Final Technical Report for

Recommendations for Design of Offshore Wind Turbines

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Introduction

This document reports on the main results and outcome achieved in the EU-project “Recommendations for design of offshore wind turbines”, in short RECOFF (contract no. ENK5-CT-2000-00322). Together with the project homepage, which contains all notes and reports prepared during the course of the RECOFF project, including a number of papers summarising the most important results of the project, this report forms the final technical reporting of the RECOFF project. For ease of access to the information embedded in the project documents, a list of the documents, with abstracts and organised by subject, has been included in this report. From this list links to the project homepage are made. The homepage address is

http://www.risoe.dk/vea/recoff/

A CD-ROM with the final reporting, including the homepage, is available.

None of the results produced in the RECOFF project are confidential, thus Chapter 2 on the detailed final reporting is not confidential, and may be published along with Chapter 1.

1 Summary of Final Report (Publishable)

1.1 Executive publishable Summary

1.1.1 Project Objectives

The objective has been to prepare guidelines and recommendations for design of offshore wind turbines. The main intended use of the project results has been the provision of recommendations for European and national standards for offshore wind turbines and the development of certification rules for offshore wind turbines. The success of the project will be marked by the delivery of reliable and robust design methods and certification rules needed for the safe development of offshore wind farms. This will have direct impact on the readiness to invest in offshore wind energy projects and cut objections connected with project safety.

1.1.2 Main Results

Readily available information has been reviewed and utilisation to the extent possible has been made. In several areas a need for research was identified and generic results were obtained. Specifically, we emphasize the following subjects where recommendations have been obtained:

- *External conditions*: review of existing standards, regulations and literature resulting in recommendations for good practice.
- *Analysis methods*: methods for lumping, mainly with respect to wave loading, of fatigue load cases.
- *Analysis methods*: principle of synthesizing load cases for different wind directions, wind speeds, and sea states in order to obtain extreme response during normal operation.
- *Design load cases*: drafting, partially based on project results, proposals for a suitable, i.e. limited and representative, DLC table for offshore turbines.
- *Probabilistic methods*: review of general methods and application of probabilistic calibration methods to the combined action of wind and wave loads in the storm event.
- *Structural integrity*: based on discussions about reliability levels onshore and offshore and based on comparisons with current practise proposals for safety factors in fatigue and extreme load events are given.
- *Operation and maintenance*: documents with recommendations regarding labour safety, and monitoring of turbine performance have been prepared.

1.1.3 Implementation of Results

The RECOFF project has run in parallel with a working group (TC88-WG03) set up by the IEC (International Electro-technical Commission) and assigned the task of preparing a separate international standard for design of offshore wind turbines. Several of the RECOFF partners are members of the IEC-TC88-WG03, which has caused a strong interaction with current international standardisation work, and a rapid implementation of the findings of the RECOFF project in terms of obtaining the status of being standards' material. Once, approx. one year from now, the IEC standard 61400-3 has been accepted it will shortly afterwards become a European CENELEC standard. Thus the intended aim of the project has been achieved. Already some project results have been applied in the IEC standard 61400-1, which is the general standard for design requirements for wind turbines to which 61400-3 refers.

1.2 Publishable Synthesis of Final Report

Since no part of the project is confidential the reader is referred directly to Chapter 2 of this report. For a summary the reader is referred to the previous Section 1.1. Moreover, a number of papers that summarise the major results of the project have been prepared with the intension of reaching a greater public. Some of them have already been published. The papers, which may be found on the project homepage, are:

1. Recommendations for design of offshore wind turbines External Conditions, RECOFF doc. no. 82
2. “Extreme structural loads at non-extreme mean wind speeds”, RECOFF doc. no. 80 (presented at EWEC 2004)
3. “Calibration of Partial Safety Factors for Extreme Loads on Wind Turbines”, RECOFF doc. no. 41 (presented at EWEC 2003)
4. “Partial Safety Factors and Characteristic Values for Combined Extreme Wind and Wave Load Effects”, RECOFF doc. no. 37 (presented at EAWE conference 2004 and published in ASME journal of Solar Energy Engineering, May 2005)
5. Design of Concrete Structures for Offshore Wind Turbines, RECOFF doc. no. 50

2 Detailed Final Report (Publishable)

2.1 Objective and Strategic Aspects

Below follows a review of the scientific/technical, socio-economic and strategic objectives of the project. Because there have been no reasons to change the direction of the project during its execution the objectives have stayed unchanged and are as stated in the project work plan. The wording below follows that of the work plan.

