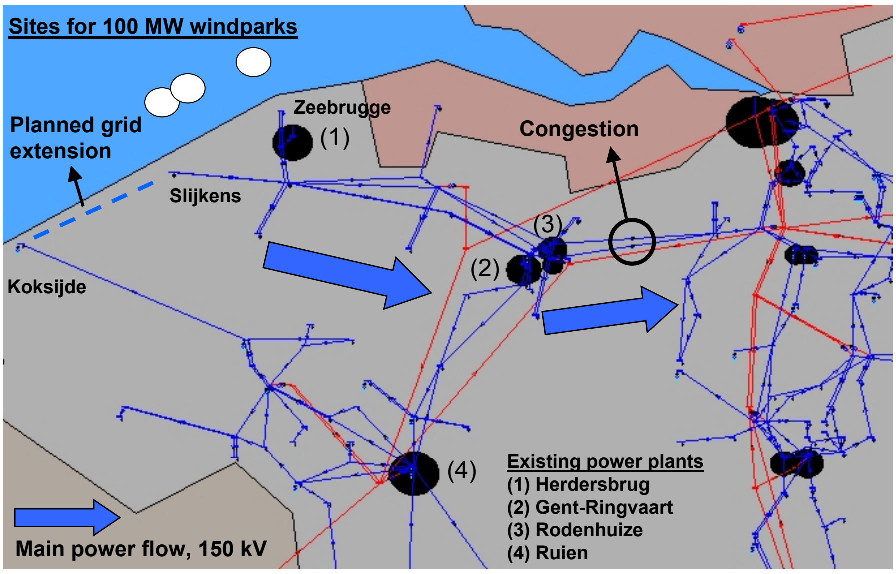


Figure 4 Main power flow on the 150 kV lines in Western Flanders

Static and dynamic simulations must be 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. Therefore the dynamic behaviour will be discussed in paragraph 3.5.2.

3.4.2 Static load flow calculations

3.4.2.1 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 380kV down to 70kV 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 4.

Table 4 Load levels of reference scenarios

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

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, 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. 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 sea-bed near Koksijde is not suited for constructing wind farms), 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.

3.4.2.2 Results

The results are presented in Tables 2 to 10 in 5.3.3. 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.

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.

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.

3.4.3 Investigation of factors limiting the potential in practice (Task 1.4)

A survey is made of the factors that are limiting the resource and as such are excluding areas for siting of wind farms. These factors are in general related to assignment of areas in the BCP for several economical and other activities such as traffic, extraction of sand, military exercises etc. In order to develop a tool for estimating quantitatively the influence on future wind farm development in the BCP, a distinction is made in 'hard' and 'soft' factors. The hard factors are the ones that cannot be changed by policy or planological decisions. The soft factors on the other hand are not per definition invariable. Quite often, the planological destination of specific areas is depending upon political or planological decisions. Some of these decisions have a 'temporary' nature. An example is the use of specific areas for military purposes.

An attempt will be made to quantify the influence on the wind resource in the investigation of the limiting factors. For this purpose an inventory is made of the potential policy measures that influence the soft factors. The estimation of the quantitative effect is made upon advice of stakeholders and authorities responsible for the activities. These activities include:

- 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.
- Shipping routes: The shipping routes are indicated on the maps with buoys. Traffic separation schemes are used to separate opposing streams. Besides these traffic lanes there are various other shipping routes for ships not bound by a separate traffic lane.
- Industrial waste sites: From the sixties onward the North-Sea was used for dumping of industrial waste. From 1989 the dumping of industrial waste was banned.
- Dumping site of war munition: After World War 1 the sand bank "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.
- Military excercices: Military shooting exercices are directed seawards from the military base of Lombardsijde on a regular basis. The excercises are announced and vessels are to stay out of the zone. A low helicopter flying zone is present as well.
- Cables and pipelines

Furthermore, restrictions can follow from the following

- Radar restrictions
- Air aviation and helicopter exercise area
- Important bird areas
- Fishery
- Ramsar sites
- Proposed special conservation areas
- Archeological sites

In 5.3.4 a map is given showing the present exclusion zones because of existing activities. Similar maps will be produced in Task 3, showing the exclusion but taking into account the dynamics of decisions on the use of the North Sea.

3.5 Calculation of technological options (Task 2)

3.5.1 Offshore wind farm technology (Task 2.1)

3.5.1.1 General

The activities for this subject actually have to be carried out in the second phase of the project. To make a start with the activities however, a summary has been made of the present state of the art in wind energy technology for offshore applications. The issues important for characterising the technology in two time windows (2005 and 2015) have been defined.

The expected technological evolutions are studied based on an international research and technological development overview. The data are collected from interviews with manufacturers, literature survey and attendance on dedicated workshops and symposia.

Based on the projected wind turbine characteristics, wind energy production simulations will be performed for the identified wind regimes of task 1.2.

3.5.1.2 Off-shore wind turbine design

Improved designs

The wind turbines in todates off-shore wind farms consist of "modified" on-shore design. However major developments in off-shore wind turbines technology are expected to bring completely new off-shore concepts. One of the major design drivers besides the reduced investment costs is the reliability of the technology. Improved designs could be achieved by means of the reduction of the number of components. Examples are gearless designs, passive blade pitch control.

It's likely that for far offshore wind farms the two bladed downwind wind turbine with high tip speed ratio's may have their second birth. Offshore concepts will include novel installation concepts, new concepts for electric conversion systems and power transportation systems, corrosion protection.

New generator concepts

In the last decade a number of new designs were introduced, which will probably will be the main line in the near future:

- The semi-variable speed using a double fed induction generator, allowing a 25% speed variation of the wind turbine rotor.
- The direct drive synchronous generator system. The rotor is directly connected to a low speed multipole generator, avoiding the need for using a gearbox and in this way reducing the amount of mechanical components.
- The direct drive system high voltage generator, which consists of a variable speed rotor with permanent magnets. The 20 kV voltage is converted to direct current by means of diodes. The wind turbines will be connected in groups and the power will be transmitted to the grid without the need for a transformer.

