Opti-OWECS Final Report Vol. 0:

Structural and Economic Optimisation of Bottom-Mounted Offshore Wind Energy Converters - Executive Summary

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Abstract

It was the particular mission of the project ‘Structural and Economic Optimisation of Bottom-Mounted Offshore Wind Energy Converters’ (Opti-OWECS) to extend the state-of-the-art, to determine required methods and to demonstrate practical solutions which will significantly reduce the electricity cost. This will facilitate the exploitation of true offshore sites on a commercial base in a medium time scale of 5 to 10 years from now.

In several fields, e.g. support structure design, installation of the offshore wind energy converters, operation and maintenance, dynamics of the entire offshore wind energy converter, structural reliability considerations, etc., the study demonstrated new propositions which will contribute significantly to a mature offshore wind energy technology. This was achieved due to a smooth cooperation of leading industrial engineers and researchers from the wind energy field, offshore technology and power management.

Moreover, an innovative design methodology devoted particularly to offshore wind energy conversion systems (OWECS) was developed and successfully demonstrated. The so-called ‘integrated OWECS design approach’ considers the components of an offshore wind farm as parts of an entire system. Therefore interactions between sub-systems are considered in a complete and practical form as possible so that the design solution is governed by overall criteria such as: levelised production costs, adaptation to the actual site conditions, dynamics of the entire system, installation effort as well as OWECS availability.

Furthermore, a novel OWECS cost model was developed which led among other work of the project to the identification of the main cost drivers, i.e. annual mean wind speed, distance from shore, operation and maintenance aspects including wind turbine reliability and availability. A link between these results and a database of the offshore wind energy potential in Europe, developed by the previous Joule project JOUR 0072, facilitated the first estimate of energy cost consistent over entire regions of Northern Europe.

The European Commission has supported the project in the scope of the framework of the Non Nuclear Energy Programme JOULE III (Research and Technical Development) under grant JOR3-CT95-0087.

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1. Background

Rationale for offshore wind energy

With world attention now focused on the damaging impact of greenhouse gases, wind energy is emerging as one of the few serious contenders for the large-scale generation of cost-effective, clean energy. The case for wind energy has been much strengthened in recent years by the significant cost reductions of wind generated electricity together with the substantially improved reliability of modern wind turbines. There is, however, an important and growing problem, which appears to be constraining further exploitation of wind energy in parts of Europe. Limitations on land use in areas where high population density is high, are beginning to slow down the installation of new wind farms. It is conceivable that in some countries in Northern Europe, public acceptance of onshore wind power projects will eventually reach saturation point in the future. Then the exploitation of the huge offshore wind resources, will considerably less environmental impact than onshore wind farms, will become crucial in providing for future energy needs.

Recent developments and perspectives

The attitude towards offshore wind energy has changed significantly in the last few years. The European Union’s White Paper proposes that 12% of energy within the European Union should be provided by renewables by the year 2010, with possibly a installed wind energy capacity of 40 gigawatt. It is unlikely all this can be accommodated onshore, but a previous study, supported by the European Joule programme, showed that we do have large offshore wind resources.

Several Northern European countries have firm plans for the installation of large offshore wind farms (each larger than 100 megawatt) along the lines of the current generation of megawatt wind turbines. For the more distinct future, plans have been developed for offshore wind farms in the gigawatt range. It is imaginable that the installed capacity of offshore wind power plant may eventually amount to several times that installed on land.

State-of-the-art of the technology

Between 1991 and 1996 the first small-scale offshore wind farms rated 2 to 5 (17) megawatt were installed in sheltered waters in Northern Europe. These prototypes operate well; nonetheless, the economics are often poor and direct extrapolation to a larger scale is regarded not promising.

Therefore the expectation is often stated that large plant comprising large (multi-)megawatt units will cut down the prices and facilitate the exploitation of the enormous potential of offshore wind energy in Europe. However, so far it has been unclear how the success of wind energy on land should be combined with the large experience of the offshore oil and gas industry to come to such a mature offshore wind energy technology.

2. Opti-OWECS project in a nutshell

2.1. Scope of the project

In the scope of the framework of the Non Nuclear Energy Programme JOULE III (Research and Technical Development) the European Commission supported the project ‘Structural and Economic Optimisation of Bottom-Mounted Offshore Wind Energy Converters’ (Opti-OWECS) under grant JOR3-CT95-0087 from January 1996 to December 1997.

Objectives of the Opti-OWECS project

The particular mission of the Opti-OWECS project was to extend the state-of-the-art, to determine required methods and to demonstrate practical solutions, which significantly reduced the electricity cost. This will facilitate the commercial exploitation of true offshore sites in a medium time scale of 5 to 10 years from now.

The specific objectives included:-
- A cost estimate and comparison of offshore wind energy converters of different sizes and different design concepts.
- An estimate of the cost per kWh of offshore wind energy at sites in different regions of the European Union.
- Development of methods for the simultaneous structural and economic optimisation of offshore wind energy converters with due considerations of the site characteristics.
- At least one typical design solution for a bottom-mounted offshore wind energy conversion system (OWECS).

Partnership

The project was an international cooperation of leading industrial engineers and researchers from the wind energy field, offshore technology and power management.
The group of participants was as follows:-

- Institute for Wind Energy (IvW), Delft University of Technology (coordinator)

  Dutch research group active since more than 20 years in various fields of wind energy applications including major offshore wind energy research since 1992.

- Kvaerner Oil & Gas, Ltd. (KOGL)

  Major engineering and construction company, settled in the United Kingdom, with an established track record for implementing innovative concepts for offshore oil and gas developments.

- Kvaerner Turbin AB (KT)

  Swedish wind turbine manufacturer with expertise in the design of multi-megawatt machines (since the 1970s) and participant in another large study on offshore wind energy (1991).

- Renewable Energy Centre, University of Sunderland (US)

  British research group involved in techno-economic studies of renewable energy sources since 1978 among two major projects on wind energy costs.

- Workgroup Offshore Technology (WOT), Delft University of Technology

  Dutch research group with particular expertise in fluid loading of offshore structures and probabilistic methods, maintaining good relations with Shell Research Rijswijk.

- Energie Noord West (ENW) (sub-contractor)

  Dutch utility supplying 600,000 households in North-Holland and operating wind farms since more than 12 years among which the first Dutch offshore plant (Lely, 1994).

2.2. Work programme and final reporting

Work programme

The project continued the previous work in the scope of JOUR 0072 and makes use of recent developments in wind engineering and offshore technology. The study considered the most feasible and the most probable concepts for the near future i.e. horizontal axis wind turbines rated approx. 1 - 3 MW and erected on bottom-mounted support structures in the Baltic or the North Sea.

The work content of the project comprised three consecutive major tasks:-

- Task 1 Identification

  The main cost drivers of offshore wind energy were identified and the base case concepts and the reference sites were selected.

- Task 2 Development

  The economic and structural optimisation and improved design methods were developed in three parallel tasks. A cost model for manufacturing, installation and operation and maintenance of offshore wind farms was compiled. Design concepts for all main sub-systems, i.e. wind turbine, support structure, grid connection and operation and maintenance aspects, were investigated and the best combination for a certain sites was selected. Also particular design methods for OWECS such as structural reliability considerations and overall dynamics of OWEC were new developed or extended.

- Task 3 Integration

  In the final phase the work of the former tasks was integrated and the relationships between them were fully considered. The achieved progress was demonstrated in a typical design solution for OWECS. Moreover, energy costs at different European sites or regions were estimated in a consistent manner.

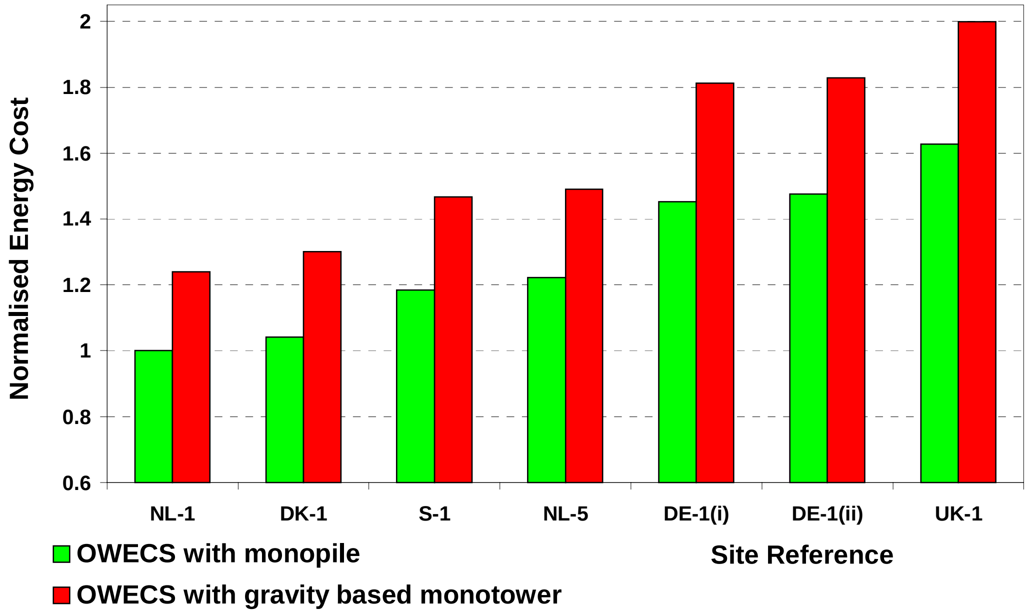
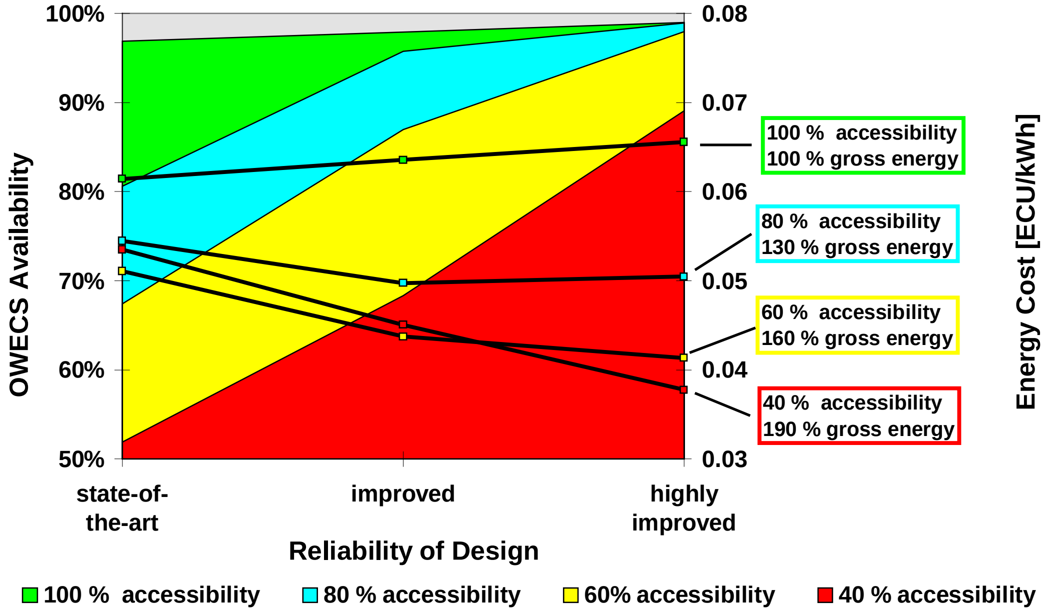


Figure 4: Comparison of energy cost for different sites and support structure concepts with the OWECS cost model



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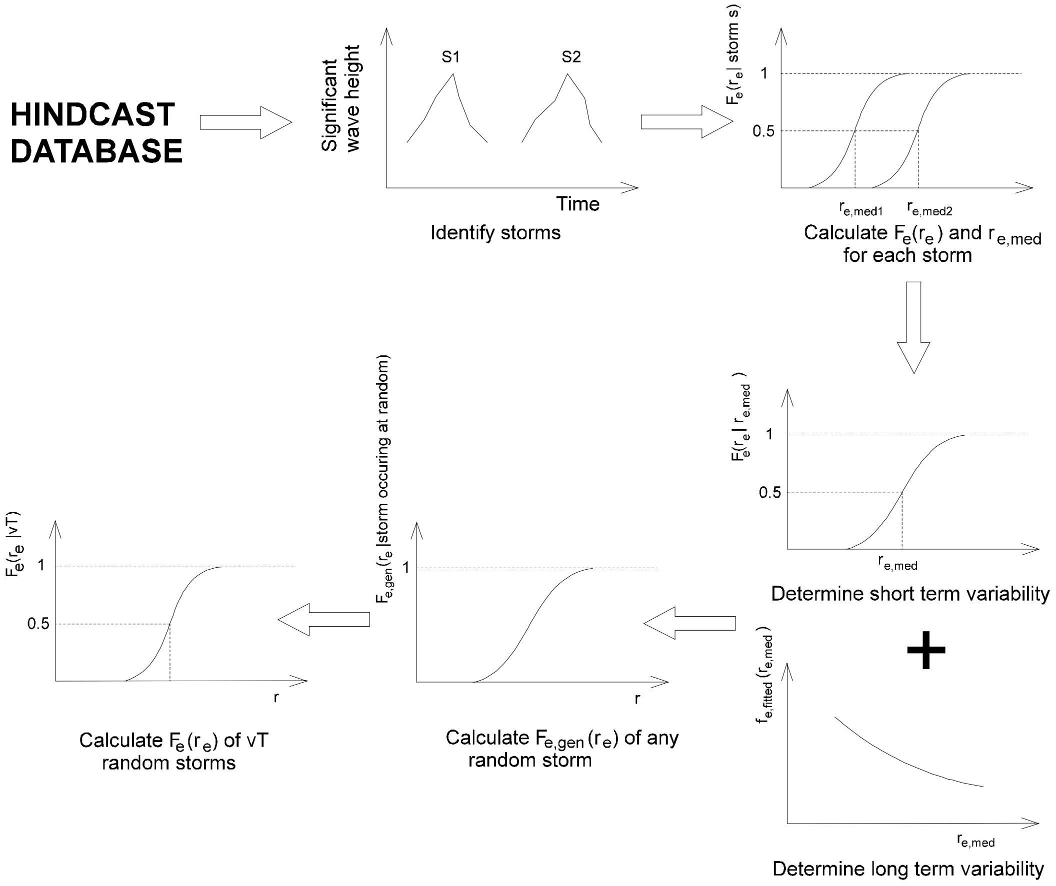

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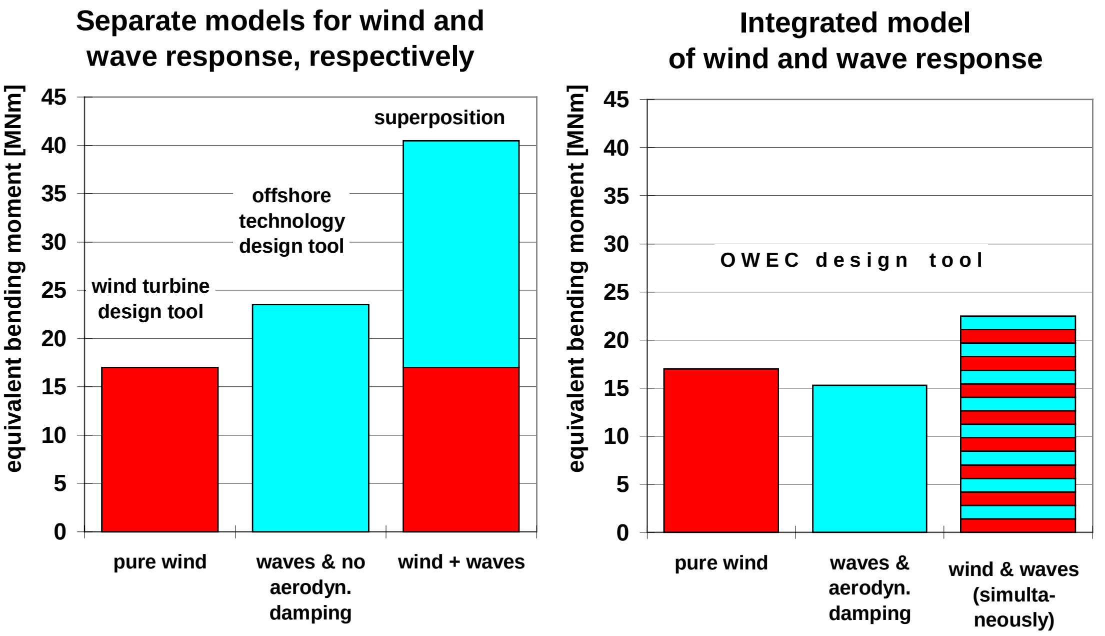
Separate models for wind and wave response, respectively