2.1.1 Scientific/Technical Objectives

The technical objective has been to prepare guidelines and recommendations for design of offshore wind turbines. The main intended use of the project results has been the provision of recommendations for European and national standards for offshore wind turbines and the development of certification rules for offshore wind turbines. Additionally, the results of the project may be used directly by manufacturers and consultants in their design process. These results may be of assistance in setting up tender documents for future offshore wind energy projects.

As described in Section 1.1.3 the main goal of contributing to standards has been achieved. Since the achievement of this goal has implied that the project has dealt with site assessment, analysis methods and safety levels, the additional objective of providing input useful for tender documents is also accomplished.

2.1.2 Socio-economic Objectives

Generally it is too early to judge the projects fulfilment of its socio-economic objectives because the fulfilment depends also on parties outside the project who should take up the outcome of the project. It may however be judged whether the project has fulfilled to provide the necessary basis for the realisation of the objectives. The socio-economic objectives have been:

- The project will help the European wind power industry keep its position as the market leader by provision and dissemination of reliable design methods for offshore wind power stations.
- The success of the project will be marked by the delivery of the reliable and robust design methods and certification rules needed for the safe development of offshore wind farms. This will have direct impact on the readiness to invest in offshore wind energy projects and cut objections connected with the project safety.
- The development of a market for large-scale offshore wind farms will bring new business to the existing wind turbine manufacturers throughout Europe. In addition, the requirement for large-scale manufacturing of offshore foundations and support structures will bring business to the offshore engineering industry and shipyards of Europe.

Having, as described in Section 1.1.3, through the project contributed substantially to the development of a draft IEC offshore standard, soon to be completed, it is the firm believe of the project partners that the project has succeed in providing one of the major prerequisites for the realisation of the socio-economic objectives.

2.1.3 Strategic Importance

There has been an immediate need for the project. Currently and over the next few years, the expansion in offshore wind energy accelerates and at project start there were no thorough and coherent guidelines for the design of offshore wind power plants. The existing offshore standards, mainly written for the offshore oil and gas exploitation, are not suitable to cover the offshore wind energy technology. A combination of these offshore standards and the existing onshore wind energy standards is a very complex process and significant technology gaps exist. One of the major tasks of the project has been to assist the IEC-TC88-WG03 standardisation group in its attempt to combine the practices of wind turbines engineering and offshore engineering. According to the main results listed in Section 1.1.2 the project has succeeded in this, and thus it is the view of the project partners that the project outcome has aided a development with the potential of preventing erroneous decision-making on large investments on a technical weak basis - and thereby avoidance of large erroneous investments that would turn the public against not only wind power but renewable energy in general.

The project partners cover a wide range of nationalities and professions. Thus research institutions, consultants and certification bodies have been involved in the project. Further people of different professional background i.e. wind energy and offshore technology are represented among the project partners. All of the mentioned aspects have contributed to forming new and strengthening existing networks, related to offshore wind power, of complementary expertise across Europe

In many densely populated countries of Europe it is becoming increasingly difficult for developers to gain the necessary approvals for installation of onshore wind farms. As a consequence there is a growing interest in the development of large-scale offshore wind farms. Because the project work has, as explained in Section 1.1.3, supported the drafting of a international standard that will eventually become a European standard the project partners finds that the project has contributed significantly to facilitate the gradual exploitation of the huge offshore wind energy resource available in the EU.