Increased installed capacity per unit

The drive towards larger machines is of course also determined by cost aspects:

- Waves are the most important factors determining the required strength and weight of offshore foundations for wind turbines. Consequently it is far more economic to use larger wind turbines, since the size and costs of foundations do not increase in proportion to the size of the wind turbine.
- Another important cost factor is grid connection. Here, it is obviously far cheaper to attach fewer turbines to the grid for a given wind farm size.
- Larger machines save money on maintenance, since the number of units that have to be visited by boat will be smaller.

Further upscaling of wind turbines is a possibility, although the logistics of handling such large units on land have already become quite difficult. Tower diameters should preferably not exceed 4.2 or 4.4 metres, if they are to be transported in normal sections by road or rail. Manufacturers and customers alike would also like to use machines which have been thoroughly tested on land, before moving out to sea.

3.5.1.3 Enhanced controllability of wind farms

The integration of wind power in the grid can be improved by enhancing the control possibilities of wind farms. In order to improve controllability, more effort will be spent in short term prediction of wind power and in development of control strategies which allow wind farms to participate in electrical network management. This aspect is very crucial in the future characterisation of the technology.

3.5.1.4 Concepts for installation, operation & maintenance

The industry will develop dedicated solutions for installation of offshore wind turbines, taking advantage in the most favourable way of equipment for other offshore construction activities. Operation and maintenance practices will be aimed at maximizing the availability of the wind farm.

The technology review will include projected characterisations of future development in this area.

3.5.2 Electrical interconnection and grid-connection schemes (Task 2.2)

As defined in the project timing schedule, the research for electrical interconnection schemes will be the main task for the second year of the project.

The electrical interconnection schemes determine the dynamic behaviour of the system. Therefore, dynamic simulations are used to investigate the systems stability in case of a disturbance (such as a change in wind speed or a short circuit on a line).

An evolution in grid connection requirements for wind farms must be noted. Until recently, wind turbines were considered as 'negative loads', free to switch on and off according to the wind turbine operator's decision. But in the near future, wind turbines will be held responsible (together with conventional generators) not only for the production of active energy, but also for the provision of ancillary services such as voltage support and frequency control. This is already the case in Germany and Denmark. Also in this project study, importance has been attached to the expected connection requirements for a wind turbine.

To investigate stability issues, a more detailed model of the Belgian HV-grid, especially in the region of Western Flanders is implemented in Eurostag, containing also the dynamic data of the main generators (e.g. in Herdersbrug). Some dynamic data, such as the setings of security relays, are not available, but are based on educated guesses.

Both type of wind turbine and the type of grid connection scheme have a large impact on the stability and the power quality.

It is believed that in the near future (2005), induction generators and doubly-fed induction generators will be the main generator type for wind energy. On a longer term, direct-drive synchronous generators will gain more importance. Innovative generator types, such as switched reluctance generators, have been the subject of academic research during the last ten years, but are still very uncertain about any commercial applications in the wind energy sector.

Own models for several types of wind turbines have been developed and are used to perform dynamic simulations, to evaluate the grid impact. These models contain an aerodynamical model of the wind turbine, a mechanical model of the shaft and an accurate electrical model of the generator. Also the control schemes, if applicable for the generator type, are included in the model. The control schemes are designed to cope as much as possible with innovative connection requirements such as voltage control capability. Figure 13 and Figure 14 in par. 5.3.5 show model layouts for an induction and a doubly fed induction generator.

Models of grid interconnections schemes, such as HVDC, and optionally FACTS, are pre-defined in the library of Eurostag, and can be used and evaluated to investigate the influence of the grid interconnection scheme.

Extensive simulations of case studies in the Belgian grid will be the subjects of further work. As an example, the connection of a 20 MW wind farm with 8 induction generators by a 150 kV, 30 km sea-cable to Zeebrugge has been simulated. Figure 15 and Figure 16 show the impact of a wind speed change from (10 to 15 m/s at t = 1500 s and back to 12 m/s at t = 1600 s) on the voltages at the wind park (node 'Zee'), Zeebrugge and Brugge. In the first case the voltage is not controlled in any way. In the second case the grid voltage is controlled by the dynamic voltage regulator of the generators in Herdersbrug. It is seen that these voltage regulators can cancel out most of the disturbances due to a change in wind speed. However the exact limits of stability and power quality detoriation have yet to be investigated.

4 Future prospects and future planning

The future planning (as evaluated from mid-term of the project) coincides in general with the original planning as described in the project proposal.

In the following a number of issues are mentioned which remain to be considered for the specific subtasks of Task 1 (Survey of the resources) of the project:

Geotechnical

- Determination of the gaps in the geological, geotechnical, sediment- and morphodynamical knowledge.
- Fine tuning of site selection criteria, taking into account technological parameters of offshore constructions

Wind resources

- Add more measuring stations and adjust wind resource map borders to existing maps of neighbouring countries (Netherlands, France, UK)
- Refine the calculation grid (smaller mazes)

Other limiting factors

- Finalise the task as described in paragraph 3.4.3.

5 Annexes

5.1 References

The references as to the geotechnical study are given in Annex 1 (separate document).

For the other parts of the report no specific references are given in the intermediate report. The references will be part of the specific technical reports.

5.2 Publications

Le Bot, S., Van Lancker, V., Deleu, S., De Batist, M. & Henriet, J.P. (2003). Lithostratigraphy and geometry of Eocene and Quaternary deposits onto the Belgian continental shelf. Applications and limitations for the definition and classification of suitable sites for offshore wind farm implantation. Integrated Land-Sea Stratigraphy, 9-11 april 2003, Utrecht, The Netherlands.