Integrated model of wind and wave response

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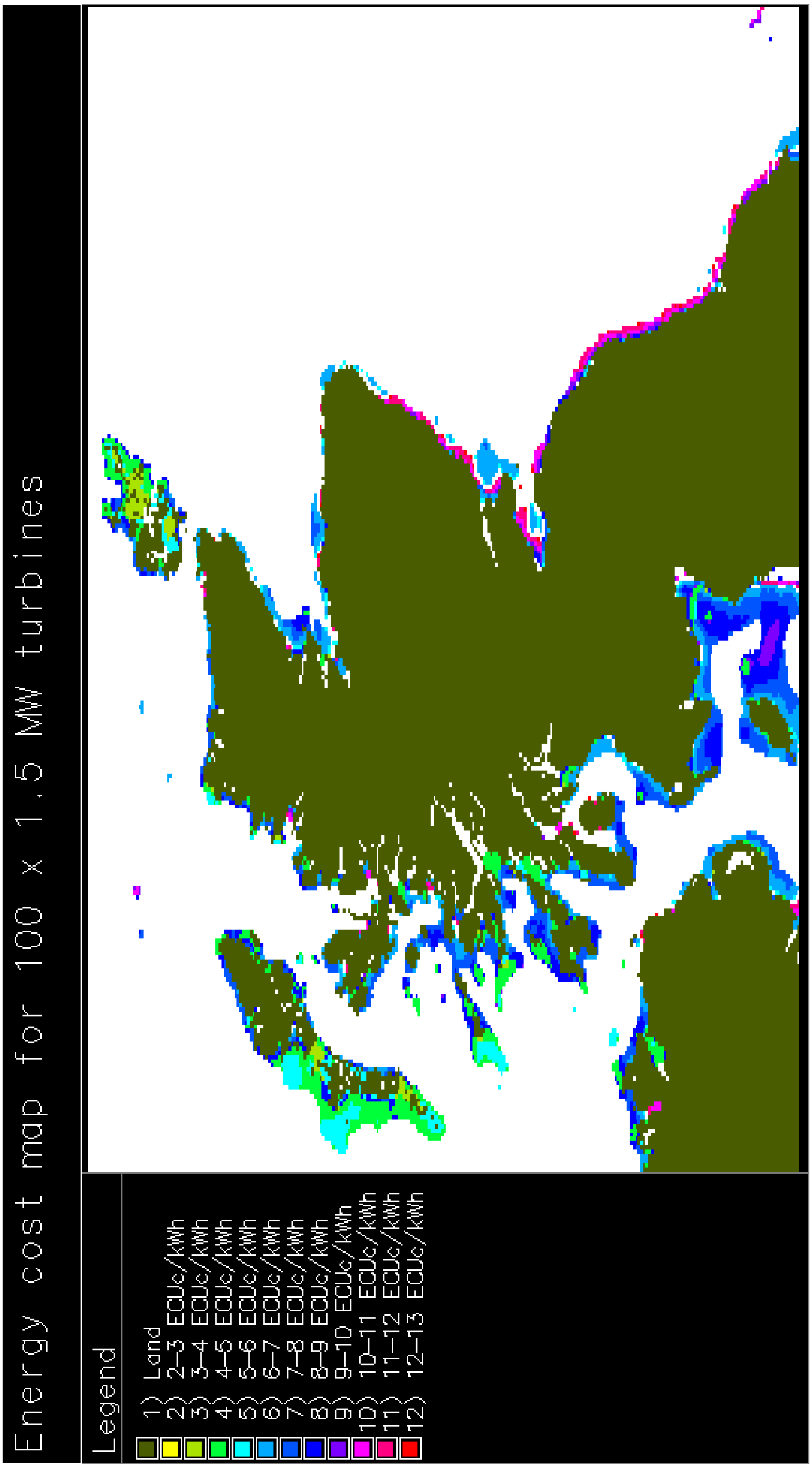

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(Energy costs without onshore grid connection,
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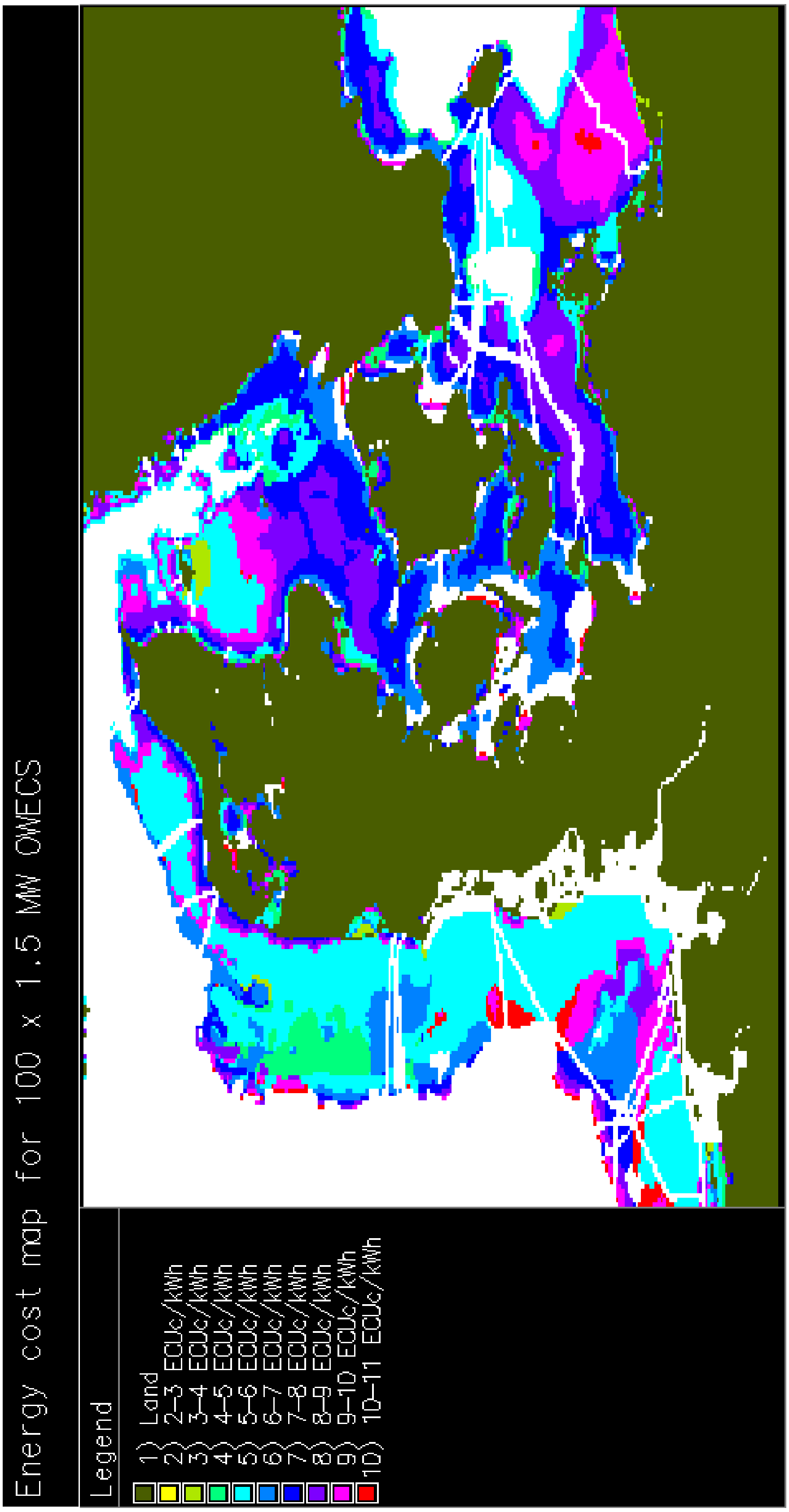

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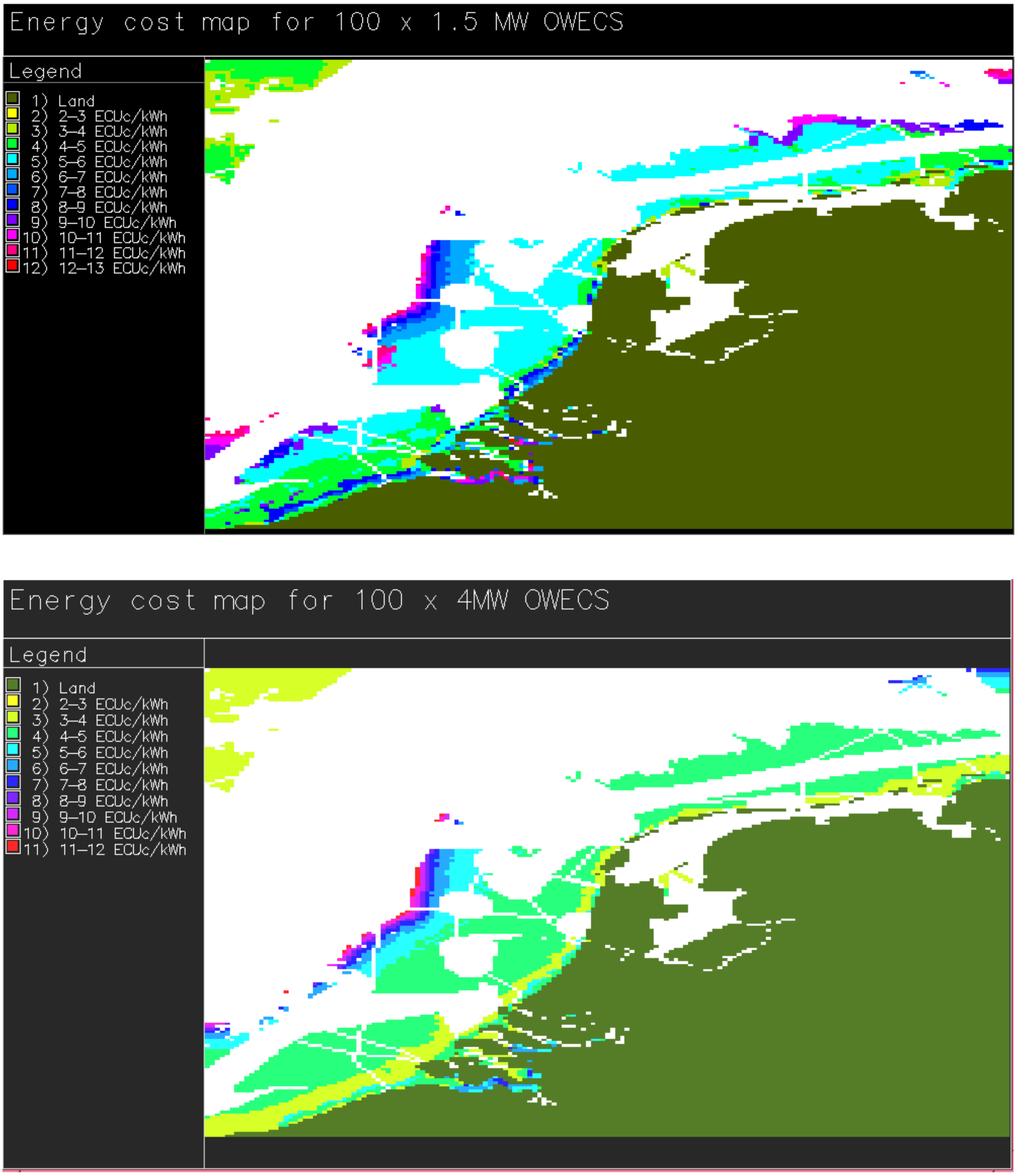
(Energy cost without onshore grid connection, for 20 years loan and 5% real interest rate.)



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(Energy cost without onshore grid connection,
for 20 years loan and 5% real interest rate.)

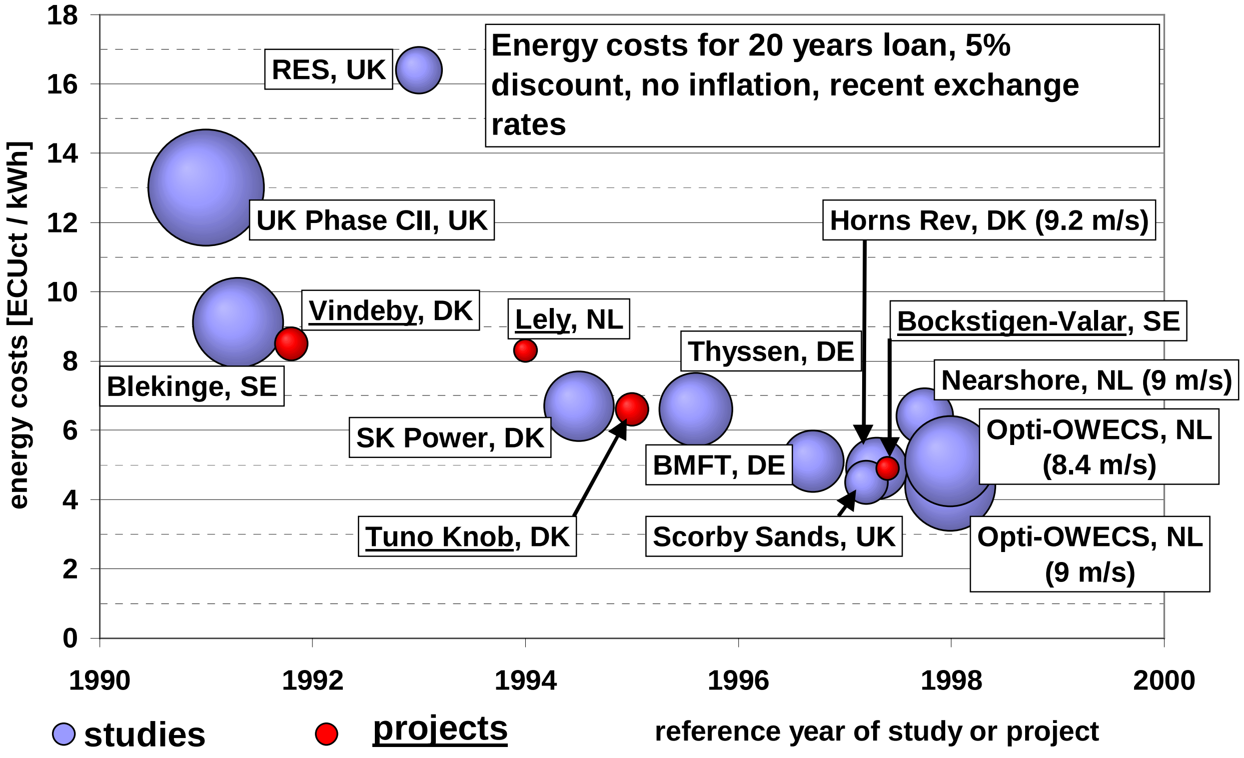


Figure 14: Comparison of energy costs between different studies and projects (Size of bubbles proportional to wind farm capacity)

Name of project or study and site	Study (S) Project (P) Year	Capacity [MW]	V_{hub} [m/s]	H_{hub} [m]	Distance from shore [km]	Water depth [m]	Spec. cost [ECU/kW]	Capacity factor [-]	Energy costs [ECUct/kWh]
Phase CII, North Sea, UK	S '91	711 * 3	8.3	~55		16 - 21	1900	19%	13
Blekinge, Baltic, SE	S '91	98 * 3	9.0	90	10	15 – 20	3000	32%	9.1
Vindeby, Baltic, DK	P '91	11 * 0.45	7.5	37.5	1.5	3 – 5	2150	27%	8.5
RES, North Sea, UK	S '93	41 * 0.4	7.4	33	~5	~12	4500	33%	16
Lely, IJsselmeer, NL	P '94	4 * 0.5	7.7	41.5	1	5 – 10	1700	22%	8.3
SK Power, Baltic, DK	S '94	180 * 1	8.2	47	17	8 – 10	1900	31%	6.7
Tunø Knob, Baltic, DK	P '95	10 * 0.5	~7.5	43	6	3 – 5	2200	34%	6.6
Thyssen, Baltic, DE	S '95	140 * 1.5	~7.8	60	4	5 – 10	1400	27%	6.6
BMFT, Baltic, DE	S '95	100 * 1.2	~7.5	60	~7	~10	1250	31%	5.1
Horns Rev, North Sea, DK	S '97	80 * 1.5	9.2	55	~15	5 – 11	1650	40%	4.9
Scroby Sands, North Sea, UK	S '97	25 * 1.5	~8.2		3		1150	~31%	~4.5
Bockstigen-Valar, Baltic, SE	P '97	5 * 0.55	8	41.5	4	6	1500	33%	4.9
Nearshore, North Sea, NL	S '97	~ 100 * 1	9	60	8	13 – 17	1900	34%	6.4
Opti-OWECS, North Sea, NL	S '98	100 * 3	8.4	60	11.5	12 – 20	1250	30%	5.1
			9					34%	4.4

Energy costs for 20 years loan and 5% real interest rate, no inflation, recent exchange rates.