The pilot offshore wind farms currently operating in Danish waters are able to generate electricity at 0.065 - 0.085 €/kWh. The predicted price for energy from large-scale (150MW) wind farms planned for the Baltic Sea is 0.055 €/kWh and in the UK contracts for offshore wind farms have already been awarded under NFFO4 at prices of about 0.05 €/kWh. The success of the project will be marked by the delivery of the reliable design methods and recommendations needed for the safe development of offshore wind farms capable of improving on these prices and approaching the goal of EU policies of 0.04 €/kWh. It is premature to evaluate the effects of the project on pricing, however sincere efforts have been made in the project to obtain cost-optimal, yet safe guidelines for the evaluation of design loads. Please refer to Section 2.3 for a detailed explanation.

2.2 Scientific and Technical Description of the Results

It should be noted that the aim of the project has not been to develop a new standard for offshore wind turbine design, rather to undertake the crucial background work required providing recommendations, which will form the basis of a standard. The work has therefore involved collation of existing relevant information, as well as a thorough review in order to identify areas of poor understanding with regard to the particular requirements of offshore wind turbines. New research was applied where appropriate to improve understanding leading to design guidelines. Thus the research approach has been as illustrated in Figure 1.

For those areas where a need for generic research was recognised the research performed was of technical and scientific nature generally relying on mathematical and physical modelling, and computer simulations.