5.3 Detailed results

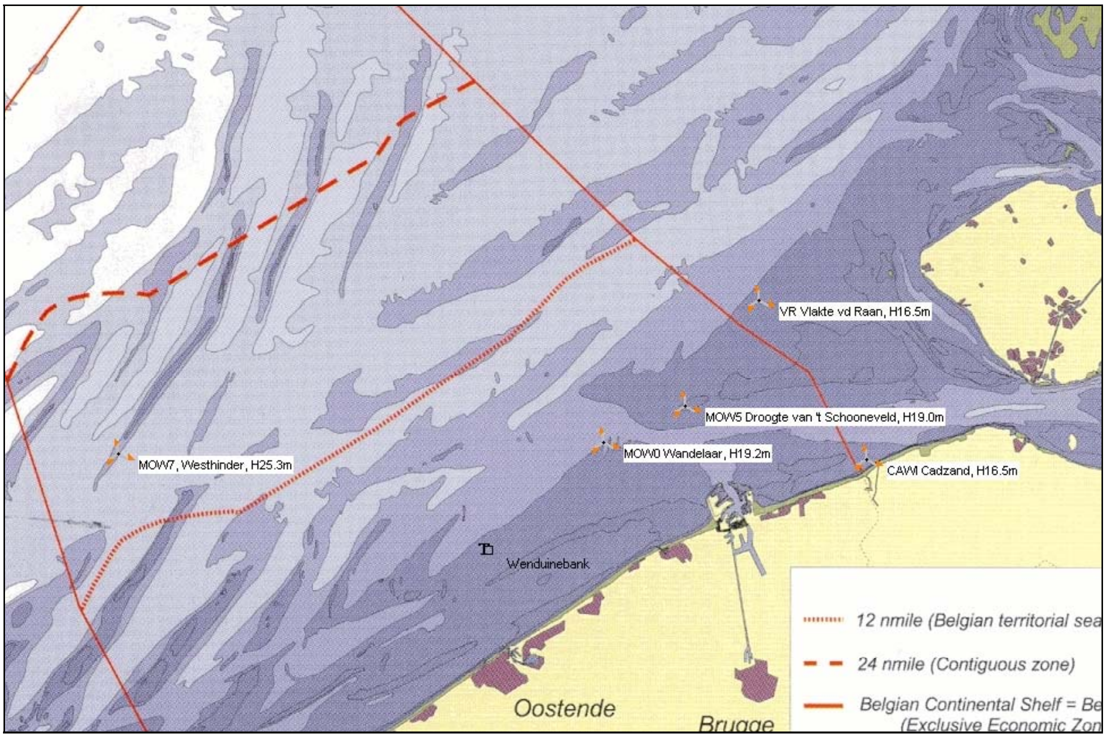
5.3.1 Geotechnical study

The detailed results of the geotechnical study are described in a separate document (Annex 1).

5.3.2 Wind resources

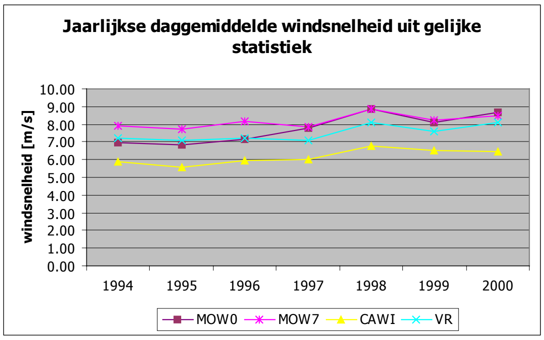
5.3.2.1 Position of the available wind measuring stations

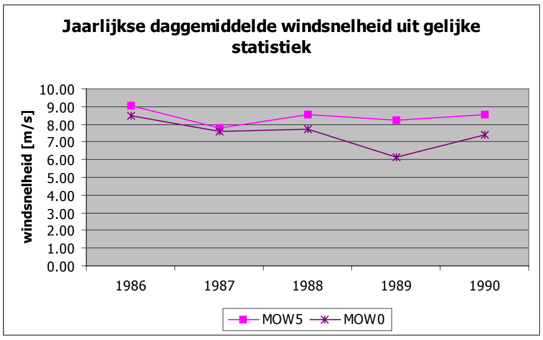
Figure 5 Position of wind measuring stations used for the calculation



5.3.2.2 Reliability of the data

Figure 6 Yearly mean wind speed for the data of common statistics



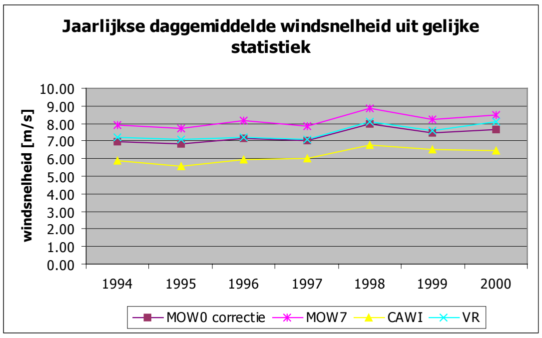


The figures above show the yearly mean wind speed for the five measuring stations, for the common statistics (the periods for which all stations were available).

The curves of Westhinder, Cadzand and Vlakte van de Raan are parallel (left figure). Data of measuring station Wandelaar (MOW0) has been rejected for the period of 1-1-95 til 30-6-95. After filtering, the data of Wandelaar has good mean values for the years 1994 and 1996, but from 1997 on, the mean yearly wind speed of Wandelaar tends to the mean yearly wind speed of Westhinder, which is not acceptable.
Therefore, a correction factor has been calculated for the measuring data of MOW0. The result is shown in the Figure 7.

Months June 1986, October and December 1987, March 1990 of measuring station Wandelaar have been filtered because of too high mean wind speed. The right figure shows the ratio between Wandelaar en Droogte van 't Schooneveld (MOW5). The yearly mean wind speed of MOW0 is always significant lower than the yearly mean wind speed of MOW5 (except for the year 1987), although both measuring stations are located at almost the same distance from the coast (7.7 km) and both have an identical measuring height (19 m).

Figure 7 Yearly mean wind speed for the data of common statistics, after correction for MOW0



5.3.2.3 Cross checks

Cross check calculations have been executed for the five measuring stations. This means that the measuring data of each station have been used to predict the wind climate at the position of the other stations. The gap between the predicted and the measured mean wind speed is an indication for the accuracy of the used data and the extrapolation method. For the Wandelaar, the corrected and filtered data series is used.

Westhinder and Droogte van 't Schooneveld result in an over-estimation of the wind climate at the other stations. Wandelaar, Cadzand and Vlakte van de Raan generate a reliable estimation of the wind climate at each others position.

For the calculation of the wind resource in the BPC, this conclusion will be taken in account.

Table 5 Cross checks

	MOW7	MOW0	MOW5	CAWI	VR
MOW7		+	=	+	+
MOW0	-		-	=	=
MOW5	=	+		+	+
CAWI	-	=	-		=
VR	-	=	-	=	

5.3.2.4 Calibration

The anemometers (type WAA151 of Vaisala) are not specially calibrated in order to perform reliable wind measurements. The measuring range of the anemometers is between 0.4 m/s and 75 m/s. The standard calibration done by the manufacturer (Vaisala) is given. The most important relative fault occurs at low wind speeds.