Table 3: Comparison of energy costs between different studies and projects

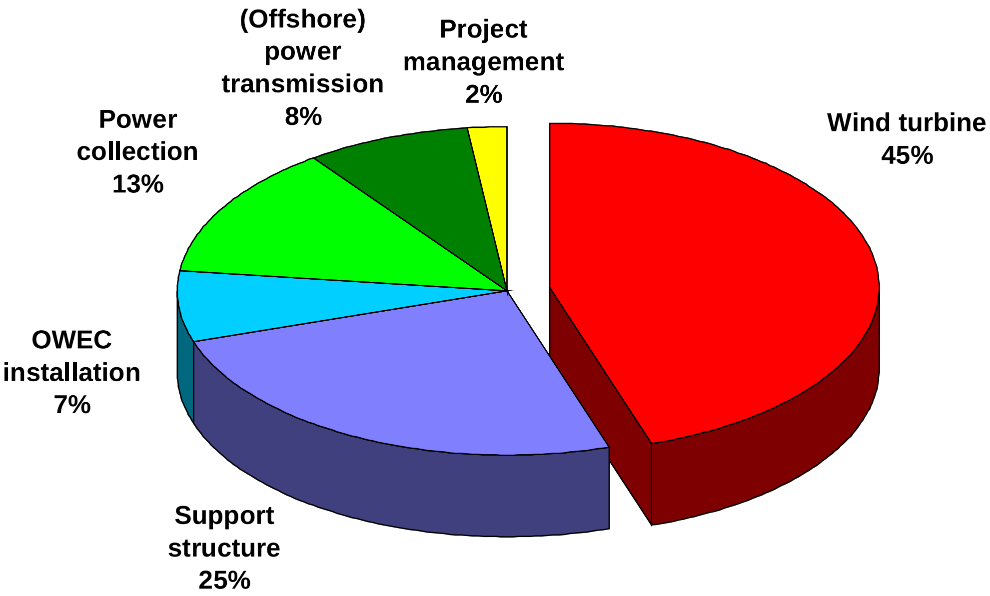
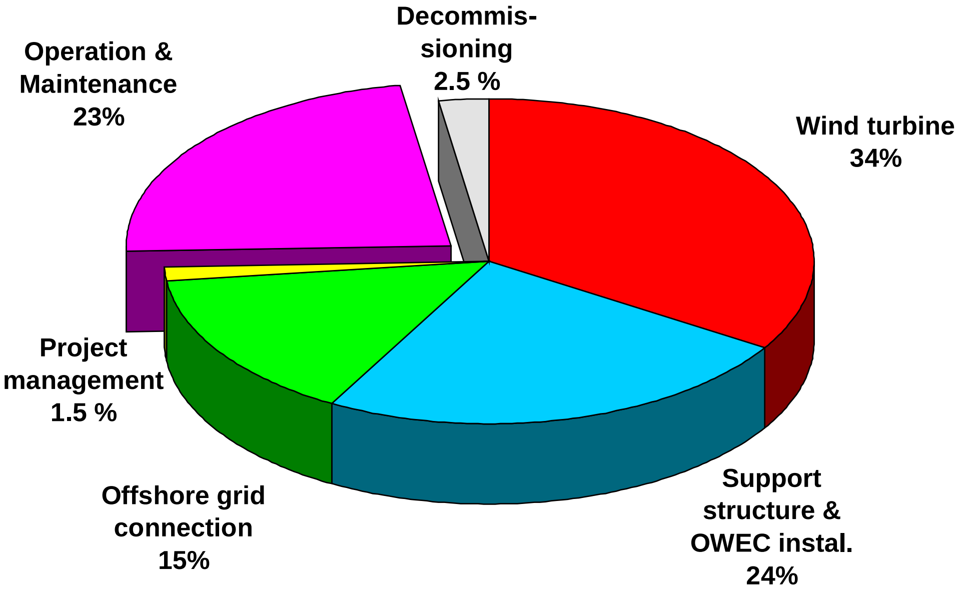


Figure 15: Breakdown of initial capital cost for Opti-OWECS design solution



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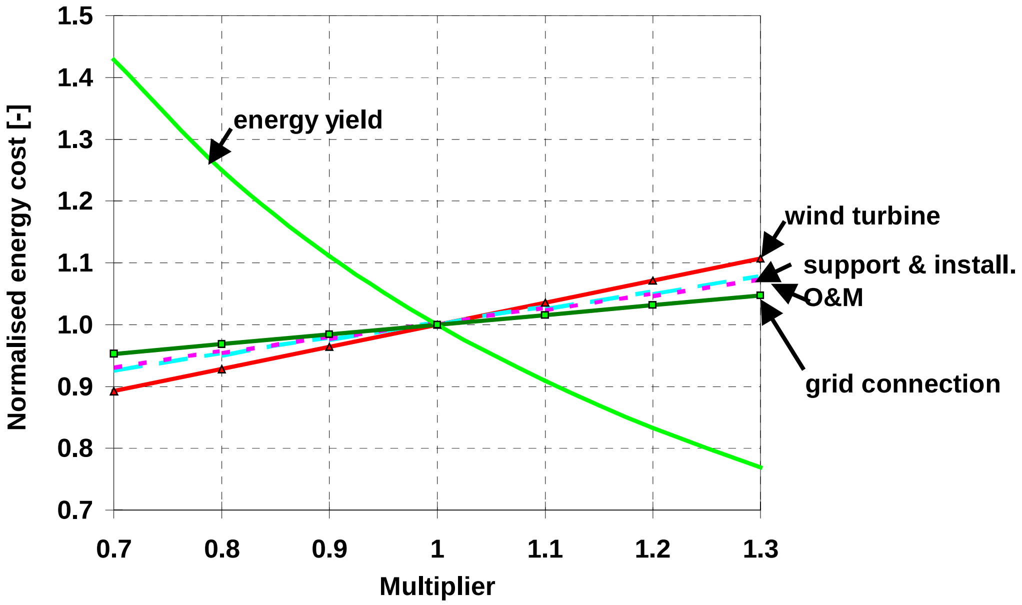

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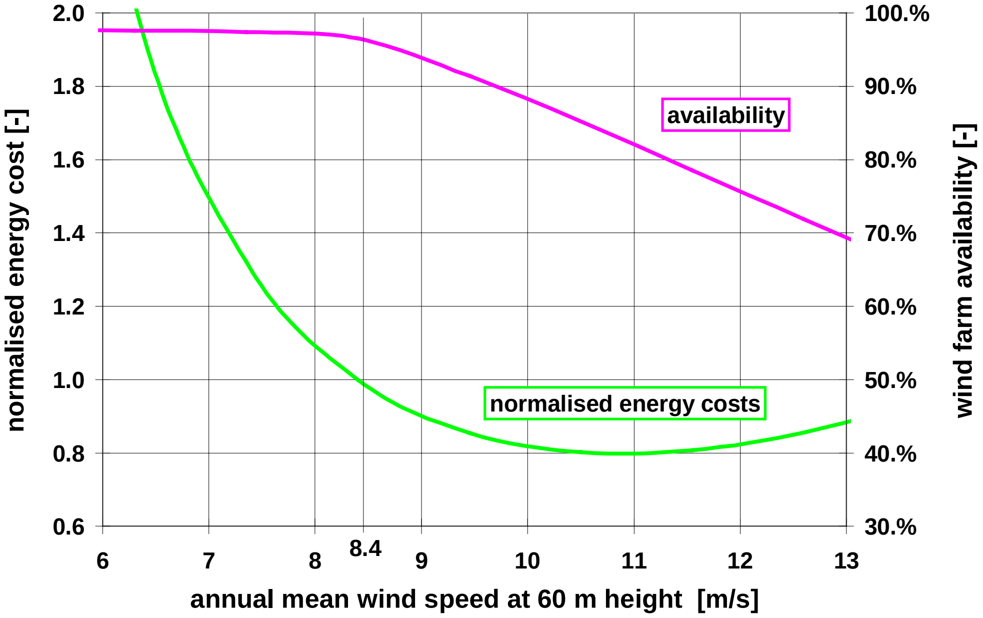


Figure 18: Normalised energy costs and farm availability against mean annual wind speed at 60 m

The final reporting is organised in a more coherent way with a view to the subjects considered rather than in the sequence the work was carried out. Therefore the report available to the public is subdivided into six volumes:-

- Vol. 0 Executive Summary
- Vol. 1 Integrated Design Methodology for OWECS [1]
- Vol. 2 Methods Assisting the Design of OWECS [2]
- Vol. 3 Comparison of Cost of Offshore Wind Energy at European Sites [3]
- Vol. 4 A Typical Design Solution for an OWECS [4]
- Vol. 5 User Guide OWECS Cost Model [5]

All volumes are written in such a way that is possible to review and use the volumes separately.

Organisation of this report

This document is the Executive Summary of the final reporting. After the description of the background (chapter 1) and an overview on the project (chapter 2), the major achievements of the project are briefly presented in chapter 3. Next, chapter 4 summarises the work content of the different volumes. The main conclusions and recommendations for further work based on the project findings are given in chapter 5.

Whilst the summaries are organised volume by volume, the major achievements, conclusions and recommendations are grouped according to particular aspects that have been addressed by several volumes, e.g. operation and maintenance aspects, cost drivers for offshore wind energy.

OWECS terminology

Use is made of a terminology for OWECS, which was developed and successfully applied during the project (see appendix A, [6]). In order to avoid misunderstandings there are two essential conventions that should be appreciated. Firstly, the acronym “OWECS” (standing for Offshore Wind Energy Conversion System) or its synonym “offshore wind farm” describes the entire system, that is the wind turbines, the support structures, the grid connection up to the public grid and any infrastructure for operation and maintenance. Secondly, “OWEC” (Offshore Wind Energy Converter) is used to refer to a single unit of an offshore wind farm comprising support structure (i.e. tower and foundation) and the wind turbine (i.e. aero-mechanical-electrical conversion unit on top of the tower).

3. Major achievements

The major achievements of the project are related to the following six generic fields of interest.

i.) Development of practical and economic solutions

- practical solutions based upon currently available technology
- design solutions for an entire offshore wind farm by means of an integrated design approach
- development of innovative support structures
    - treatment tower and foundation as one unit
    - reduction of installation efforts
    - optimisation with respect to site, wind turbine and dynamics
- state-of-the-art marinisation of an existing wind turbine design
- innovative operation and maintenance solution

ii.) Identification of cost drivers and estimation of costs

- comprehensive concept analysis and cost modelling of offshore wind farms
- consistent estimation of energy costs for different European regions
- parameter study on site conditions and design parameters
- design work for three distinctly different concepts and sites

iii.) Extending the state-of-the-art

- symbiosis of wind energy and offshore technology
- consideration of real *off*shore rather than *in*shore or *near*shore sites
- European dimension, e.g. consortium, site selection
- progress towards a mature offshore wind energy technology

iv.) Consideration of offshore wind farms on a system level

- compilation of a particular terminology
- *development* of an integrated design approach for offshore wind farms
- *demonstration* of the integrated design approach
- development of design tools for offshore wind farms
- design optimisation by tuning of dynamics of wind turbine *and* support structure

v.) Highlighting the importance of operation and maintenance

- identification of operation and maintenance as main cost driver
- consideration of system behaviour and site conditions
- solution of operation and maintenance problem by a rational approach

vi.) Development of a cost model and other tools for offshore wind farms

- new tool for cost analysis and preliminary design
- first structural reliability analysis of a support structure
- novel code for simulation of operation and maintenance behaviour
- extension of simulation techniques for overall dynamics
- first application of met-ocean database from the offshore technology

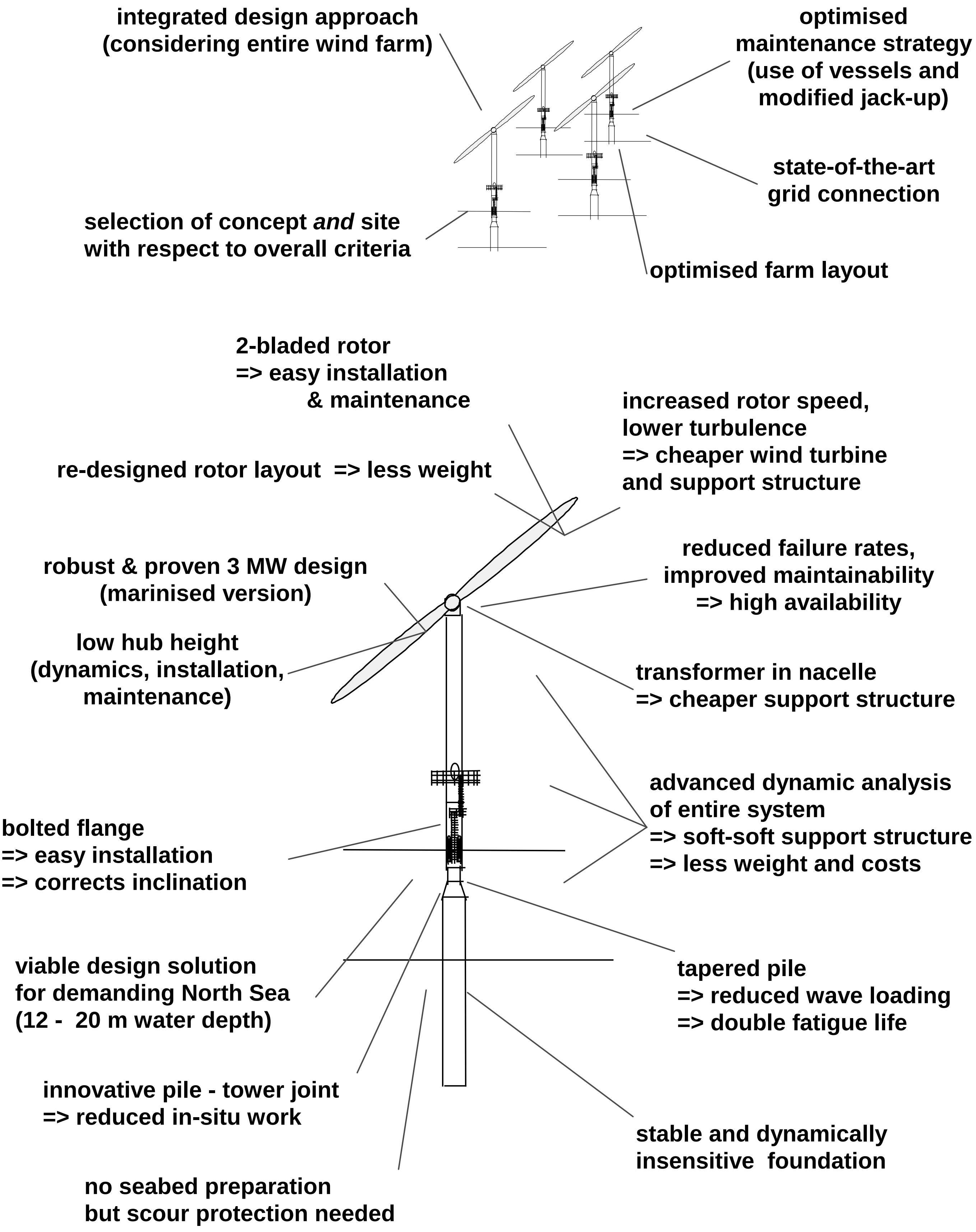


Figure 1: Innovative features of the design solution
for a 300 MW offshore wind farm (see section 4.4)

4. Summaries

4.1. Integrated design methodology for offshore wind farms

The purpose of the first volume is to propose, based upon the experience gained during the Opti-OWECS project, a particular methodology, the so-called 'integrated OWECS design approach', in order to meet the challenge of cost-efficient and reliable offshore wind energy conversion systems (OWECS).

The integrated design approach considers the components of an offshore wind farm as parts of an entire system, i.e. the OWECS (figure 2). Therefore interactions between sub-systems are considered in a complete and practical form as possible so that the design solution is governed by overall criteria (i.e. so-called aspect-systems) such as: levelised production costs, adaptation to the actual site conditions, dynamics of the entire system, structural reliability considerations, installation and commissioning effort as well as OWECS availability.

Figure 3 illustrates the integrated OWECS design approach based on a methodology recently developed for large, complex civil engineering projects [7]. The client's goals are translated (as much as possible) into quantifiable criteria at the system level, the aspect-systems, which facilitate goal control of the design process. Furthermore, the system is decomposed into sub-systems and elements for efficient control of the structural design.

Design practice applied so far to the design of the first prototype installations or within other studies can broadly be categorised as a 'robust and traditional approach' or as a 'parallel design approach'.

In the first case the design process is organised in two main clusters according to the parent technologies, i.e. wind energy technology (comprising wind turbine, tower, farm layout, grid connection design) and offshore technology (related to foundation, marine installation and submarine cables). The treatment is denoted as robust since conventional design solutions are used (e.g. standard wind turbine with small modifications, stiff foundation) and traditional because of the direct application of experience from the normal scope of work of the parties involved.

In the latter case the OWECS design implications are indeed recognised but are considered individually in the main sub-systems as wind turbine, support structure, grid connection, etc. Thus the overall performance is limited to the sum of the separate optimisations of the sub-systems.

Both approaches fit the objectives of demonstration or (near) commercial plant but are not suitable to arrive at commercial, large offshore wind farms to be erected by the beginning of the new millennium.