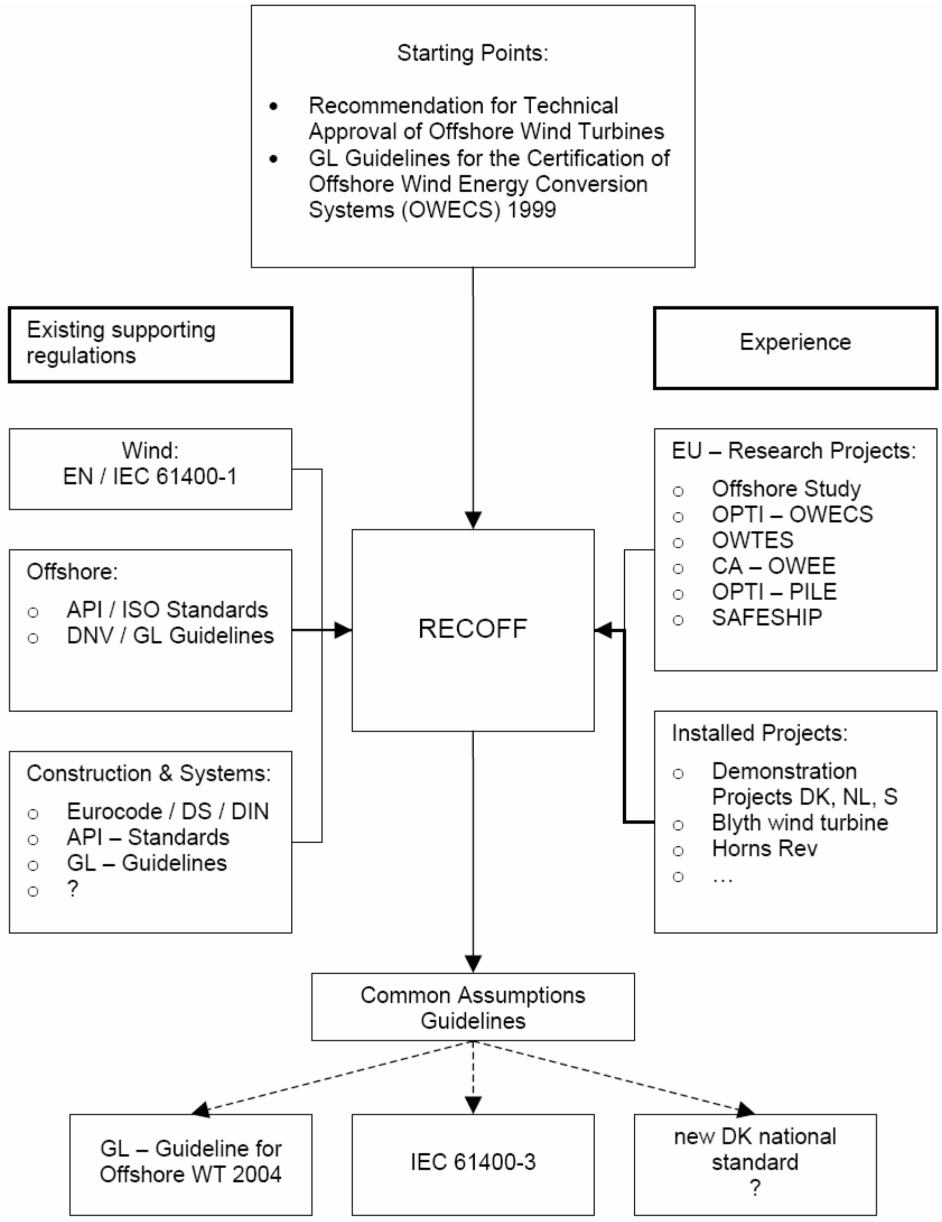

Figure 1: Overview of the methodology used in the project[1].

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[1] Abbreviations: IEC 61400-1: International standard on wind turbine safety; GL-OWT: GL regulation for the certification of offshore wind energy conversion systems (1995); API: American Petrol Institute – recommended practice for planning, designing and constructing fixed offshore platforms; GLO: GL rules for classification and construction, III offshore technology (1999); DoE: UK Dept. Of Energy; GL: regulation for certification …. (1999); DBD: design basis for Danish demonstration offshore projects; DS: Danish Standard.

Reflecting the typical outline of standards and regulations the work programme has been divided into seven major tasks, which have formed the work packages of the project:

1. External conditions
2. Analysis methods
3. Design load cases
4. Probabilistic methods
5. Structural integrity
6. Operation and maintenance
7. Project management and communication

The reporting of results follows this subdivision, work package by work package. The main instrument of dissemination of results is the homepage of the project, from which the documents have been accessible to the project participants during the project period. Following the submission of this final report, the homepage is accessible to everyone. As mentioned in the Introduction a list of the documents prepared, with abstracts and organized by subject, has been produced and included in this report's Chapter 4. Instead of giving a very detailed presentation of the various results of the project a listening of tasks is made for each work package and references to the abstracts of those notes that document these results are made. Where a task is not covered by a note a few words of explanation are offered. Further the accomplished results are compared to the initial work plan. Deviations occur, but they are not substantial.

2.2.1 WP 1: External conditions

Task	**Result**
Over-all task: Develop analytical and numerical tools in order to model and describe the properties of the simultaneous acting external conditions.	Analytical tools have been developed as described in the following tasks of this WP. Numerical tools have not been developed, since these already exist. The tools have been developed as part of maturation of the offshore oil and gas exploitation industry.
Review of existing literature, design codes, standards and offshore guidelines with respect to defining and modelling the descriptive parameters for the external conditions.	See abstract: 4.2.1 but also 4.1.1, 4.1.2.
Identification of possible data sources and their quality.	Relevant data have not been available as the increasing competition in the wind turbine market implies the all contractors keep such to themselves.
Guidelines for sites/situations with insufficient information (selecting conservative design values).	See abstract: 4.2.2