For the calculations of the wind resource, the standard calibration curve of the manufacturer will be taken in account.

5.3.2.5 Wind resource at 60 m level

Figure 8 Mean windspeed at 60 m [m/s], lower limit

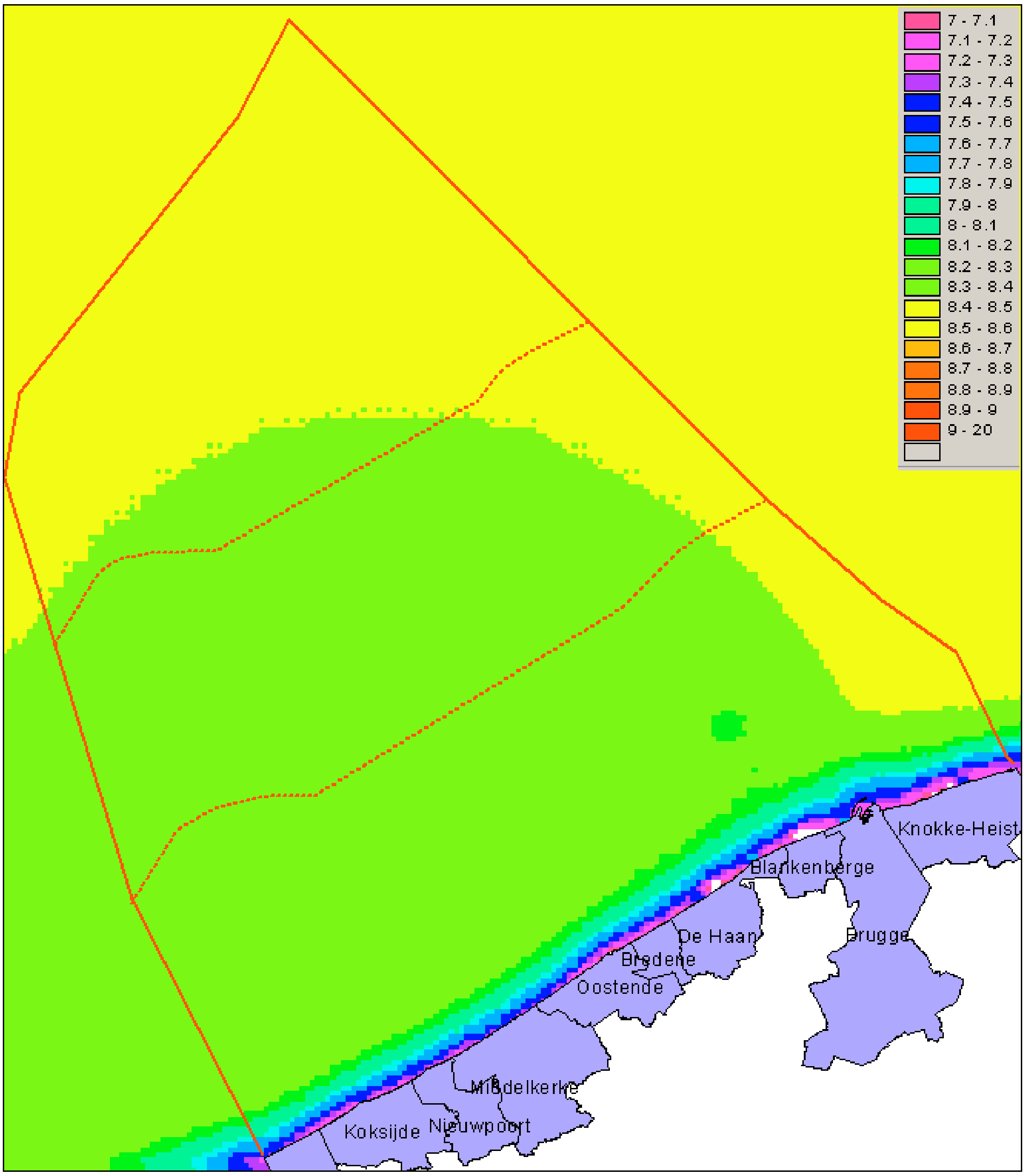

7 - 7.1
7.1 - 7.2
7.2 - 7.3
7.3 - 7.4
7.4 - 7.5
7.5 - 7.6
7.6 - 7.7
7.7 - 7.8
7.8 - 7.9
7.9 - 8
8 - 8.1
8.1 - 8.2
8.2 - 8.3
8.3 - 8.4
8.4 - 8.5
8.5 - 8.6
8.6 - 8.7
8.7 - 8.8
8.8 - 8.9
8.9 - 9
9 - 20
Knokke-Heist
Blankenberge
Brugge
De Haan
Bredene
Oostende
Middelkerke
Koksijde
Nieuwpoort