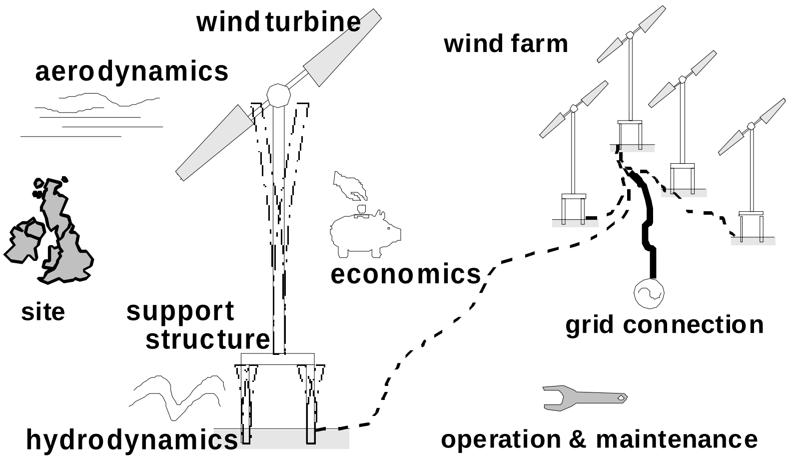


Figure 2: Components and aspects of an Offshore Wind Energy Conversion System (OWECS)

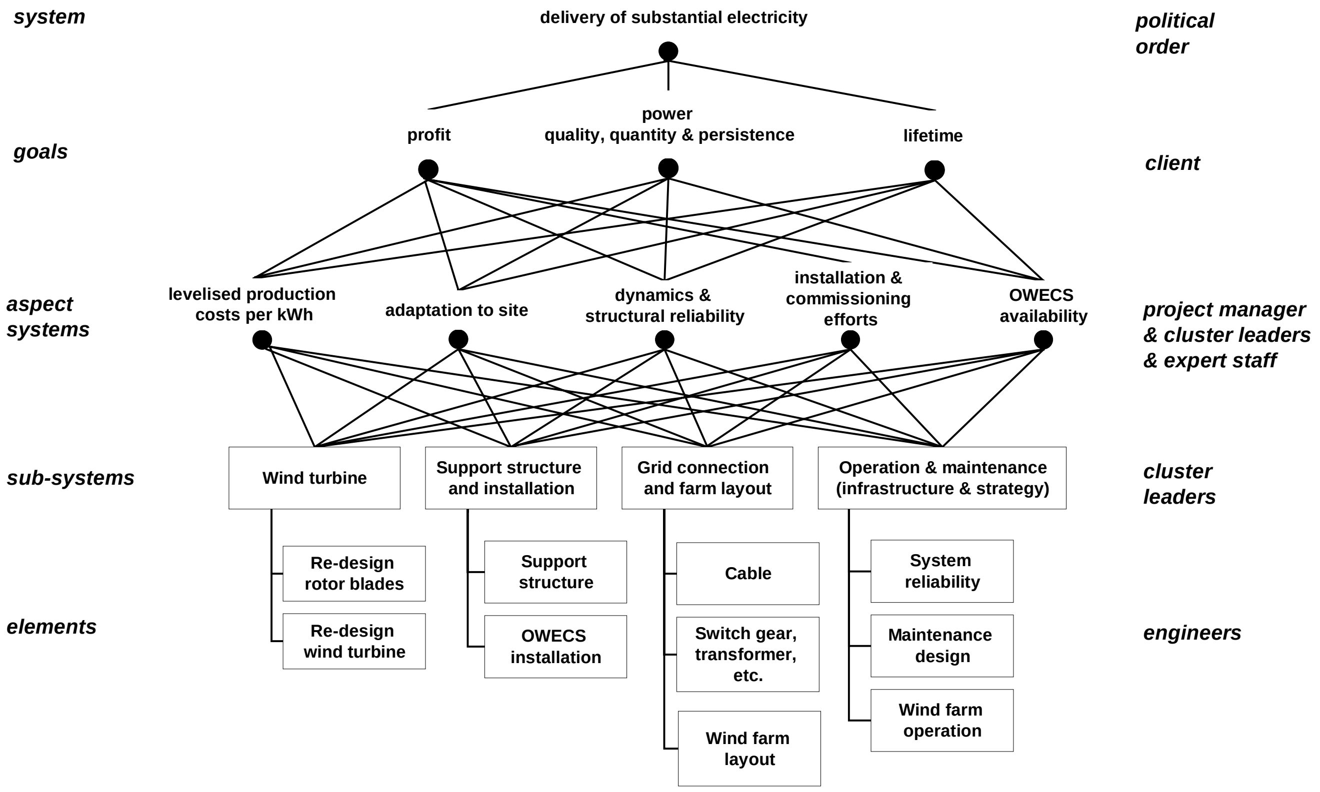


Figure 3: Multi-level control system within the integrated OWECS design approach

4.2. Methods assisting the design of offshore wind farms

The integrated treatment of an offshore wind energy conversion system (OWECS) requires assistance of particular methods or tools in order to account for the interactions of the subsystems and to evaluate the system with respect to overall criteria (aspect-systems). The second volume describes four of such ‘building-blocks’ that were developed or extended during the project.

4.2.1 Concept analysis and cost modelling of offshore wind farms

A comprehensive analysis of the sub-system options for OWECS was carried out as preparation of the design work and the economic analysis. For instance, different generic support structure types, options for grid connection, etc. were investigated.

In close cooperation with the design work a computer based cost model for the economic assessment of certain OWECS concepts was developed next. The model also allows investigation of the effect of changes in important parameters on the cost of energy from an OWECS, including the wind speed, the support structure height, the size of the turbine, the distance from the shore, etc.

The model was validated through re-evaluation of some well-known OWECS proposals and some real plants. Its predictions were compared to published data for the chosen validation cases and exhibited an acceptable correspondence.

Although cost modelling studies in wind energy are not new, this model has a number of novel features in relation to its predecessors. One particular point is that many of the calculations are undertaken on what could be termed a first principles basis. This means that the model reaches its cost estimates by actually making a preliminary design of an OWECS meeting parameters specified by the user, albeit in a highly simplified manner, and then costing the result. This is in contrast with some previous work that estimated costs by merely interpolating between pre-specified costs. A further feature of the model is the flexibility in configuration that it incorporates. Options are available to allow both detailed examinations of well-defined OWECS concepts and more general study of broad trends.

Figure 4 shows one result of the application of the model during the selection of the final site (see table 1 for assumed site data) and the final wind farm concept for the OWECS design solution in the present study (section 4.4).

Quantity	**NL-1 IJmuiden**	**DK-1 Horns Rev**	**S-1 Blekinge**	**NL-5 IJmuiden**	**DE-1 (i) Rostock**	**DE-1 (ii) Rostock**	**UK-1 The Wash**
Mean wind speed (60m)	9 m/s	9.2 m/s	8.4 m/s	9.5 m/s	7.8 m/s	7.8 m/s	8.2 m/s
Water depth (LAT)	15 m	11 m	15 m	25 m	8 m	14 m	20 m
Distance from shore (to collection point)	8 km	20 km	7 km	50 km	5 km	10 km	30 km

Table 1: Some of the assumed data of the site comparison

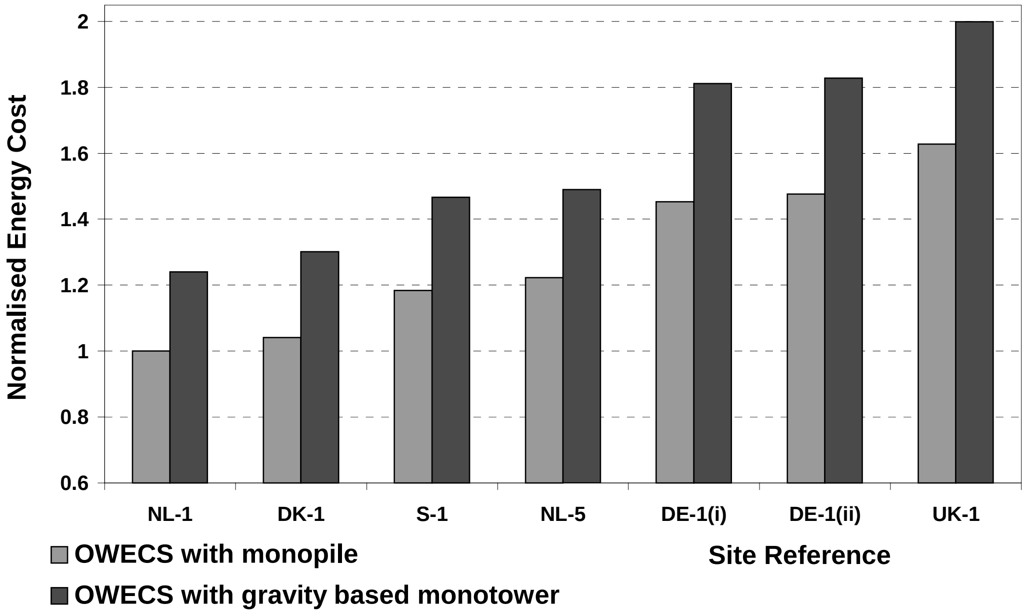


Figure 4: Comparison of energy cost for different sites and support structure concepts with the OWECS cost model

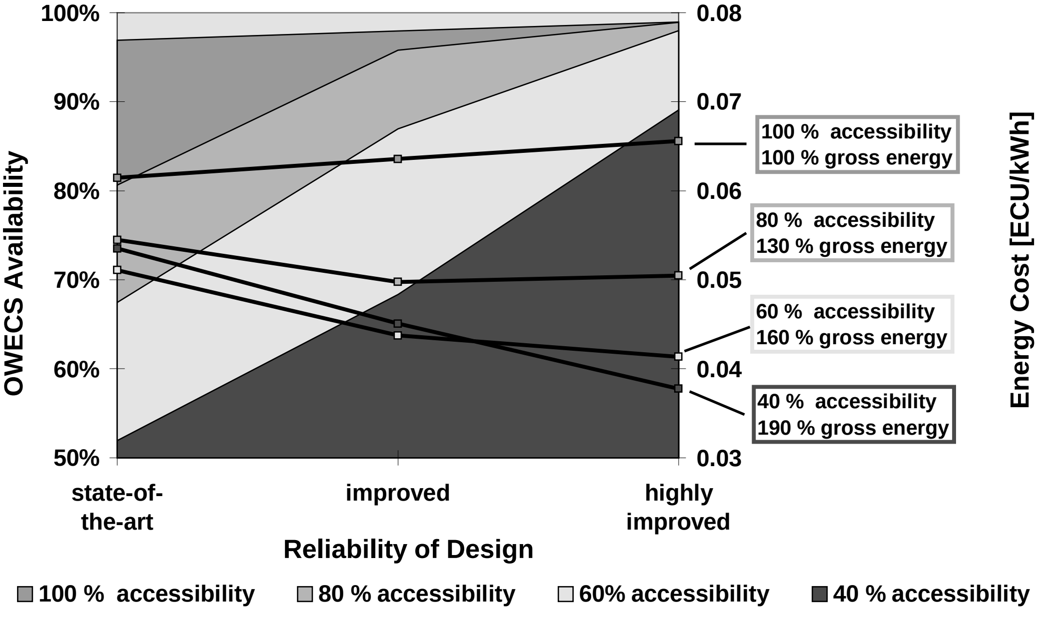


Figure 5: Qualitative relation between site conditions (accessibility and gross energy yield) on one hand and availability respectively energy costs for different level of reliability of OWECS design on the other hand

4.2.2 Simulation of operation and maintenance of offshore wind farms

Two striking differences with onshore wind farms are that the accessibility of an offshore farm is largely reduced by bad weather conditions (wave height, wind speed and visibility); furthermore the costs of an offshore operation such as transport or lifting is an order of magnitude larger than onshore. Therefore the operation and maintenance (O&M) aspects of offshore wind farms were analysed in a comprehensive way.

A Monte-Carlo program simulating the O&M behaviour of an offshore wind farm was developed. With the help of this program it was possible to investigate various possibilities for deployment of maintenance hardware, crews and O&M strategies. As to equipment a distinction can be made between crew transport (e.g. vessel and helicopter) and lifting equipment (e.g. modified jack-up, crane vessel and built-in lift system).

The program simulates the O&M behaviour of an OWECS over a lifetime period by following the state of each component of the wind farm one time step at a time.
At the start of each simulation run, the failure rates of the used wind turbines and the O&M strategy is defined. Further, the number of crews and shifts, the kind and quantity of equipment, the site parameters are specified. Different maintenance strategies can then be evaluated by changing the input parameters, e.g. for the time interval between preventive maintenance visits.
Stochastic events, such as the occurrence of failures (of the wind turbine components) and the state of the weather, are simulated by a random number generator acting on the assumed probability distributions.
At the end of the simulation run the total O&M costs, the achieved availability and the produced energy of the wind farm are presented as output.

Figure 5 gives one example of the application of the O&M tool. Firstly, the OWECS availability is shown as function of reliability of design and accessibility of the wind turbines (area plot). A site without restriction with respect to accessibility (i.e. onshore) reaches 97% availability for a state-of-the-art design increasing up to 99% for an extremely reliable design under the assumed maintenance strategy. As weather conditions get worse availability may fall down to 53% (!) to 89% depending upon the failure rate of the turbines.

Secondly, also shown in the figure is the calculated energy cost (20 years loan, 5% real interest rate) as a function of failure rate and accessibility (line plot). The assumption is made that the cost at 100% availability increases from 0.06 to 0.065 ECU/kWh with increasing reliability. Harsher weather conditions will simultaneously lead to decreased accessibility and increased gross energy yield. With state-of-the-art reliability, cost values below 0.05 ECU/kWh are not reachable since increased gross energy yield is more or less compensated by decreased availability. However, improved reliability will find its pay back in terms of significant reduce energy cost.

4.2.3 Optimisation of the design of a support structure using advanced offshore engineering technology

The economic exploitation of the offshore wind energy potential requires a symbiosis of wind energy and offshore technology, for instance by the application of structural reliability methods. For an example OWEC (offshore wind energy converter) support structure located at a demanding North Sea site it turned out that applying such a method reduced the extreme design loading with about 40% relative to the conventional design approach.

In conventional design practice for offshore structures the environmental conditions are determined on the basis of independent estimates of extreme wave, extreme current and extreme wind conditions, each having a return period of e.g. 50 years. These conditions are next assumed to occur at the same time and to act in the same direction. This results in environmental design conditions and a corresponding global load condition with a very long return period and an unnecessarily conservative design. Recent advances in offshore engineering have led to a reliability based design method that takes correlations between the environmental conditions into account which allows matching of structural design with pre-defined risk criteria. This approach consists of four steps (figure 6):-

1.) Definition of the environment in terms of storm events, in which wave, current and wind conditions are correlated instead of in independent environmental conditions. An essential requirement for this is the availability of a large database containing information on the simultaneous occurrence of wind, waves and current at the intended site during a long period (e.g. 25 years).

2.) Determination of the long-term distribution of the extreme response of the structure during an arbitrary storm. A storm consists of a succession of sea states, each with its associated current and wind conditions. The most straightforward manner to determine the response behaviour in a particular sea state is, in principle, to perform a time domain simulation using a FE model. This has to be repeated for many different realisations of the same sea state, for all sea states in a storm and for all storm events in the database. The huge computational effort involved can be drastically reduced by application of the technique of constrained random simulations, but remains substantial. By appropriate combination of the individual response distribution from each simulation the long-term distribution of the extreme response during an arbitrary storm can be determined.

3.) Determination of the long-term distribution of the extreme response during the lifetime of the structure. The results of step 2 are now combined with the probability that a storm will actually occur, using the storm arrival rate derived from the database.

4.) Determination of the probability of failure of the structure in a given lifetime by combining the result from step 3 with information on the ultimate strength of the structure. When the lifetime is longer than the duration of the database this inevitably requires extrapolation, which should be done with care. The results of this step make it possible to perform an economic risk evaluation or, alternatively, to determine an environmental load level for structural design which meets a pre-defined reliability level.

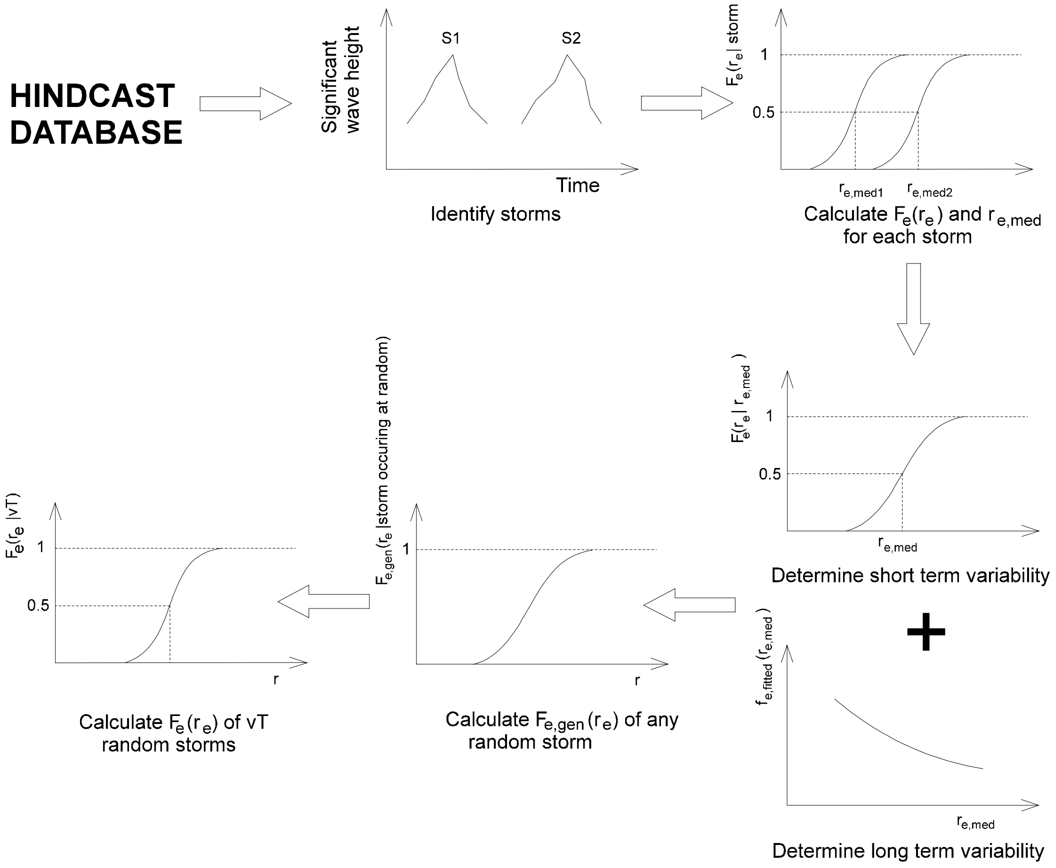


Figure 6: The determination of the extreme response distribution with a desired return period based upon the structural reliability method

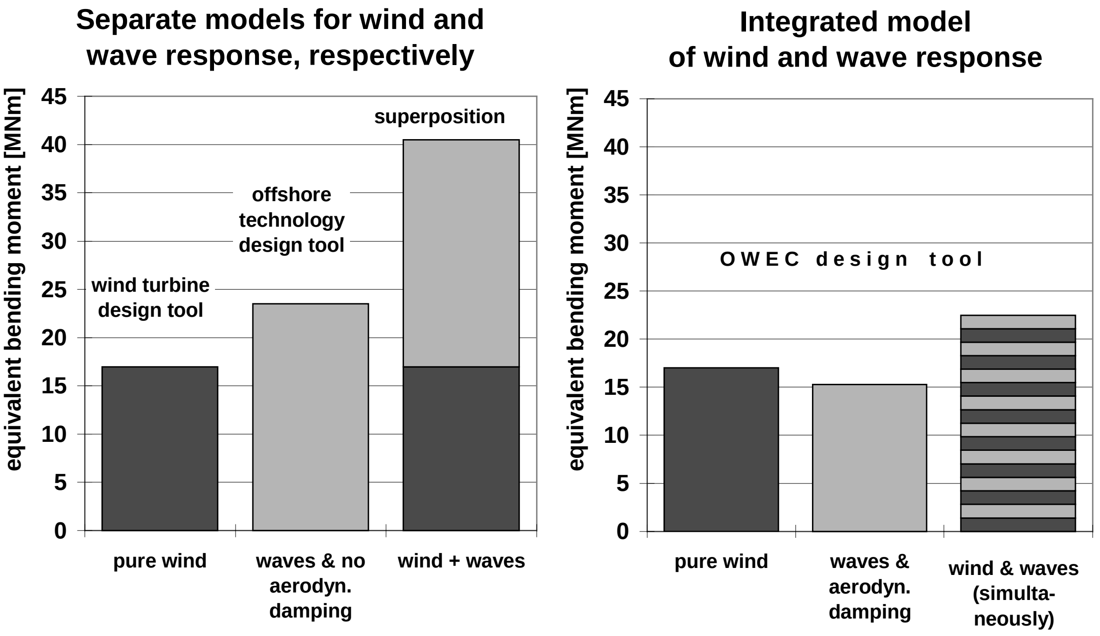


Figure 7: Reduction of calculated fatigue loading due to integrated modelling of wind and wave response (right) with respect to superposition of separate models for wind and wave response, respectively (left)

4.2.4 Overall dynamics of offshore wind energy converters

The dynamic properties of an offshore wind energy converter (OWEC) and its complex loading result in interactions between several sub-systems. Certain phenomena, e.g. drive train dynamics, are restricted mainly on some components while others, e.g. support structure fatigue, aerodynamic damping, controller and generator behaviour, require a model of the entire OWEC or even inclusion of certain aspects of the wind farm (e.g. wake effects or electrical interactions between different units).