2.2.2 WP 2: Analysis methods

Task	**Result**
Review the state of the art within analytical, numerical and experimental methods.	It has been decided not to perform an in-depth review because 1) it turned out that it would be too time consuming, and 2) the gain would be questionable. In stead the standard methods of the offshore and wind turbine industries where considered and enhanced. Furthermore, as the work with WP2 and WP3 progressed it turned out that there was some overlap. Where such an overlap is present, this is explained in the following.
Wind load models, including loading effects such as (offshore) gust models and turbulence in large-scale wind farms.	Because fatigue loads are often design driving special focus have been put on them. See abstract 4.3.10, which covers abstracts 4.3.1 through 4.3.9. Also extrapolated extreme loads (or response) during normal operation have been extensively considered. See abstracts 4.3.11, 4.3.12, 4.3.13, 4.7.12, and 4.3.15 that also includes 4.3.14. Extreme loads in the storm event have been treated in WP4 and WP5. For turbulence in large-scale wind farms see abstract 4.3.20.
Hydrodynamic loading, i.e. loading from wave and currents. The load models are to include the applicability of wave theories, breaking waves on shallow water and use of model experiments.	The abstracts referred to in the task above apply here as well, as they have dealt with the influence of the wave loads too. For guidance on applicability of wave theories and breaking waves, and on wave loads, see abstracts 4.3.17 and 4.3.18.
Sea-ice load models.	These issues have generally not been covered since these are already covered by the offshore industry. However some documents have been produced; see abstracts 4.3.19 and 4.5.1
Earthquakes.	
Loading from ships, including ship impact and mooring.	
Environmental deterioration processes derived from specific external processes e.g. soil scour.	
Guidelines on selecting characteristic design loads for the different loads are to be specified.	This has been dealt with in WP3 (tasks 3 & 4) and WP5 (tasks 2 & 4).

2.2.3 WP 3: Design load cases

Task	**Result**
Review of existing design methods using analytical and numerical tools for integrated design procedures.	Not many methods exist; see abstract 4.5.3.
Developing a probabilistic procedure for identification of deterministic load cases.	A number of structural reliability methods (which are the relevant probabilistic procedures in the present context) applicable to offshore wind turbines already exist, see abstract 4.4.6, however they do not account for the reliability of the control and safety system. The Danish R&D project "Optimised and Uniform Safety and Reliability of Offshore Wind Turbines", (contract BRO-91.058, PSO no. FU1101), which has run in parallel to the RECOFF project, has demonstrated how the reliability of the control and safety system can be included in structural reliability methods. These methods are applicable if sufficient data are available. The methods are presented in [1], which is included on the project homepage for easy reference, see abstract 4.8.2.
Deciding on different acceptance criteria for different load cases.	A rational approach to these tasks is very difficult and involved and would rely on data that, as mentioned in WP1, is very hard – if not impossible – to obtain (see abstract 4.8.2). Therefore the design load case table (DLC table) of the newly revised IEC standard 61400-1 was taken up and an extension of this into the offshore case was made, see abstract 4.3.21. The rationale is that the DLC table of the 64100-1 standard reflects generally accepted acceptance criteria developed over years of experience. However, for a single load case, namely the storm load case, a simplistic application of probabilistic procedures was made, see WP4 task 4. The specification of the proposed DLC has been intimately connected to the second, third and eighth task of WP 2.
Determining deterministic load cases or alternatively specifying a procedure for this action.	
Perform a parametric sensitivity study, investigating the load-type influence on a specific turbine having different foundation concepts.	Only mono-piles have been examined. Other types like tripod and gravity have not been considered. Reality is that only limited experience with other foundation types exists. Thus computer codes for this are still under development.

… Continued.	Since computer code development is outside the scope of this project (though CRESS has done some for mono-piles) investigation of different foundation types have not been pursued. Investigation of load influence on specific turbines with mono-pile foundations have been made; see abstracts 4.3.10 and 4.3.29.

2.2.4 WP 4: Probabilistic methods

Task	**Result**
Review existing probabilistic models for onshore wind turbine and models for offshore applications. On basis of this review to possibly develop new models for offshore use. The models shall support decision-making on design load cases and ensuring a proper safety level of the offshore wind turbines.	See the results reported in tasks 2, 3 and 4 of WP3.
Assess structural safety during normal events, including safety of the foundations.	Two types of normal events have been considered: fatigue (see abstract 4.4.7) and extrapolated extreme response during normal operation (see abstract 4.4.1). In any of these cases safety of foundations have not been considered as reliable models for soil conditions have been difficult to establish.
Evaluation of the control and safety system for the turbines.	As reported in WP3 (task 2) control- and safety system reliability has been considered in [1], i.e. abstract 4.8.2. In that the conclusion was that generally too little data is available to reliably evaluate control- and safety system reliability.
Consider safety during other emergency and rare external events, such as ship collision, extreme storms.	Extensive work has been carried out regarding storm events. As a reference case the structural reliability of onshore wind turbines has been considered, see abstract 4.4.1. Analysis on offshore turbines is described in abstract 4.4.3 and the related document 4.4.4. Ship collision has not been treated, as this is part of another EU-project named Reduction of Ship Collision Risks for Offshore Wind Farms - SAFESHIP (EU contract NNE5/2001/521).