Figure 9 Mean windspeed at 60 m [m/s], upper limit

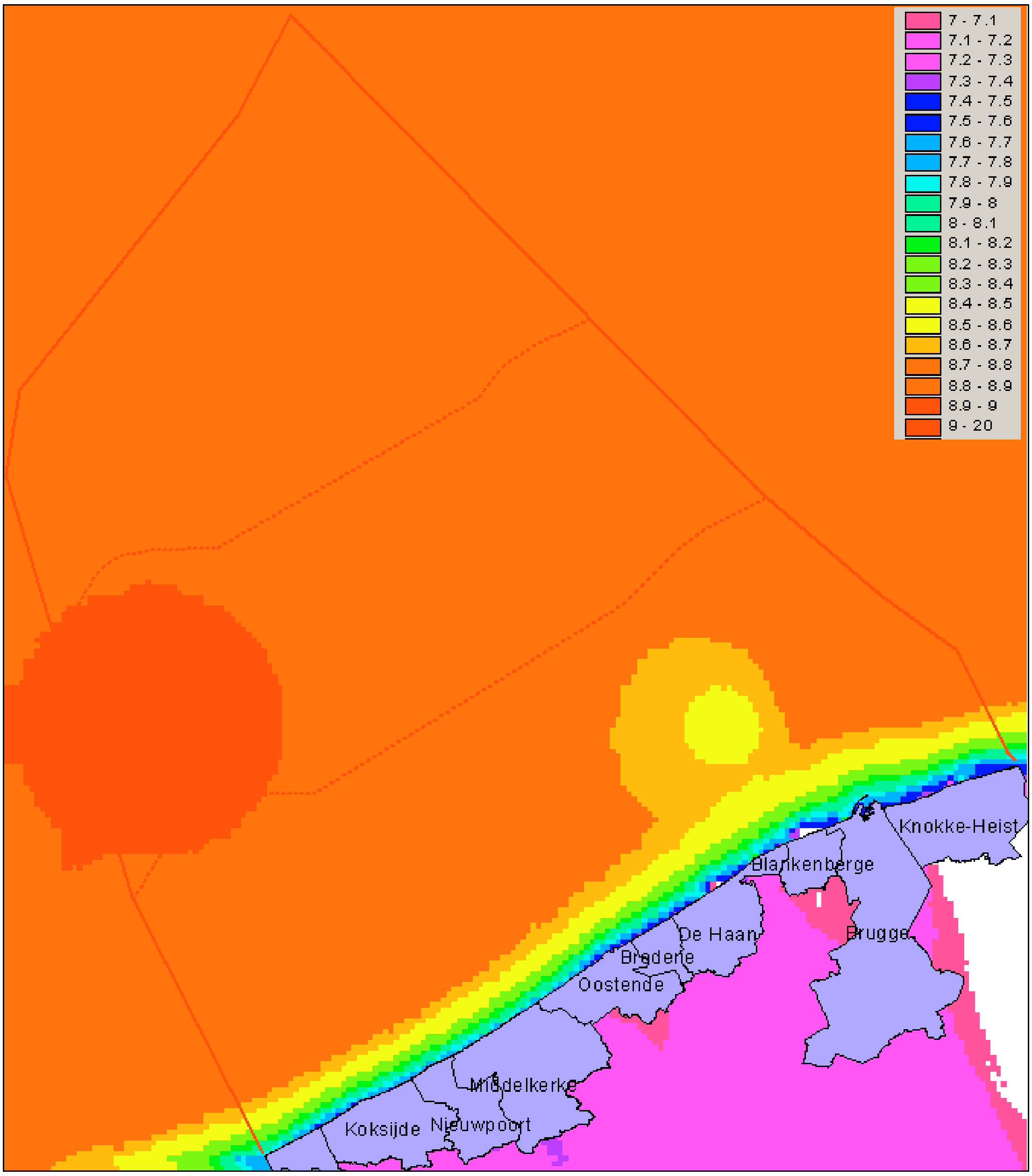
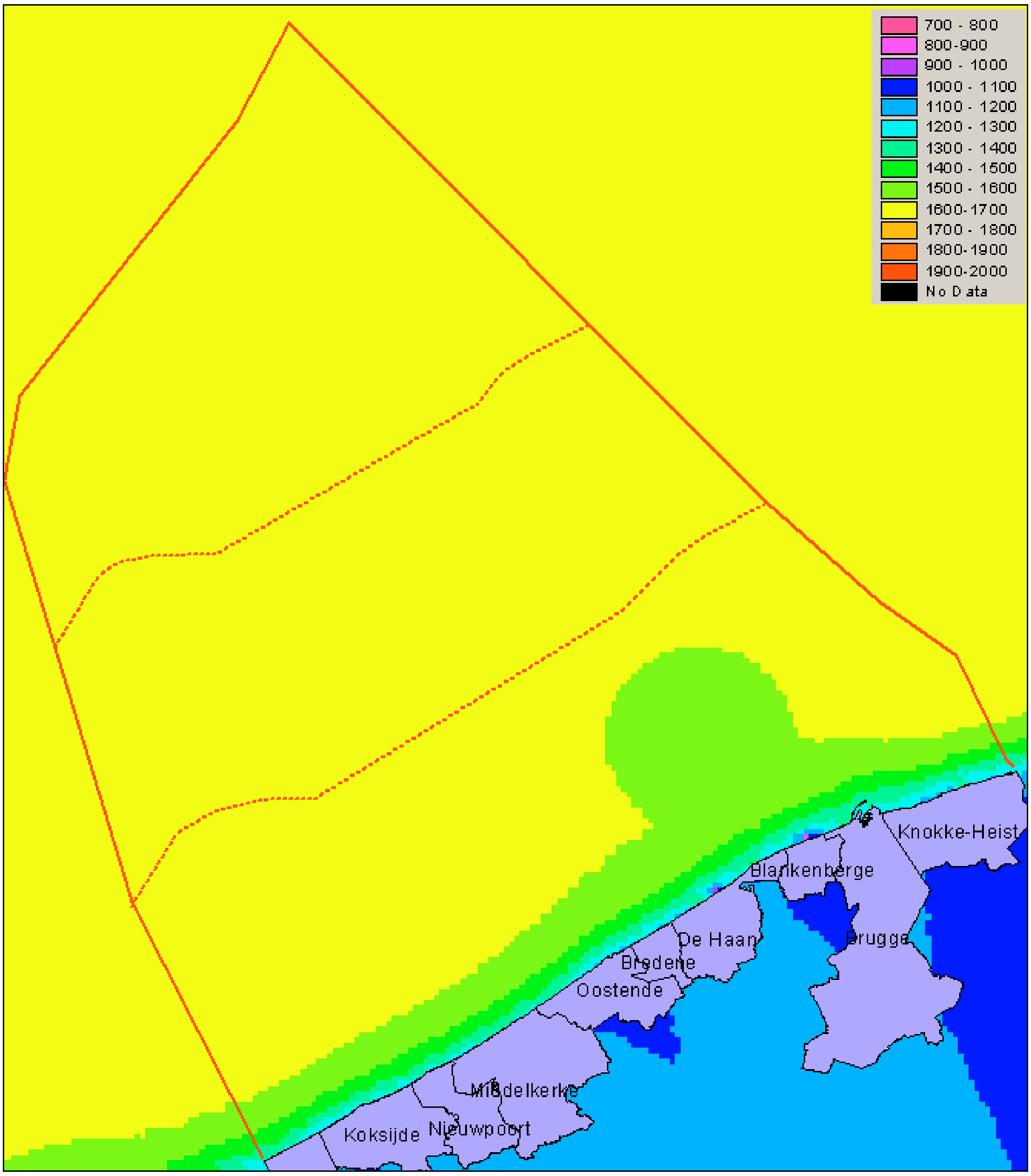
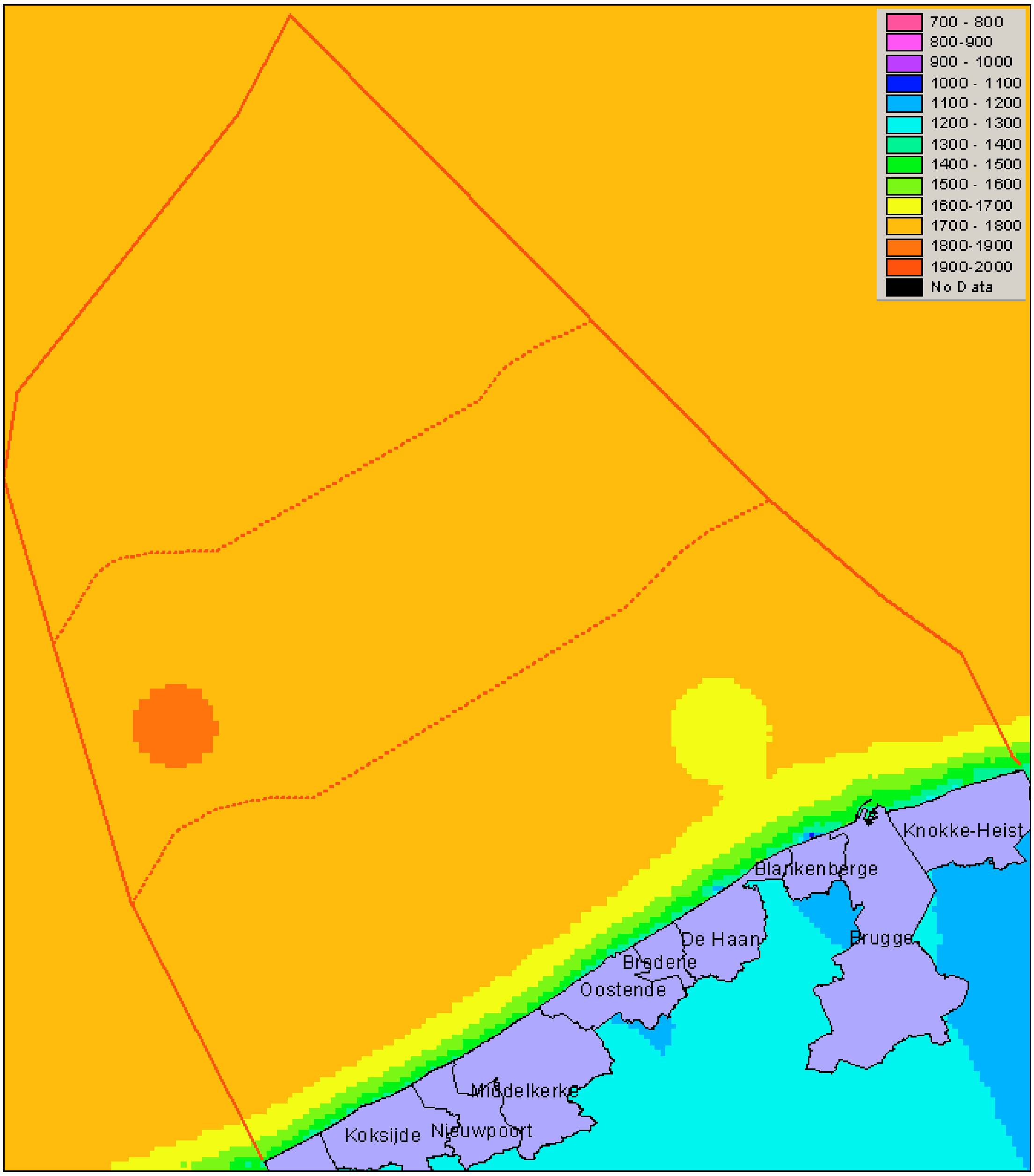