Such aspects of OWEC dynamics played a pronounced role during the Opti-OWECS project. As a matter of fact this reaped benefits by a more cost-efficient design solution, e.g. soft-soft instead of soft-stiff monopile, and more reliable design calculations, e.g. by consideration of inherent uncertainties of the environmental conditions.

The former effect is demonstrated by figure 7 comparing the effect of two separate models respectively one integrated model on the equivalent bending moment at the mudline of the Opti-OWECS design solution. The pure wind loading is identical in both approaches. In contrast, the combined wind and wave response of the integrated model is reduced because of two particular features: Firstly, proper consideration of the aerodynamic damping obtains a lower wave response. Secondly, the partial cancellation of the wind and wave response is accounted for by considering the actual phase relation between both load components.

Analytical tools previously developed for OWEC in the scope of JOUR 0072 [8] and at the Delft University of Technology as modal analysis and time domain simulations were extended by state-of-the-art methods in both wind energy and offshore technology. Furthermore, dynamic considerations and application of an OWEC design tool formed an integral part of the design process (see integrated OWECS design approach) rather than only a check of the final design solution. By this further significant cost reduction e.g. of the support structure was achieved. Moreover, the design of the large two bladed wind turbine profited from the tailored dynamics of the entire OWEC by adjusting support structure stiffness, rotor speed and blade design.

4.3. Estimate of costs of offshore wind energy at European sites

In the earlier study, ‘Offshore Wind Energy in the EC’ (JOUR 0072) [8] the enormous offshore wind energy potential was identified. Generally only a poor understanding has however been developed of the cost drivers involved in exploiting this vast resource. All that could be found in the literature were cost estimates for using specific OWECS concepts at particular locations, which were difficult to compare rationally as a result of the differing assumptions each embodies.

Volume 3 of the main report estimates, on a consistent basis, how the electricity cost of bottom-mounted OWECS might vary at all technically feasible sites within the northern regions of the EU.
It should be noted that this part of the project work has a more general basis than the demonstrated design solution described in the next section.

Methodology and scope

In order to assess the economic potential of offshore wind energy in EU regions a link was developed between an European database of offshore wind energy potential produced by the JOUR 0072 project and the insight into cost drivers gained during Opti-OWECS. A simplified cost model, derived from a more detailed OWECS cost model (section 4.2.1), was implemented within a Geographical Information System (GIS). This GIS based model was used to calculate cost estimates across the waters of the Northern EU, based on information from the JOUR 0072 database and a limited number of other sources.

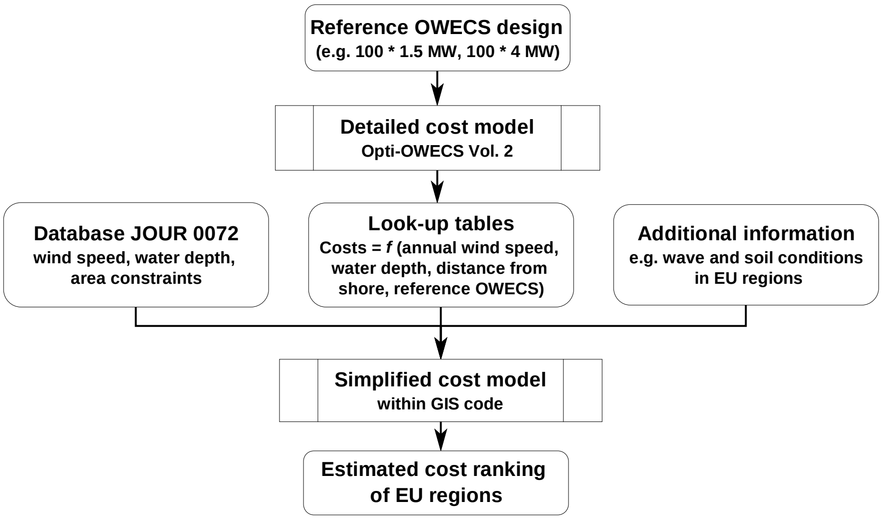


Figure 8: Approach followed in the comparison of energy cost at European sites

The approach employed in the development of the GIS model is illustrated in figure 8. Although the diagram, and the methodology, seems straightforward, it must be stressed that a large number of design and site parameters have complex, inter-related influences on the cost of OWECS produced energy. Still considerable simplifications had to be made in the calculations. As an example, the calculations presented here neglected the costs involved in the construction of an onshore grid connection. Furthermore, only one type of support structure (the monopile) was considered, even though the rest of the project considered a wide range of bottom-mounted support structure concepts. It is unlikely that the monopile structure is a good choice of support in all of the regions investigated. Furthermore, for the time being it was assumed that the power transmission cable is directed to the nearest shore even if it turns out to belong to a (small) island. Therefore cost estimates in regions as Northern Scotland or near the Wadden Sea require careful interpretation.

Regions considered and reference OWECS.

Calculations were undertaken for certain northern regions of the European Union including the waters of Great Britain, Belgium, The Netherlands, Germany and Denmark. These regions were selected because they are generally perceived as being hospitable to bottom-mounted offshore wind farms, and because the principle expertise of the project partners. With the objective of comparing the potential of different types of sites and technology two distinct classes of offshore wind farms were considered.

The first, comprising 100 OWEC each of 1.5 MW rated capacity was intended to represent the first large scale, commercial OWECS that will be erected at the beginning of the next century. Comparable OWECS are proposed for specific locations in Danish and Dutch waters. Sites with good wind conditions, but only a moderate depth of water and reasonable proximity to the shore are considered most suitable for this concept.

The second class of wind farm employed very large, multi-megawatt OWEC with a rated capacity of 4 MW each. Again the farm consisted of 100 units. Such offshore wind farms are most suitable for more remote and exposed locations in comparison to their smaller brethren, and construction is conceived within a much longer time frame, perhaps 10 years from now. Such a development period will be required to achieve the same high level of reliability assumed in the study for both reference OWECS.

Results

Cost maps for OWECS based on megawatt class turbines are shown as an illustration for northern Great Britain (figure 10), and for the region of Denmark, Germany and Southern Sweden (figure 11). Energy costs are based on an economic life of 20 years with a 5% real interest rate. Any blank areas of the maps signify locations at which the reference OWECS cannot be built either because the water depth is too large for the monopile support structure (i.e. greater than 30 m), or because the location is already used for other purposes (e.g. shipping lanes, oil platforms, wildlife reserves).

The results suggest that the annual mean wind speed and distance from shore are the most important parameters influencing energy cost. The western shores of the British Isles, for example, are economically more attractive than the ‘less windy’ eastern shores. Likewise, most Danish North Sea locations, although in a more demanding environment, show better performance than Baltic sites. Despite the improved wind conditions found further offshore, energy costs increase significantly with distance from the shore caused by reduced turbine availability and the increased cost of constructing long power transmission cables. However, more complex relations do arise as can be seen between the Cumbrian coast of Great

Britain and the Isle of Man where offshore sites are potentially more interesting than nearshore locations.

One advantage of using a GIS for this type of work is that it enables statistical comparisons of data to be carried out with comparative ease. Figure 9 compares the cumulative cost distribution of the total capacity of all technically feasible wind farms as a function of cost level for both type of reference plant in the Belgian-Dutch region. In addition, a distinction is made by a certain distance from shore in order to consider in a preliminary way that inshore and nearshore sites might not be exploitable due to non-technical reasons. See also figure 12 for the corresponding energy cost maps.

The cumulative distribution of the capacity starts for both wind farms types at approximately the same cost level but rises more steeply for the larger scale OWECS than for the in relation smaller scale wind farms. Employing multi-megawatt machines does not have much influence on the absolute minimum cost level for which electricity can be produced by an OWECS. In other words, larger turbines and larger OWECS offer little advantage over their smaller counterparts at the most economically attractive sites. Instead, the benefit offered by the larger OWECS is visible at the more mediocre sites. The figure clearly shows that a greater proportion of sites is available for lower cost levels if larger scale wind farms are used.
Therefore exploitation of the sites with superior performance can start on a near to medium time scale based on mature ‘megawatt technology’. For a utilisation in the range of (tens of) gigawatt on a longer time scale, development of multi-megawatt technology may offer advantages.

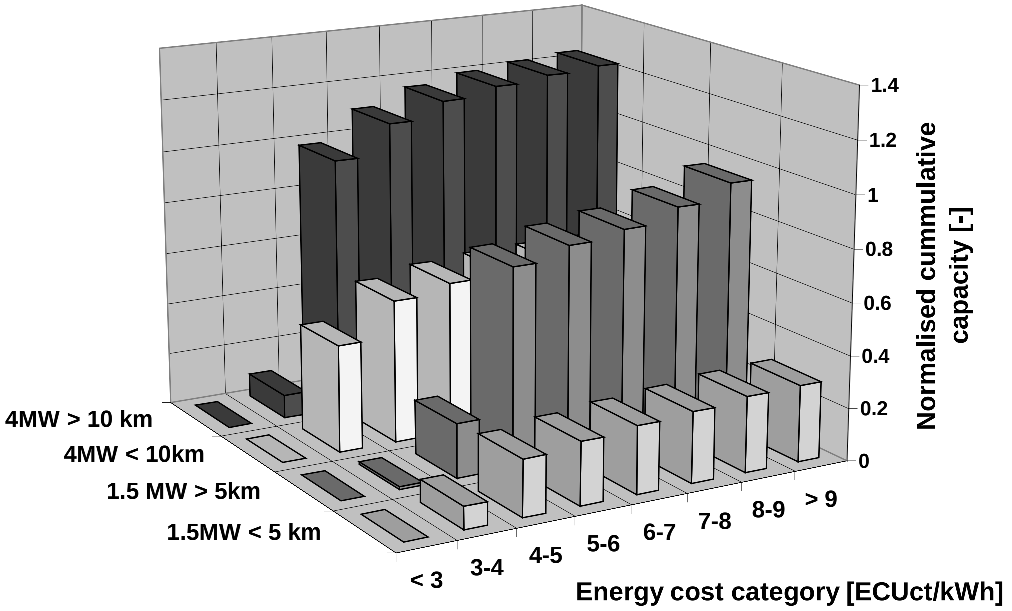


Figure 9: Distribution of proportion of installed capacity available at or below particular cost levels employing 100 turbines of 1.5 MW compared to wind farms with 100 units of 4 MW in Belgium and Dutch waters
(Values normalised with total capacity employing 1.5 MW units further than 5 km from shore.)

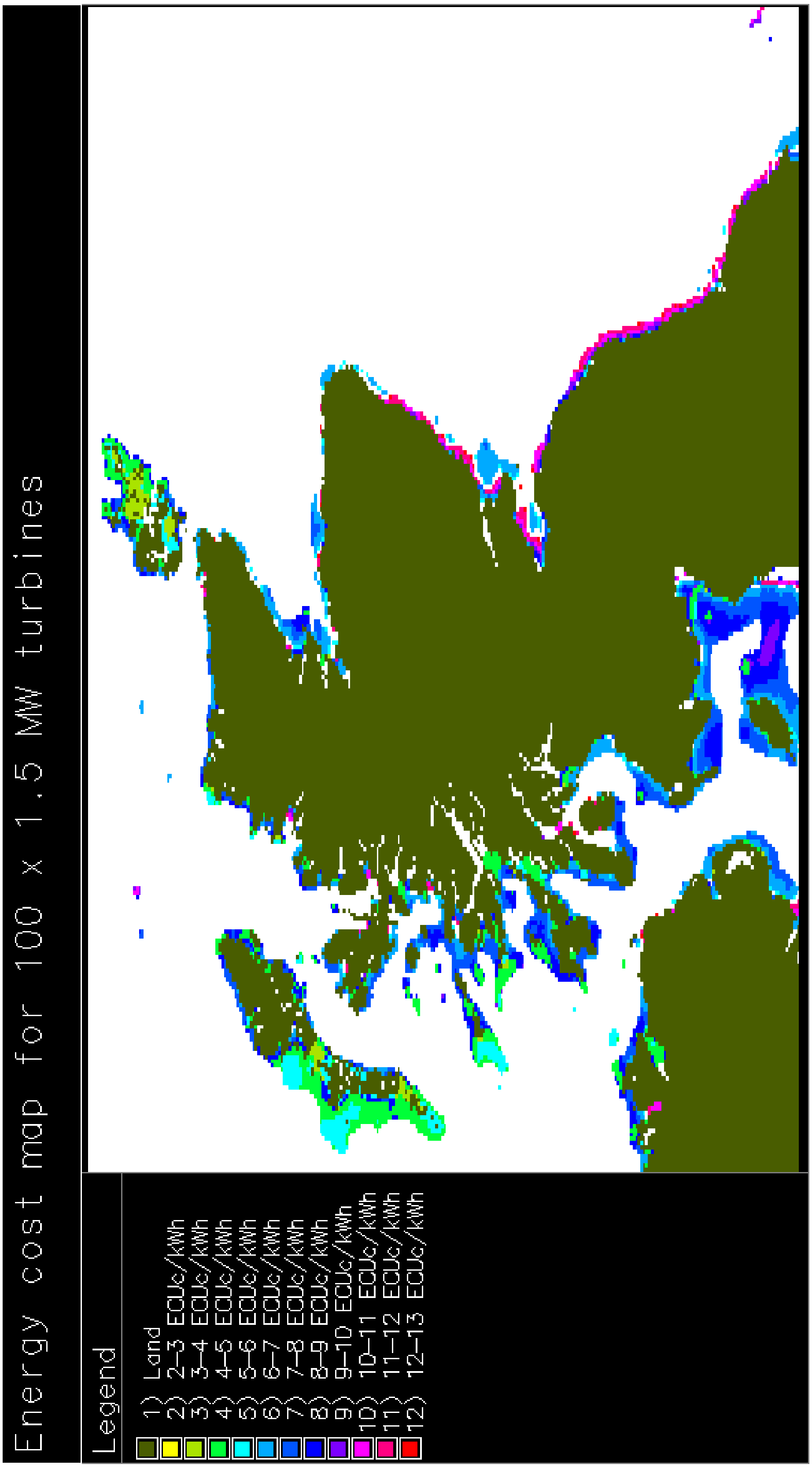


Figure 10: Energy cost map for OWECS (100 * 1.5 MW) around northern Great Britain
(Energy costs without onshore grid connection, for 20 years loan and 5% real interest rate.)