2.2.5 WP 5: Structural integrity

Task	**Result**
Perform a review of existing design codes, standards and current offshore projects with focus on the structural design of offshore wind turbines. This review is to focus on discrepancies in the required safety levels in different codes and different applied material models.	A survey of all standards *and* offshore projects was considered too time demanding compared to the potential outcome. Instead a focused review of a number of standards, offshore as well as onshore, with respect to a selected number of design cases was conducted; see abstract 4.5.2. See also abstract 4.4.1 for discrepancies in the required safety levels in different types of codes.
Specify partial load safety factors as well as load reduction factors for offshore wind turbine use considering extreme loading as well as fatigue models.	For extreme loads in the storm situation an effort has been made to asses a proper combination of characteristic values and safety factors, see abstracts 4.4.3. For extrapolated loads during normal response see abstract 4.4.1. With respect to fatigue it has been found (abstracts 4.4.7 and 4.5.2) that large differences in design practise and standards exist. This makes it difficult to make clear proposals on fatigue load and material safety factors and fatigue models.
Recommend models for structural strength during extreme loads and for fatigue evaluation. Including partial safety factors for materials.	Selected standards were reviewed see abstracts 4.5.2 and 4.5.11. The review did not reveal offshore wind turbine specific needs not already sufficiently well covered by offshore standards. Thus existing models and safety factors are recommended.
Specify acceptance criterion for different load types, e.g. different safety levels may apply for highly correlated events – where all turbines in a farm is at risk – and uncorrelated events where only one turbine may fail.	A proposal for the formulation of the design load case table (table 7.2) in the IEC 61400-3 draft standard and proposals for associated safety factors cover this task. See WP 3 (tasks 3 and 4), and task 2 of the present WP for further details.

2.2.6 WP 6: Operation and maintenance

Task	**Result**
Proposal for a standardisation in collecting failure data.	See abstract 4.6.3.
Methods for ensuring labour safety.	See abstract 4.6.1.
Limiting energy cost by optimisation of operating and maintenance procedures.	See abstract 4.6.2

2.3 Assessment of Results and Conclusions

The major results are here evaluated and assessed on the basis of application-related criteria. Generally all of the results are useful in applications, as they all give guidance and recommendations on how to evaluate external or internal loads for offshore turbines as derived from environmental conditions. More important for the application-related value is that efforts have been made in the project to provide guidelines that ensure safety, penetrability, and applicability, and at the same time support cost-optimal design where conservatisms inevitably implied by those short-cuts, which are present in design rules that must both ensure safety and be easy-in-use, are kept at a minimum. The following accounts for those subjects where such design guidelines have been developed and thoroughly discussed, both among the partners and with colleagues outside the project.

First of all it has been proposed to the IEC-TC88-WG03, and adopted by the group, that design of support structures should be site-specific. This is unlike onshore turbines where towers of only a few types are made and used according to a classification of sites. Contrary to what is the case for the rotor-nacelle-assembly the site-specific design approach is justified for offshore turbine support structures as it ensures a higher degree of cost-optimality than mass production does, especially for the substructure, and especially for large wind farms.

With respect to loads the design drivers for support structures are extreme and fatigue loads. The extreme loads considered in the project embrace the storm event, and extreme load effects during normal operation, in both cases – as for fatigue – resulting from the concerted action of wind and wave loads. 4 major improvements of design guidelines obtained in the project, both with respect to simplicity in use and with respect to cost-optimality, and concerned with extreme and fatigue loads are pinpointed below.