7 - 7.1
7.1 - 7.2
7.2 - 7.3
7.3 - 7.4
7.4 - 7.5
7.5 - 7.6
7.6 - 7.7
7.7 - 7.8
7.8 - 7.9
7.9 - 8
8 - 8.1
8.1 - 8.2
8.2 - 8.3
8.3 - 8.4
8.4 - 8.5
8.5 - 8.6
8.6 - 8.7
8.7 - 8.8
8.8 - 8.9
8.9 - 9
9 - 20
Knokke-Heist
Blankenberge
De Haan
Brugge
Bredene
Oostende
Middelkerke
Koksijde
Nieuwpoort

Figure 10 Specific energy density [kWh/m²/jr] at 60 m, lower limit



700 - 800
800-900
900 - 1000
1000 - 1100
1100 - 1200
1200 - 1300
1300 - 1400
1400 - 1500
1500 - 1600
1600-1700
1700 - 1800
1800-1900
1900-2000
No Data
Knokke-Heist
Blankenberge
Brugge
De Haan
Bredene
Oostende
Middelkerke
Koksijde
Nieuwpoort

Figure 11 Specific energy density [kWh/m²/jr] at 60 m, upper limit


700 - 800
800-900
900 - 1000
1000 - 1100
1100 - 1200
1200 - 1300
1300 - 1400
1400 - 1500
1500 - 1600
1600-1700
1700 - 1800
1800-1900
1900-2000
No Data
Knokke-Heist
Blankenberge
De Haan
Brugge
Bredene
Oostende
Middelkerke
Koksijde
Nieuwpoort

5.3.3 Grid study

5.3.3.1 Results for Slijkens

Table 6 Maximum power injection in Slijkens, summer scenarios, before overload

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 7 Maximum power injection in Slijkens, intermediate 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 8 Maximum power injection in Slijkens, winter 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 9 Maximum power injection in Zeebrugge, summer 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 10 Maximum power injection in Zeebrugge, intermediate 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 11 Maximum power injection in Zeebrugge, winter 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

5.3.3.2 Results for Zeebrugge plus Slijkens

Table 12 Maximum power injection in Slijkens and Zeebrugge, summer scenarios, before overload