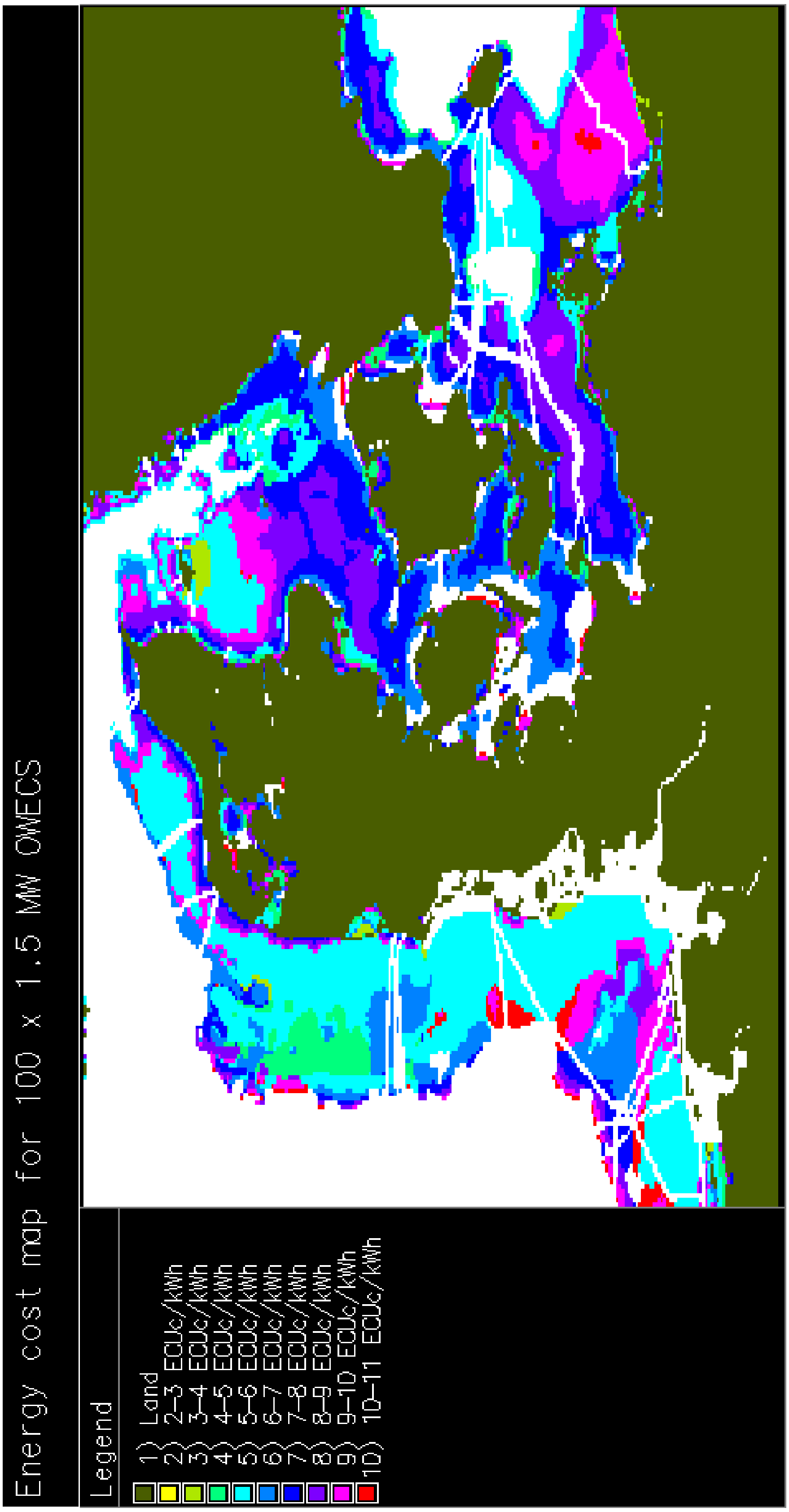


Figure 11: Energy cost map for OWECS (100 * 1.5 MW) in Danish and German waters
(Energy cost without onshore grid connection, for 20 years loan and 5% real interest rate.)

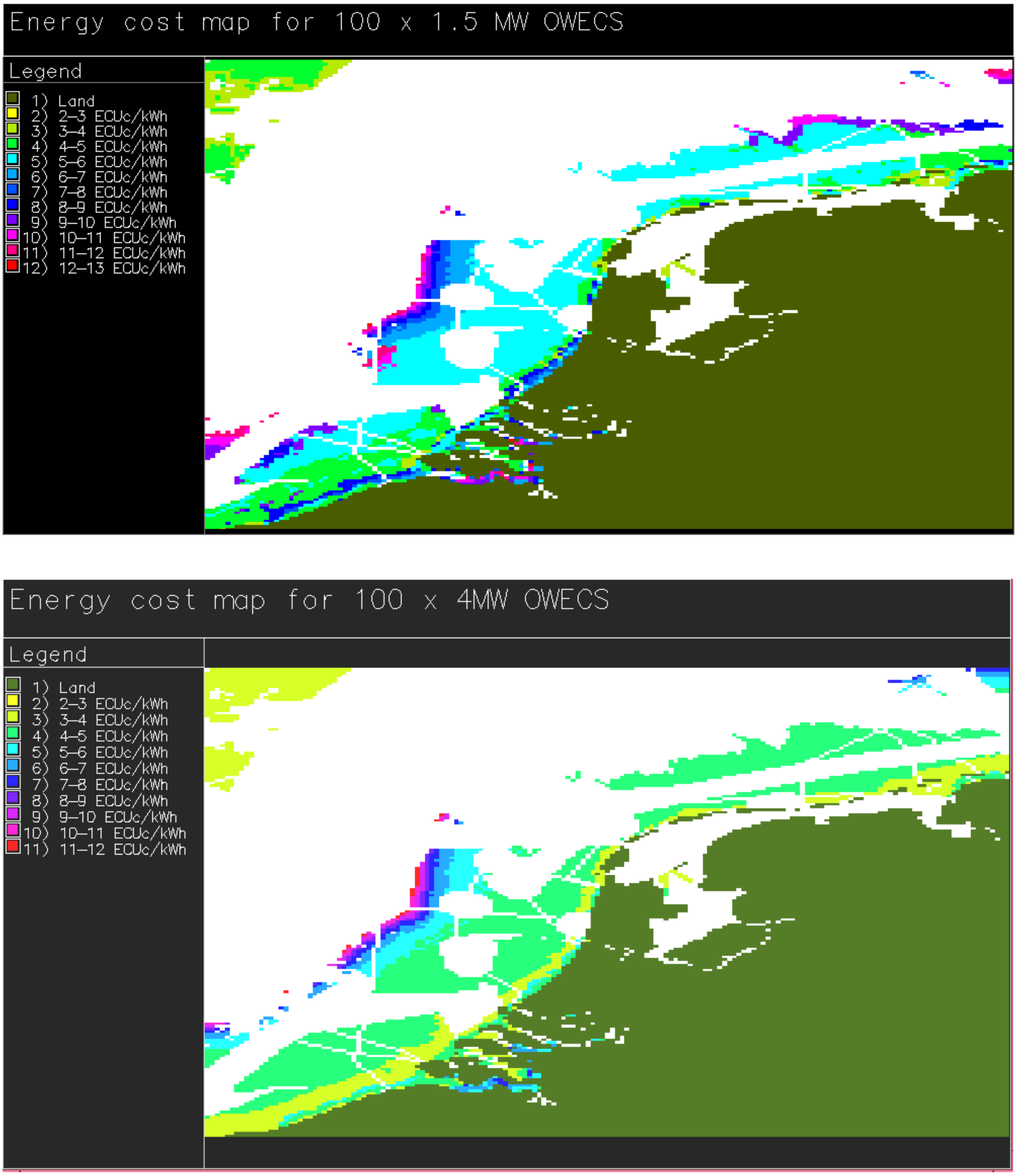


Figure 12: Energy cost map for OWECS employing 100 * 1.5 MW units (above) respectively 100 * 4 MW units (below) in Belgian and Dutch waters
(Energy cost without onshore grid connection,
for 20 years loan and 5% real interest rate.)

4.4. A typical design solution for an OWECS

Rationale

An OWECS design solution was developed against the background of three objectives.
Firstly, improved understanding of the principles underlying the design of OWECS, gained during the course of the project, was demonstrated by practical solutions. Application of promising innovations for large-scale utilisation, e.g. novel installation methods, consideration of operation and maintenance aspects, integrated design approach, etc., was more important than achievement of the absolute economic optimum.
Secondly, during the design process areas of poor understanding were identified and relevant solutions were developed.
Finally, the economic feasibility of large OWECS was demonstrated.

With these particular intentions in mind it was decided to follow the novel, integrated OWECS design approach (section 4.1). Consequently, not only the final result is described here but also the way in which it was achieved.

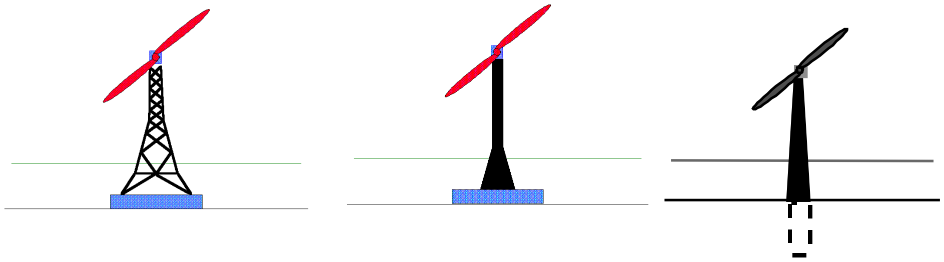
Project identification

The initial phase of the project identification comprised three aspects:-

- the establishment of the project group
- the determination of project conditions (i.e. objectives and work programme)
- the particular design conditions e.g. wind turbine size of 3 MW or larger, neglect of onshore grid connection aspects, etc.

PILED - BRACED MONOTOWER
Installation: Lifted

GBS - BRACED MONOTOWER
Installation: Floated Out



GBS - LATTICE TOWER
Installation: Floated Out

GBS - MONO TOWER
Installation: Floated Out

MONOPILE
Installation: Lifted *or* Floated Out

Figure 13: Examples support structure concepts
(Concepts in the lower row considered for conceptual design.
GBS: Gravity Based System.)

Feasibility study

During the first step of the feasibility study a broad inventory of all relevant aspects and concepts was made and pre-selections for the conceptual design were identified. Furthermore, a particular terminology appropriate to OWECS was established in order to promote a smooth communication (appendix A).

The identification of six distinctly different reference sites in northern European waters (table 1) was carried out in parallel with the investigation of sub-system concepts and of essentials features of overall dynamics and operation and maintenance aspects.

Based upon a qualitative OWECS evaluation the following sub-system concepts were selected for the further development:-

- The 3 MW 80 m diameter Näsudden development line was chosen as reference turbine since it is the only one in the multi-megawatt league with a reasonable operational track record. A recent design study [9] demonstrated that a commercial cost level can be achieved even for turbines of this size. In addition, the turbine rating of about 3 MW extends the state-of-the-art of other offshore project currently under development.
- two wind turbine concepts (geared - fixed speed, direct-drive - variable speed),
- rotor variants with diameters between 80 and 100 m and different rotor speeds,
- distinctly different combinations of support structure configuration and installation procedure (figure 13), dynamic characteristics (i.e. stiff-stiff, soft-stiff, soft-soft), and site (i.e. North Sea, Baltic Sea),
- base cases for grid connection and wind farm layout.

Conceptual design

The conceptual design phase was carried out mainly in parallel with work on sub-systems and development or extension of OWECS tools on cost modelling, O&M simulation, structural reliability considerations and overall dynamics.

Improved knowledge on particular OWEC aspects gained during this phase (e.g. fatigue due to dynamic response on combined wind and wave loading, very significant heave forces on gravity based support structures due to extreme waves in shallow waters) led to the consideration of three support structure concepts rather than the initially considered two (lower row in figure 13).

Particular innovations were directly related to the integrated approach:-

- integrated development of support structure concepts and installation procedure,
- simultaneous optimisation of wind turbine (rotor speed, blade layout) and support structure (i.e. structure stiffness) with the main goal of reduction of aerodynamic fatigue loads,
- consideration of overall dynamics of OWEC in the support structure design,
- development of O&M strategies based on Monte-Carlo simulations,
- development of structural reliability analysis for an OWEC support structure.

Next, the novel cost model was used to evaluate different offshore wind farms assembled from the developed sub-system concepts (see conceptual design) for the six pre-selected sites (see feasibility study). For the same OWECS concept the

energy costs between the six compared sites, which all were considered initially as promising, differed by a factor of up to 1.6 (figure 4). Furthermore, a reduction of the energy cost of about 20 % (!) was found by application of a support structure of the monopile instead of a gravity based monotower type.
The economic performance together with some other criteria led to the selection of the final OWECS concept and the related site (table 2).

Structural design

During the structural design phase the selected concept was further worked out and interactions between sub-systems were fully considered.

This integration facilitated several innovations:-

- An appreciably high farm availability of 96.5% offshore in relation to 98.5% when land-based was achieved by a rational approach comprising a gradual improvement of the turbine's reliability and maintainability with respect to the current onshore state-of-the-art and an innovative operation and maintenance solution. The latter included both an optimised operation and maintenance strategy and a cost-efficient treatment of the 'cranage problem' by a permanently and quickly available self-propellered modified jack-up.
- Close cooperation between structural design and dynamic simulations of the OWEC facilitated a soft-soft monopile design even in a demanding North Sea environment which was beneficial for the large two-bladed wind turbine and resulted in an even further cost reduction of the support structure and the installation procedure.
- The aerodynamic efficiency of the wind farm, the cable costs of the grid connection and the space requirement of the OWECS was balanced.
- Placement of the OWEC transformer in the nacelle was found optimal after consideration of wind turbine, support structure, grid connection and maintenance aspects.

It is worth noting that neither during the structural design phase nor after the final evaluation of the design solution, major revisions of the design were required. The main reason for this was that the conceptual design had already been carefully examined with respect to technical feasibility and economic performance.

Economic performance of design solution

The structural design phase was concluded with a detailed economic analysis and parameter study on important cost drivers that confirmed the viability of the solution. An overview of main data is given in table 2.

Based upon economic parameters as usually applied by public sector utilities, i.e. 20 years loan and 5% real interest rate [10], the levelised production costs were determined at 5.1 ECUct/kWh. This energy cost is related to a rather conservative estimate of the annual mean wind speed of 8.4 m/s at 60 m height.
With a higher wind speed of 9 m/s, as adopted by other recent studies, e.g. [8, 11], for very similar sites the energy cost is significantly lower down to approx. 4.4 ECUct/kWh.

Main design data	
Farm capacity	300 MW i.e. 100 times 3 MW
Wind turbine	Kvaerner Turbin WTS 80M (3 MW - 80 m)
Support structure	soft-soft monopile
Offshore grid connection	AC submarine cables 24 / 150 kV
Array efficiency	93% (uniform spacing 10 *D*)
Transmission efficiency	96%
Availability	96.5%
Net annual energy yield	787 GWh/year
Site data	
Location	Dutch North Sea, near IJmuiden
Assumed annual wind speed (60 m)	8.4 m/s (*A* = 9.5 m/s, *k* = 2.2)
Distance from shore	11.4 – 18.6 km (15 km from centre)
Water depth	14 - 19 m (LAT)
Economic data	
Wind turbine cost	170 MECU
Support structure & OWEC instal. costs	118 MECU
Offshore grid connection cost	77 MECU
Project management cost	2% of total capital cost
Total capital costs	372 MECU (1240 ECU/kW)
Operation & maintenance cost	9 MECU / year
Decommissioning cost	10% of initial capital
Economic lifetime	20 years
Real interest rate	5%
Levelised Production Cost (LPC)	5.1 ECUct/kWh (4.4 ECUct/kWh for 9 m/s at 60 m)

Table 2: Main design and economic data of the design solution

For the particular site onshore grid connection costs, which were not considered so far, would account for only relatively small additional costs (i.e. some percents of the energy cost) as long as no major grid reinforcement, which would be beneficial also for other plant or consumers, have to be paid.

In order to judge the economic value of the design solution the results are compared to some other recent projects and studies on offshore wind energy (table 3, figure 14). Three groups can be distinguished. Firstly, four existing plant all employing turbines of the 500 kW class at sheltered location are given, i.e. Vindeby [12], Lely [13, 14], Tunø Knob [15] and Bockstigen-Valar (Gotland) [16]. Next, some older studies are compared, i.e. the Phase CII [17] and the Blekinge study [18], both considering 3 MW machines and the RES (Renewable Energy System) study [19] referring to 400 kW units.
Finally, attention is directed to six recent studies based upon wind turbines in the megawatt class i.e. the SK Power Study [20], the Thyssen study [21], the German BMFT study [22], the proposed project Scroby Sands [23], the prime location 'Horns Rev' of the Danish Plan of Action for Offshore Wind Energy [10] and the Dutch Nearshore study [11].

Any economic comparison of the different studies and projects is difficult and is therefore only of more or less qualitative nature. Beside the inherent inaccuracy of any paper study also significant differences exist in price level, economic parameters, exchange rates, environmental and technical conditions and complicate a comparison. Therefore here not only the energy costs but also a number of specific costs and the energy yield are provided. Levelised production costs are all based on an repayment period of 20 years and a real interest rate of 5% regardless the economic parameters used in the original studies.

Despite all differences some trend can be seen in the different projects.

- Firstly, a dramatic economic achievement is observed between on one hand the old studies carried out in the 1970s and 1980s from which the Phase CII is a typical representative and on the other hand of the small scale prototypes and the studies from the mid to end 1990s.
- Secondly, a learning curve can be seen from the small-scale prototypes and the latest studies which is founded on improving maturity of the technology and increase in the size of both the wind turbines and of the entire wind farms.
- Thirdly, offshore wind energy likewise to wind energy on land is approaching the cost level of other energy sources. For instance typical energy costs based on 5% real interest rate of coal and gas fired plant range in the order of 3.7 - 5.5 ECUct/kWh and 3.1 - 4 ECUct/kWh, respectively. Further comprehensive information on the economic situation of wind energy and its relation to other plant is provided by [24] or in the appendix of the Vol. 3 of the Opti-OWECS report.
- Finally, the Opti-OWECS design solution achieves a prime position with respect to other studies and it is clear that it meets its particular objectives, i.e. demonstration of a commercial large-scale OWECS to be built in a medium time scale and identification of optimal designs which lead to a significant reduction in energy costs.

Cost breakdown and parameter study

Operation and maintenance costs showed a significant contribution in the cost breakdown of the estimated energy costs (figure 16). This effect resulted from an optimisation process because optimum energy costs required high OWECS availability, which could only be achieved through high O&M effort and permanently available heavy maintenance equipment.

Furthermore the energy cost showed an appreciably high sensitivity with respect to the energy yield (figure 17) which implies a number of consequences. Firstly, excellent wind conditions are essential and great care is required in the estimate of the long term wind conditions. Secondly, only if high availability is guaranteed the potential of exposed sites can be exploited. Finally, it is economic to invest a relatively high amount of capital in order to achieve high and reliable energy output. For instance, a 30% increase in wind turbine costs corresponds only to 10% extra energy cost.

A parameter study on the relation between the annual mean wind speed and the levelised production cost (figure 18) demonstrated again the paramount importance of operation and maintenance aspects since without even further improvement of the reliability the energy cost at more hostile sites flatten or even increase due to the poorer farm availability.

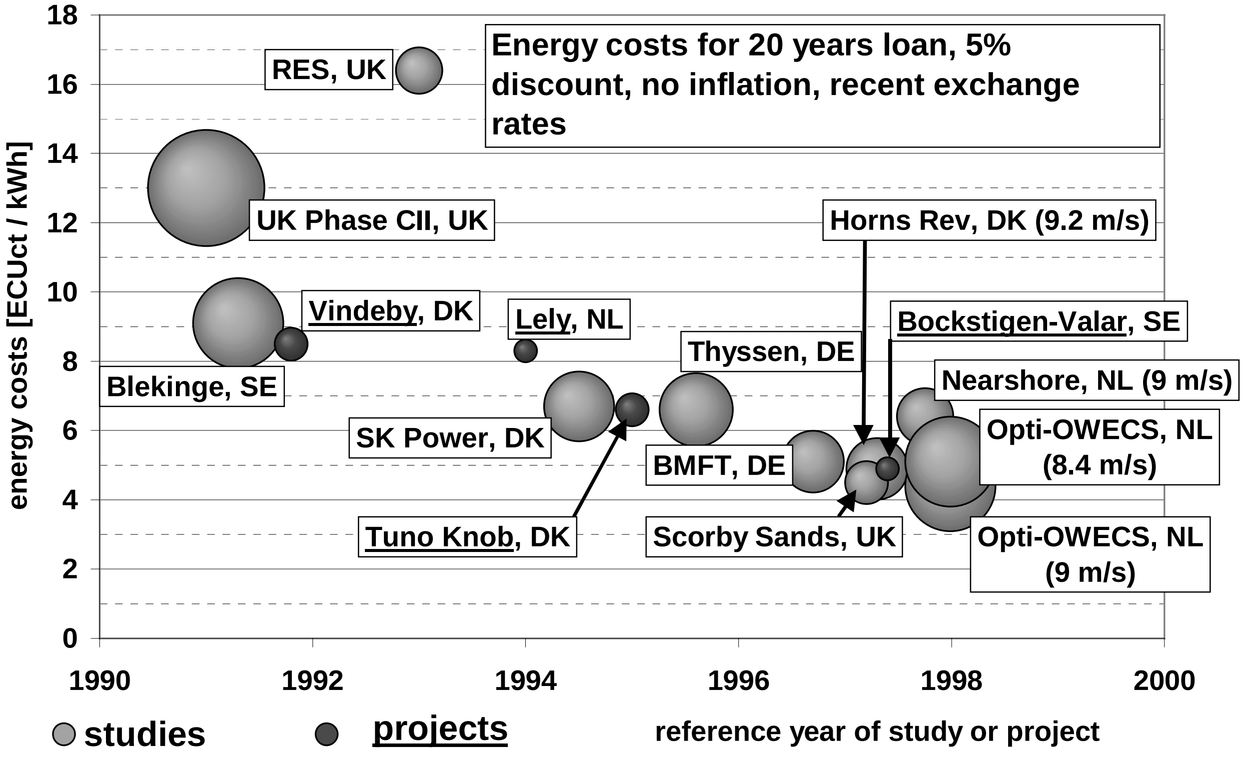


Figure 14: Comparison of energy costs between different studies and projects
(Size of bubbles proportional to wind farm capacity)

Name of project or study and site	Study (S) Project (P) Year	Capacity [MW]	V_{hub} [m/s]	H_{hub} [m]	Distance from shore [km]	Water depth [m]	Spec. cost [ECU/kW]	Capacity factor [-]	Energy costs [ECUct/kWh]
Phase CII, North Sea, UK	S ‘91	711 * 3	8.3	~55		16 - 21	1900	19%	13
Blekinge, Baltic, SE	S ‘91	98 * 3	9.0	90	10	15 – 20	3000	32%	9.1
Vindeby, Baltic, DK	P ‘91	11 * 0.45	7.5	37.5	1.5	3 – 5	2150	27%	8.5
RES, North Sea, UK	S ‘93	41 * 0.4	7.4	33	~5	~12	4500	33%	16
Lely, IJsselmeer, NL	P ‘94	4 * 0.5	7.7	41.5	1	5 – 10	1700	22%	8.3
SK Power, Baltic, DK	S ‘94	180 * 1	8.2	47	17	8 – 10	1900	31%	6.7
Tunø Knob, Baltic, DK	P ‘95	10 * 0.5	~7.5	43	6	3 – 5	2200	34%	6.6
Thyssen, Baltic, DE	S ‘95	140 * 1.5	~7.8	60	4	5 – 10	1400	27%	6.6
BMFT, Baltic, DE	S ‘95	100 * 1.2	~7.5	60	~7	~10	1250	31%	5.1
Horns Rev, North Sea, DK	S ‘97	80 * 1.5	9.2	55	~15	5 – 11	1650	40%	4.9
Scroby Sands, North Sea, UK	S ‘97	25 * 1.5	~8.2		3		1150	~31%	~4.5
Bockstigen-Valar, Baltic, SE	P ’97	5 * 0.55	8	41.5	4	6	1500	33%	4.9
Nearshore, North Sea, NL	S ’97	~ 100 * 1	9	60	8	13 – 17	1900	34%	6.4
Opti-OWECS, North Sea, NL	S ‘98	100 * 3	8.4	60	11.5	12 – 20	1250	30%	5.1
			9					34%	4.4

Energy costs for 20 years loan and 5% real interest rate, no inflation, recent exchange rates.

Table 3: Comparison of energy costs between different studies and projects

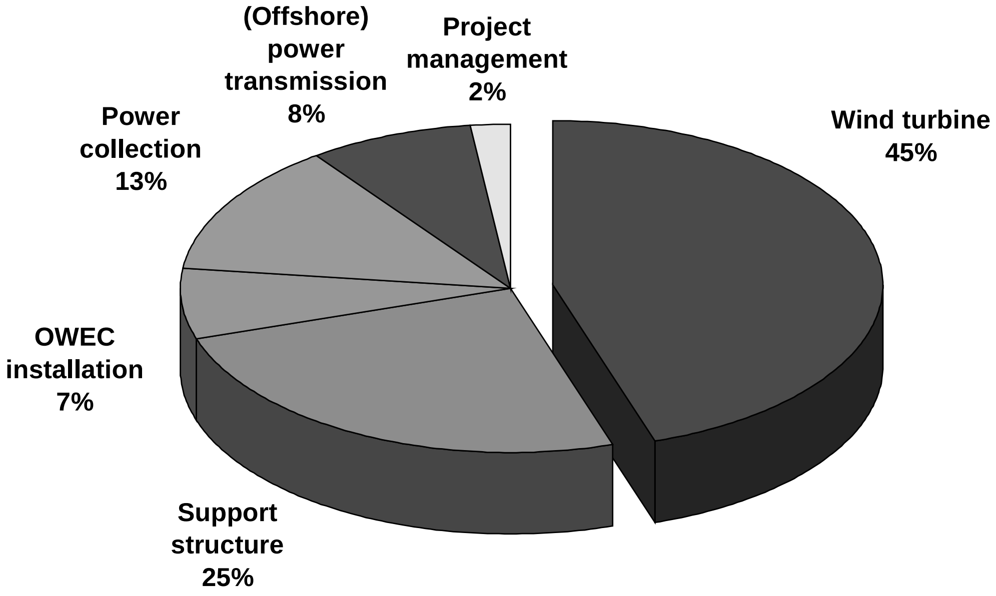


Figure 15: Breakdown of initial capital cost for Opti-OWECS design solution

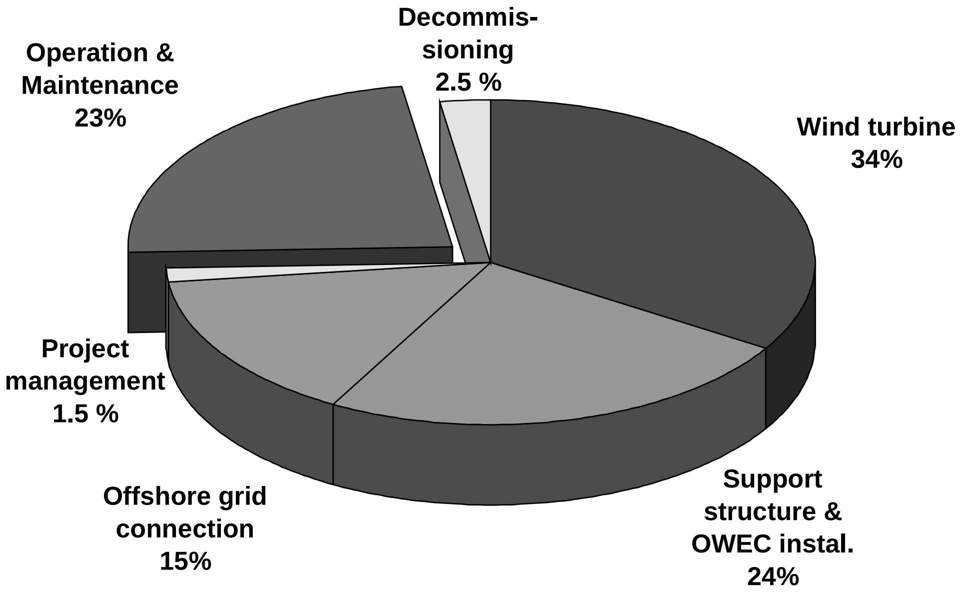


Figure 16: Contributions to energy costs of Opti-OWECS design solution
(Annual mean wind speed 8.4 m/s, 20 years loan, 5% real interest rate)

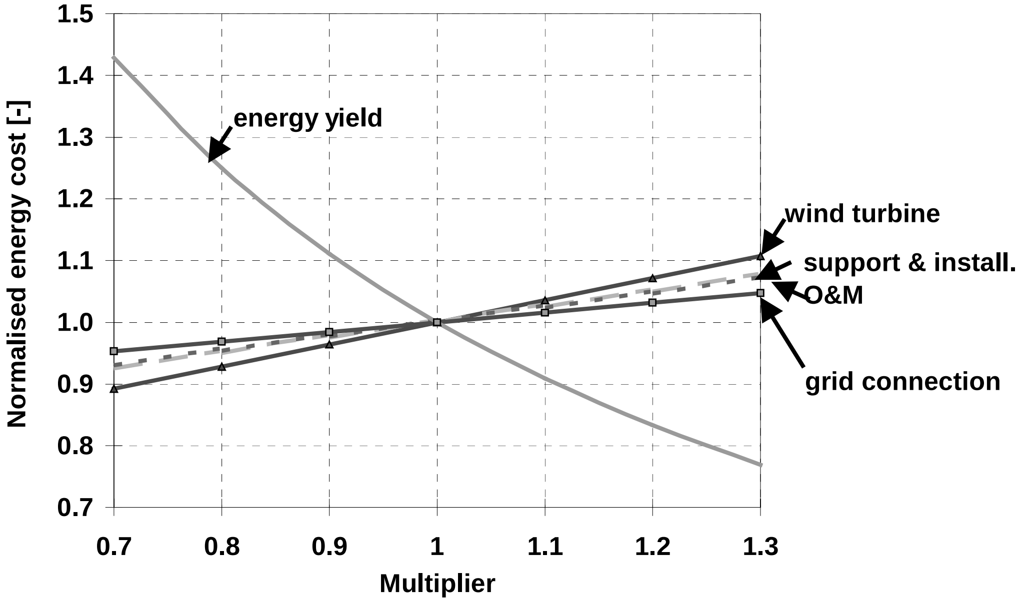


Figure 17: Sensitivity of normalised energy cost on (isolated) variation of sub-system cost, O&M costs and energy yield, respectively

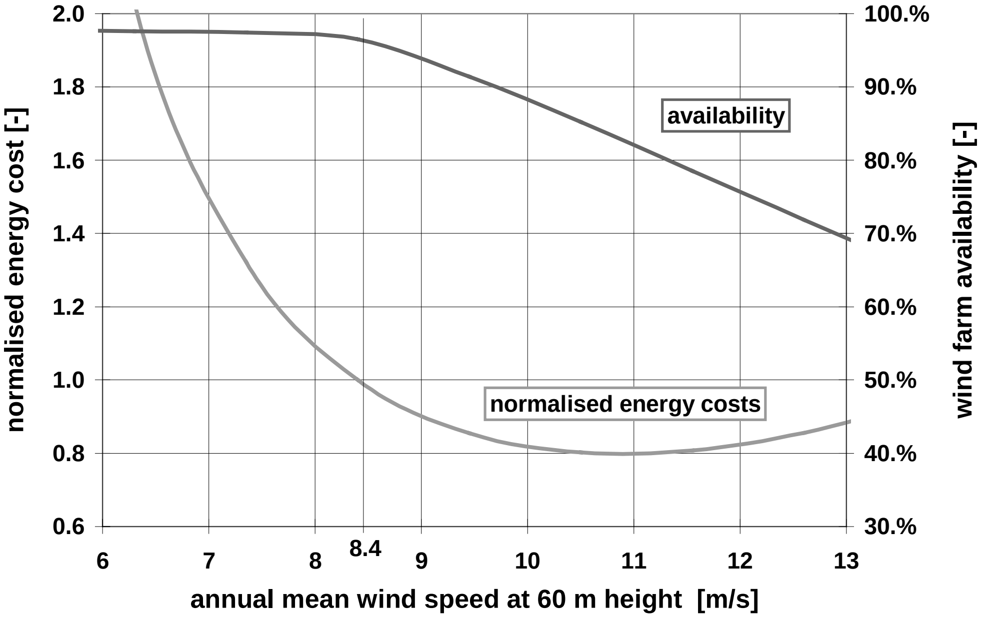
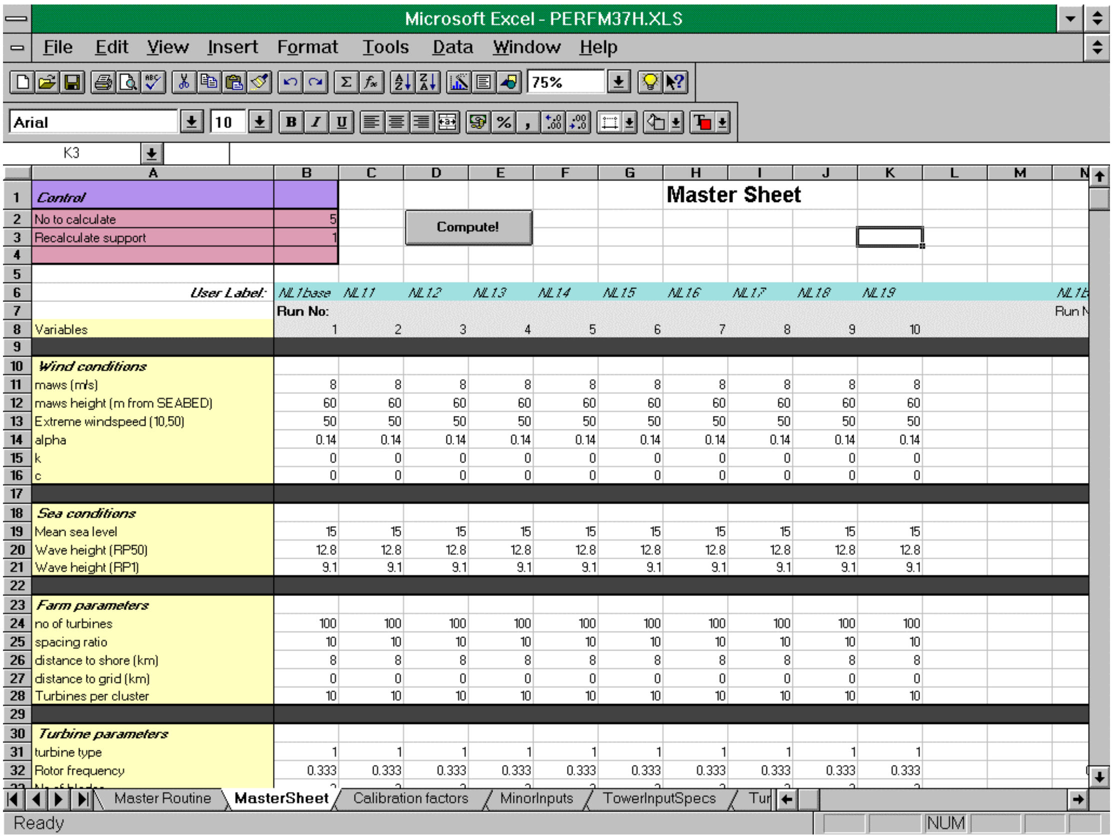


Figure 18: Normalised energy costs and farm availability against mean annual wind speed at 60 m

4.5. User Guide for OWECS cost model

To ensure that it has a good applicability on a standard PC, the novel OWECS cost model runs within the widely used Microsoft Excel 5.0 spreadsheet system. This environment offers the advantage of providing a proper programming language (Visual Basic for Applications), with which the vast majority of the models computational features have been implemented. At the same time, the user can interact with the model using a familiar spreadsheet interface (figure 19). The model runs relatively quickly, taking less than 10 minutes to evaluate a single OWECS configuration on an IBM PC compatible with an 80 MHz 486 DX2 processor.