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 13 Maximum power injection in Slijkens and Zeebrugge, intermediate 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 14 Maximum power injection in Slijkens and Zeebrugge, winter 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

5.3.4 Limiting factors

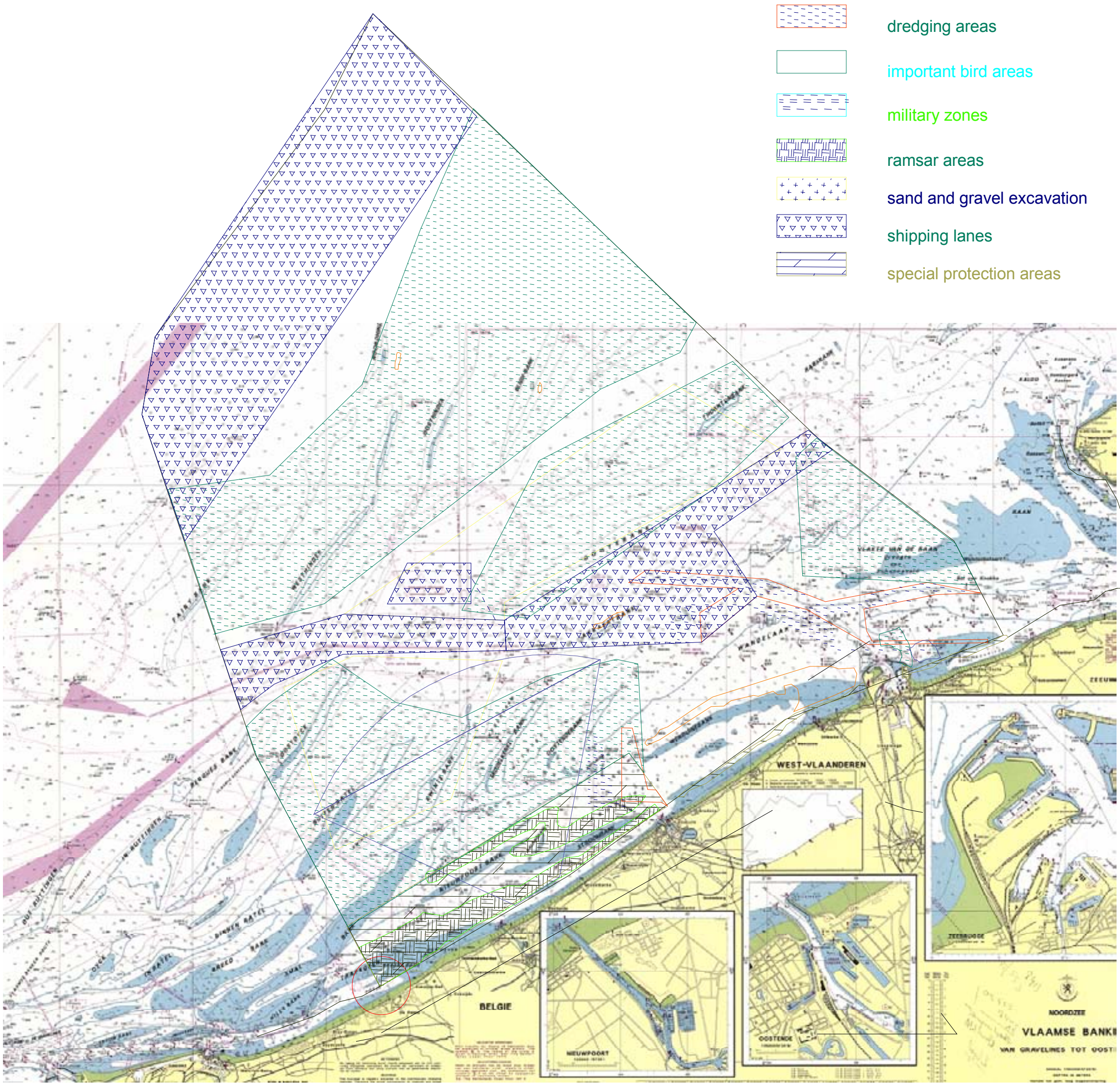


Figure 12 Areas in the BCP where restrictions exist as to the implementation of offshore windfarms.