	A	B	C	D	E	F	G	H	I	J	K
1	*Control*							**Master Sheet**			
2	No to calculate	5									
3	Recalculate support	1									
4											
5											
6	*User Label:*	*NL1base*	*NL11*	*NL12*	*NL13*	*NL14*	*NL15*	*NL16*	*NL17*	*NL18*	*NL19*
7		**Run No:**									
8	Variables	1	2	3	4	5	6	7	8	9	10
9											
10	***Wind conditions***										
11	maws (m/s)	8	8	8	8	8	8	8	8	8	8
12	maws height (m from SEABED)	60	60	60	60	60	60	60	60	60	60
13	Extreme windspeed (10,50)	50	50	50	50	50	50	50	50	50	50
14	alpha	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
15	k	0	0	0	0	0	0	0	0	0	0
16	c	0	0	0	0	0	0	0	0	0	0
17											
18	***Sea conditions***										
19	Mean sea level	15	15	15	15	15	15	15	15	15	15
20	Wave height (RP50)	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8
21	Wave height (RP1)	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1	9.1
22											
23	***Farm parameters***										
24	no of turbines	100	100	100	100	100	100	100	100	100	100
25	spacing ratio	10	10	10	10	10	10	10	10	10	10
26	distance to shore (km)	8	8	8	8	8	8	8	8	8	8
27	distance to grid (km)	0	0	0	0	0	0	0	0	0	0
28	Turbines per cluster	10	10	10	10	10	10	10	10	10	10
29											
30	***Turbine parameters***										
31	turbine type	1	1	1	1	1	1	1	1	1	1
32	Rotor frequency	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333	0.333

Figure 19: The main user interface of the cost model

5. Main conclusions

i.) Development of practical and economic solutions for OWECS

- Offshore wind energy is fully viable and energy costs in the order of 5 ECUct/kWh (8.4 m/s at 60 m, 20 years loan, 5% real interest rate, without costs for onshore grid connection) are achievable at sites with good wind conditions and good availability.
  This estimate is based upon currently available technology within an innovative, integrated design approach considering the entire system. Such cost level depends to a large extent on the OWECS availability achieved. At hostile offshore sites values close to the onshore performance are possible only if the failure rate of the wind turbines is reduced by a factor of (at least) 2 within the next 5 years.
- Offshore application of a 3 MW wind turbine with improved reliability and maintainability is achievable, realistic and economic.
- The support structure of the soft-soft monopile type combined with wind turbines up to about 3 MW offers superior performance at demanding Southern North Sea environments with water depths up to 20 m (LAT) and firm soil conditions. Beyond this turbine size, for greater water depth, weaker soils or even more exposed sites other support structure concepts are probably required.
- Significant cost reductions are possible by innovative installation methods considering the entire OWEC unit. Conceptual solutions have been developed for floating installation of gravity based designs as well as for both floating and lifted installation of monopile structures.
- The dynamics of economic support structures have to be tailored with respect to the sometimes-opposing requirements from the wind turbine and the offshore environment.

ii.) Identification of cost drivers and estimation of costs

- Energy costs of entire regions in northern European waters have been estimated in a consistent manner.
- Results of the comparison of energy costs in different regions confirm the huge offshore wind energy resources within the EU also reported by previous work. While the absolute values of the figures in the energy cost maps are at best tentative in nature, it is concluded that a significant proportion of these resources will be exploitable on a commercial or near-commercial basis within the near future (assuming that technical innovation within the wind energy industry continues its current rapid progress).
- Comparisons are made of OWECS concepts based on turbines with rated capacities of both 1.5 MW and 4 MW at many real locations around Northern Europe.
  Using a larger scale wind farm does not influence the absolute minimum cost level for which electricity can be produced at prime sites in a significant way. Instead, the benefit offered by large scale OWECS is the greater proportion of sites available for lower cost levels. Therefore exploitation of the sites with

superior performance can start on a near to medium time scale based on mature ‘megawatt technology’. For an utilisation in the range of (tens of) gigawatt on a longer time scale, development of multi-megawatt technology may offer advantages.

- Real offshore sites offer the most promising locations but require innovative solutions for the operation and maintenance problem, e.g. by tackling the personnel transport and cranage problem, specific operation and maintenance strategies and improved turbine reliability.
- Windy North Sea sites offer better economics than most sites in the more sheltered Baltic Sea.
- Gravity based support structures might require an economically unattractive high amount of ballast due to the quite considerable heave forces generated by extreme waves in shallow waters.
- Reduced wind shear and the costs involved in the support structure, OWEC installation and maintenance, lead to a lower optimum hub height at sea in comparison to the land situation
- Although is it not a sensitive parameter, the most economic turbine spacing offshore is considerably larger than on land.

iii.) Extending the state-of-the-art

- In several fields, e.g. support structure design, OWEC installation, operation and maintenance, OWEC dynamics, design approach, structural reliability considerations, etc., the study demonstrated new propositions which contribute significantly to a mature offshore wind energy technology.
- The economic exploitation of the offshore wind energy potential requires a symbiosis of wind energy and offshore technology. Although this seems obvious it is by no means evident and requires open minds of both communities.

iv.) Consideration of offshore wind farms on a system level

- Consideration of tower and foundation as one sub-system, of wind turbine and support structure as one unit and of the offshore wind farm (including all operations, infrastructure and onshore grid connection) as the main system, results in more appropriate and economic designs than the separated treatment of sub-systems.
- Design methodologies recently developed for complex civil engineering systems are also adequate for offshore wind farms. Within the integrated OWECS design approach the goal of the design process can be controlled effectively by aspect-systems as for instance levelised energy costs, adaptation to site conditions, installation and commissioning efforts, availability, overall dynamics, etc.
- The application of a consistent terminology for OWECS proved its value, not only in the daily communication between the participants but also in the philosophy underlying the design work within the project.
- The dynamics of an entire offshore wind energy converter (OWEC) are complex but their consideration from the outset of the design solution offers a significant

potential for cost reduction especially if fatigue (whether of aerodynamic, hydrodynamic or combined origin) is governing.
- Dedicated design tools for OWECS are required due to the system properties of an offshore wind farm and the variety of relevant site parameters.

v.) Highlighting the importance of operation and maintenance aspects

- The availability of wind farms at real offshore sites employing commercial wind turbines without significantly improved reliability and without optimised operation and maintenance solution may be unacceptably low, e.g. 70% or even less.
- Reliability of offshore wind energy converters and operation and maintenance solutions should be optimised with respect to the (levelised) energy production costs rather than either to capital or operation and maintenance costs.
- Operation and maintenance costs mainly related to the wind turbine can account up to 30% and more of the energy costs.
- The operation and maintenance problem can be tackled by a rational approach using realistic assumptions on failure rates, Monte-Carlo simulations of the O&M behaviour of the system, etc.

vi.) Development of a cost model and other OWECS tools

- Estimates of investment as well as energy costs of offshore wind farms are much more complex than for their land based counterparts; therefore any cost prediction requires careful interpretation and different studies are difficult to compare. Nonetheless, an OWECS cost model valid for a specific configuration is an extremely useful tool during the conceptual design phase and for the comparison of different sites.
- If extreme loads are governing significant savings in support structure cost are possible by application of state-of-the-art methods for structural reliability analysis as have recently become available in the offshore engineering community for the oil & gas industry.
- Development of a Monte-Carlo based simulation tool for the operation and maintenance behaviour of offshore wind farms proved to be a prerequisite for a rational operation and maintenance approach.
- Time domain simulations of the overall dynamics of OWEC are an important design tool. Proper use can result in less risky and more economic solutions.
- Support structure design for demanding environments, certainly if fatigue becomes important, requires usage of high quality databases on the correlation of wind and wave conditions as state-of-the-art in offshore technology

6. Recommendations for future work

i.) Development of practical and economic solutions for OWECS

- Installation of large multi-megawatt OWEC remains an area of potential cost reduction and further investigations are recommended on both floating and lifted installation.
- Apart from further cost reduction in the field of operation and maintenance new techniques for more cost-efficient cable-laying and cable connection to the OWEC units should be developed.

ii.) Identification of cost drivers and estimation of costs

- Further cost reduction and economic benefits are expected from development of industrial infrastructure for construction of OWEC units, HVDC transmission, financial instruments for exploitation.
- The cost modelling and cost analysis of OWECS should be extended, e.g. by additional support structure and wind turbine models, refinement of the GIS based cost model.

iii.) Extending the state-of-the-art

- The integration of very large offshore wind farms in the international electricity system will result in specific design requirements. Thus, large OWECS should be designed with due consideration for the level of the overall energy system rather than *only* for the level of the particular offshore wind farm. The consequences of this demand on e.g. wind turbine design need careful investigation.
- The risk involved in large offshore wind farms should be reduced by improving the understanding of the offshore wind conditions and associated other met-ocean parameters in order to facilitate more reliable predictions of the energy yield, optimum design and optimum strategy for both installation and operation and maintenance.

iv.) Consideration of offshore wind farms on a system level

- The integrated OWECS design approach should be further developed, e.g. by application to real plant.
- The OWECS guidelines of Germanischer Lloyd were, as far as known by the authors, used for the very first time in a design situation. Application proved to be successful, nonetheless verification, further development and clarification of particular issues should be addressed in the near future.

v.) Highlighting the importance of operation and maintenance aspects

- The importance of O&M aspects should be considered as a main design driver, especially for the wind turbine. Even further advanced design approaches, e.g. design for RAMS (Reliability, Availability, Maintainability and Serviceability), should be developed.

vi.) Development of a cost model and other OWECS tools

- With respect to the high importance of operation and maintenance aspects the O&M simulation tool should be further developed e.g. improved weather simulation, wind turbine reliability model.

- Dynamic considerations particular to OWEC should be taken into account already at an early stage of the design process. Although very successful, the analysis approach of the overall dynamics of OWEC should be further refined and verified by measurements on suitable offshore wind energy converters of different type and at distinct sites.
- The structural reliability methods should be applied not only to the support structure under extreme conditions but also to the entire OWEC under different operating conditions.

7. Anticipated benefits and exploitation plans

7.1. Anticipated benefits

The results obtained from the Opti-OWECS Project are an important contribution in making the use of large-scale offshore wind turbines a viable proposition.

The possible industrial applications of the derived results include:-

- the (preliminary) site selection of offshore wind farms (OWECS),
- the (preliminary) selection of the design concepts of the sub-systems of an OWECS (wind turbine, support structure, grid connection),
- the detailed structural design of the sub-systems of an OWECS (wind turbine, support structure, grid connection),
- the economic optimisation of an OWECS (including all costs),
- the installation procedure of an OWEC support structure,
- the determination of the Operation & Maintenance strategy of an OWECS

7.2. Exploitation plans

Institute for Wind Energy, Delft University of Technology, NL

The Institute for Wind Energy (IvW) is one of the two leading institutes concerning the development of design tools for OWECS. During the course of the Opti-OWECS project the expertise of the IvW on offshore wind energy in general has been largely extended. It is the objective of the IvW to apply this knowledge in (inter)national projects and studies on offshore wind energy and to do design consultancy work. The institute is already involved in the preparations of several offshore projects and studies, among which a study on the verification of OWECS design tools.
Another objective is the extension of the research work on offshore wind energy; part of the project work will be used in the scope of a Ph.D. work on offshore wind energy.

The results of the project will be presented to a broad public. To this end publications are foreseen in (inter)national journals, magazines and newspapers. Furthermore the main results will be presented at (inter)national conferences and possibly a special workshop will be organised.
In addition the IvW will continue its role as focal point of information for the industry on offshore wind energy.

Renewable Energy Centre, University of Sunderland, UK

The primary strategy pursued by the University of Sunderland (US) will be to disseminate the work through academic publications. This will assist US in securing further research and consultancy work in wind energy and other fields.

The scope for selling the cost models on a commercial basis will be investigated. If a suitable market can be identified, then it is hoped that it will be possible to pursue this opportunity. If, as is thought likely, there does not appear to be a sufficient market then it is hoped to make the cost model available to interested parties on an unsupported ‘incurred costs’ basis.

The cost models could form the basis for further substantial investigations of the technical economics of novel wind energy schemes. Possibilities for further collaborative development and use of the models will be actively sought.

Kvaerner Oil & Gas Ltd., UK

Kvaerner Oil & Gas is one of the World’s leading suppliers of oil and gas offshore platforms. Kvaerner has ambitions to achieve a similar market position in the supply of OWEC structures as they do for oil and gas structures.
Kvaerner propose to develop a strong design capability for support structures and to bid, as appropriate, for fabrication and installation activities.

Based on experience from the Opti-OWECS Project, Kvaerner Oil & Gas have already undertaken consultancy work directed to the deployment of offshore wind farms in the United Kingdom and Denmark and as such have established a design reputation.

Kvaerner Turbin AB, S

To be successful in the energy market reference applications are a must. The strategy from Kvaerner Turbin has been to try to realise a project with a small wind farm together with the Swedish utilities and the government. This wind farm should be placed near shore so that a few offshore turbines could be added to the group when the operation of the first 2-3 onshore machines is satisfactory.
The application and further development of the offshore turbine for the Opti-OWECS project covers aspects which are also of value for the on land development at Kvaerner Turbin, such as system cost reduction, availability increase and serviceability improvements.

Workgroup Offshore Technology, Delft University of Technology, NL

As an academic institution commercial exploitations of its contribution to the Opti-OWECS project is not the prime motivation of the Workgroup Offshore Technology (WOT). However, the knowledge and experience gained in offshore wind energy applications and the further research and development efforts already planned as a direct result of the success of the project may well assist WOT in playing a role as a consultant in future offshore wind energy projects.

During the next few years WOT will present the results of its work at international conferences, both at offshore and wind energy conferences. They are firmly committed to continue their R&D efforts in this field. A Ph.D. project has been initiated on the development of advanced design methods for OWEC support structures, with particular emphasis on research into fatigue due to combined wave and wind loading and the reliability of the structure against extreme environmental loading.

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Appendix A OWECS terminology

Offshore wind energy is a fairly new and multi discipline field. Unfortunately no uniform terminology exist and misunderstandings can occur quite easily. Therefore within the Opti-OWECS project one has agreed upon a particular terminology, conventions and reference systems in order to make the internal and external communication more effective. Here a short version of [6] is presented.

Preface

In principle, the common practice concerning notation and convention within the considered disciplines, i.e. wind energy technology, offshore technology and engineering economics should be used. However, harmonisation is required in the description of the entire system and its components, the interfaces between sub-systems and the structural design. The two former aspects are treated in this appendix.

1 Offshore wind energy conversion system (OWECS)

offshore wind energy conversion system (OWECS)

Entire system, comprising (usually) several wind energy converter units, for conversion of wind energy into electric power including the wind turbines, the support structures, the grid connection to the power delivery point and operation and maintenance aspects.

Note that the environment, i.e. air, water and soil as well as the utility grid, are not considered as a part of the OWECS.

offshore wind farm

synonym for OWECS

2 Sub-systems of the OWECS

```
OWECS
(offshore wind energy conversion system, offshore wind farm)
   |
   ├─ offshore wind energy converters (OWEC)
   |        |
   |        ├─ wind turbine (WT)
   |        └─ support structure
   ├─ grid connection and wind farm layout
   └─ operation and maintenance aspects
```

Figure A-1: Sub-systems of the (bottom-mounted) OWECS

Sub-systems of an OWECS (figure A-1) comprise either physical parts of the system e.g. wind turbine, support structure or important aspects as for instance operation and maintenance aspects.

offshore wind energy converter (OWEC)
single unit of the OWECS comprising wind turbine and support structure.[*]

wind turbine (WT)
Component of an offshore wind energy converter that transforms wind energy into electric power on generator voltage or AC-rectifier voltage, comprising rotor, nacelle with entire interior, control and safety system and electrical turbine system.

support structure (bottom-mounted)
Structure that supports the wind turbine and transfers the loading into the soil. Hence, the support structure comprises both the tower *and* the foundation.

grid connection and wind farm layout
This comprises two main parts that are considered for convenience as one sub-system.

Firstly, electrical system that takes the power provided at the turbine connection points and collects it at the wind farm collection point(s) and successively transmits it to the onshore connection point with the public grid.

Secondly, the physical arrangement of the OWEC units.

operation and maintenance aspects
auxiliary facilities, equipment and strategy required for operation, maintenance, control and administration of an OWECS

3 Boundaries of OWECS sub-systems

wind turbine and support structure
The fixed end of the yaw mechanism of the nacelle is defined as boundary between the (horizontal axis) wind turbine and the support structure. All geometric and dynamic conditions are expressed with respect to the reference frame of the support structure.

wind turbine and grid connection
The turbine switch gear or circuit breaker at the tower base is defined as boundary between electrical system of the turbine and the grid connection. The voltage at the connection point corresponds to the generator or the inverter (if any). Although a transformer might be installed at the wind energy converter unit it is regarded as part of the grid connection.

grid connection and utility grid
The power of the OWECS is provided as three-phase AC at the voltage level of the utility grid to which the wind farm is connected. In absence of other explicit

---

[*] No plural of the abbreviation ‘OWEC’ should be used; instead one may use ‘OWEC units’, full out spelling or the singular form of ‘OWEC’, if possible.

conventions the connection point is situated at the first dry location onshore regardless the actual grid infrastructure on land.

The main components of the OWECS sub-systems are defined by figure A-2.

```
OWECS
  ├─ wind turbine
  │    ├─ rotor
  │    ├─ (mechanical) drive train
  │    ├─ nacelle housing and bedplate
  │    ├─ control and safety system
  │    └─ electrical turbine system
  ├─ support structure
  │    ├─ tower
  │    └─ foundation
  ├─ grid connection and wind farm layout
  │    ├─ power collection
  │    └─ power transmission
  │    │    ├─ offshore
  │    │    └─ onshore
  │    └─ wind farm layout
  └─ operation and maintenance aspects
       ├─ maintenance facilities and equipment
       ├─ control, safety and administration facilities
       └─ operation and maintenance strategy
```

Figure A-2: Components of the OWECS sub-systems