5.3.5 Interconnection

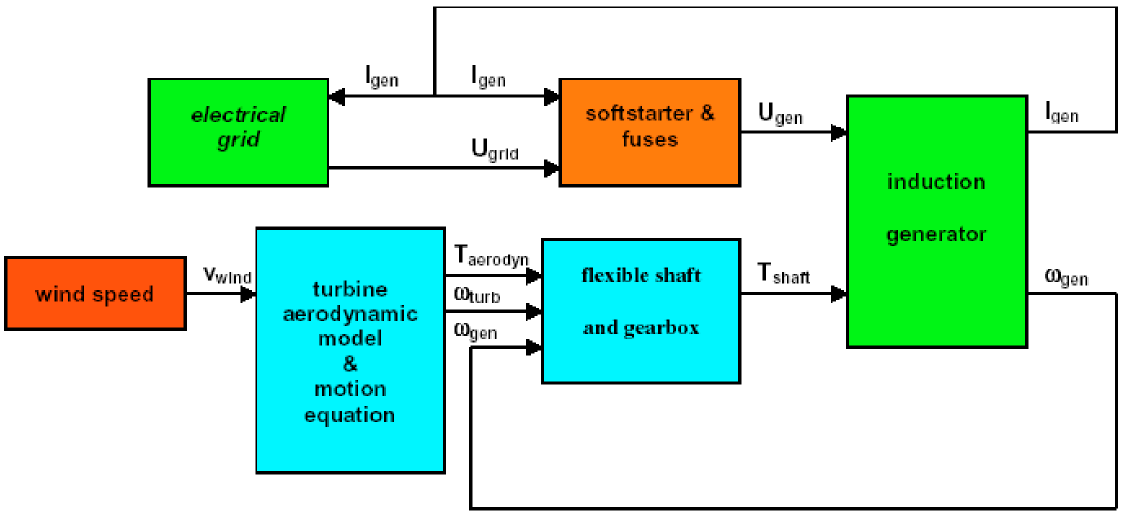


Figure 13 Block diagram model of a wind turbine with induction generator

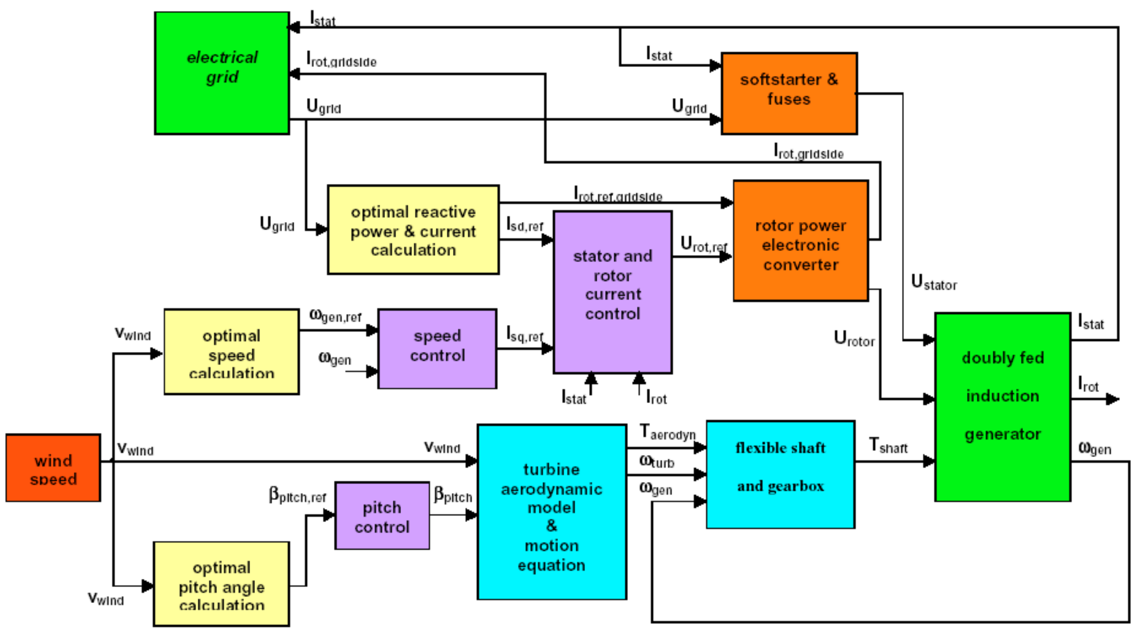


Figure 14 Block diagram model of a wind turbine with doubly fed induction generator

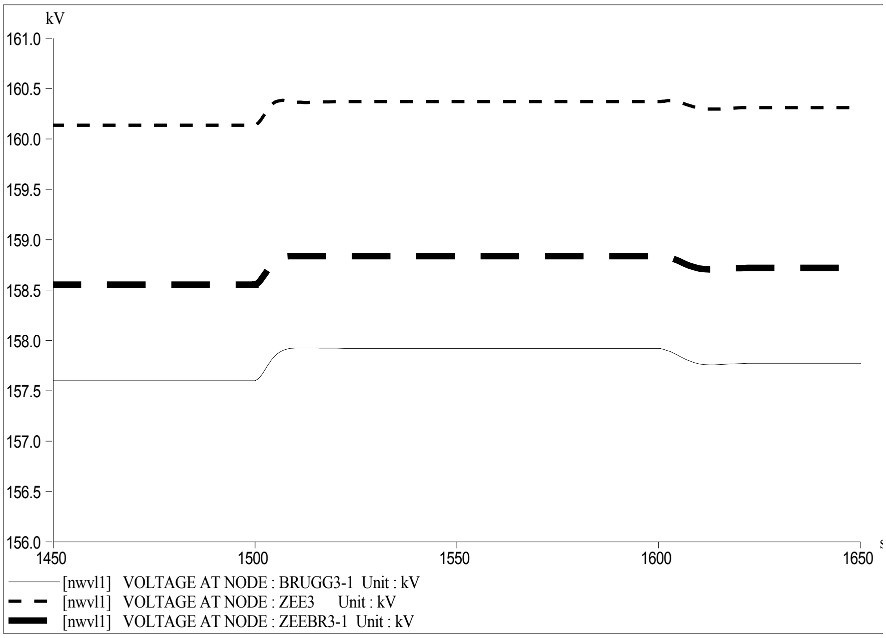


Figure 15 Voltage at Zeebrugge, Brugge and a 20MW offshore wind farm (Zee), without voltage regulation

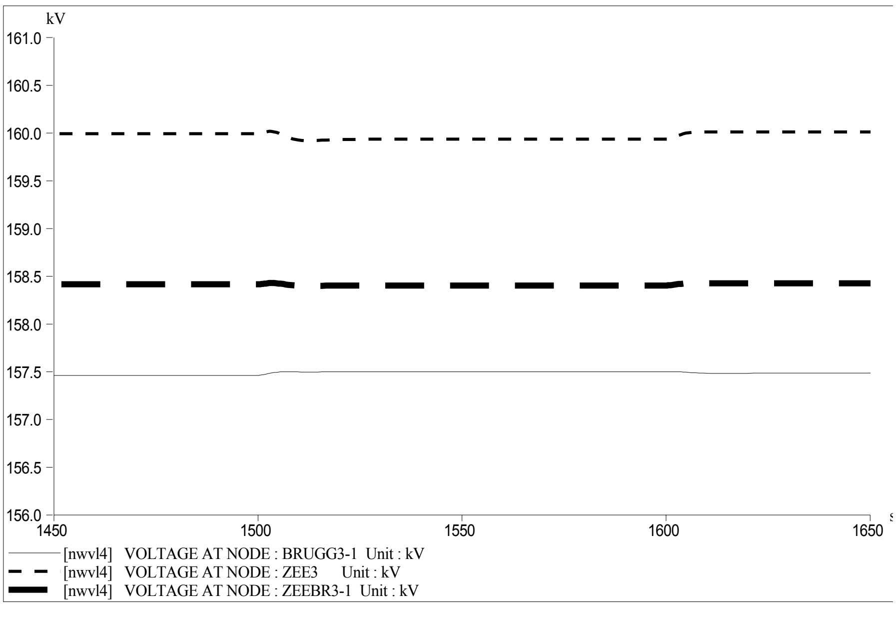


Figure 16 Voltage at Zeebrugge, Brugge and a 20 MW offshore wind farm (Zee), with voltage regulation in Herdersbrug