In the document 37 on the homepage (see abstracts 4.4.3) it is demonstrated how well-established design rules for wind turbines and fixed offshore structures can be merged with a minimum of conservatism and still preserving safety. Specifically the typical 100-year return period used in offshore engineering is reduced to a 50-year return period in accordance with normal wind engineering practice. This is done without increasing the load safety factor accordingly. Thus costs are reduced with respect to design against extreme wave loads while the well-known level of safety for onshore wind turbines is maintained.

The newly introduced requirement in the general wind turbine standard (IEC 61400-1) of assessment of extreme load effects during normal operation ideally requires enormous amounts of simulations. Investigations have been carried out in order to determine possible short cuts, see documents 59 and 80 (i.e. abstracts 4.3.14 and 4.7.18). Thorough tests demonstrate the validity, limitations and most importantly the limited unconservatism of the proposed simplified approaches. Thus the methods are accurate to the order of 3%, which is practically negligible compared to other soureces of uncertainty.

For fatigue loads, methods for lumping, mainly with respect to wave loading, of fatigue load cases have been investigated. Procedures that cut down on the high dimensionality of full fatigue analysis accounting for wind-wave misalignment and the distribution of wave climate parameters conditional on mean wind speed and that exhibit minor conservatism amounting to less than 5% have been proposed. See document 27, i.e. abstract 4.3.10.

The methods introduced in documents 28, 74 and 75 (see abstracts 4.6.1, 4.6.3 and 4.6.2) to increase labour safety and optimise O&M to reduce the cost of energy give a good starting point for designers and operators to design off shore wind turbines and make procedures to operate and maintain these wind farms at a safe cost effective level. Although it has to be mentioned that for the safety and labour regulations,

- It is not possible to give uniform guidelines on health and safety procedures for all wind farms in all countries; they do not exist. On different locations, (within the twelve miles zone or further on in the Exclusive Economic Zone, EEZ) different licensing authorities need to approve the health and safety plans.
- From the investigations, it could not be concluded that health and safety provisions will have (limiting) influence on the design of the offshore wind turbines. All measures, procedures, and provisions that deal with health and safety, need to be assessed and approved individually.

For the reduction of the O&M cost, a probabilistic model has been introduced and explained. The model presented is only a brief description of the modelling approach and the relationship between the applied models. The presented model makes use of the database on failure behaviour. With the proposed models, different O&M procedures can be analysed and compared on the basis of the cost of energy.

2.4 References

[1] Tarp-Johansen, N.J. et al. ‘Optimised and Balanced Structural and System Reliability of Offshore Wind Turbines, An account’, Risø report R-1420, 2004, ISBN 87-550-3240-0, (included on the RECOFF homepage as document no. 76, abstract 4.8.2)

3 Management Final Report (Confidential)

4 Abstracts of Documents Prepared as Part of the Project (Publishable)

This chapter lists the documents prepared in the RECOFF project with abstracts and organised by subject. The number in the parentesis following the title of a document refers to the original working numbering applied in the project. The numbering may be usefull when contacting project partners for follow up, and because some references are made by number.

List of documents with reference to the page where one finds the abstract:

4.1 Existing Standards

4.1.1 List of rules and regulations for offshore wind turbines (4)

This document gives a comprehensive list of standards and other relevant material for offshore wind turbine design at the start of the RECOFF project.

4.1.2 Relevant British Standards (9)

This document gives a comprehensive list of relevant British standards for offshore wind turbine design at kick-off of the RECOFF project.

4.2 External Conditions

4.2.1 Deliverable D1: External conditions, state of the art of existing regulations (26)

The scope of this report is to supply information for the selection of most applicable regulations which could apply for the erection of turbines at offshore sites. In this report an overview and analysis of existing regulations and standards is performed. Were possible a comparison is made to support decision taking on the formulation of recommendations. This is part of the EU-project “Recommendations for design of offshore wind turbines”.

A main goal in this work package is to identify suitable descriptive parameters for modeling a joint probability function appropriate for modeling simultaneous occurrences of the slow fluctuating part of the external conditions. This is primarily done by reviewing excising specialist literature and design codes. If possible, it is attempted to specify offshore wind turbine classes (turbines designed for a specific combination of the external conditions) – see also the IEC 61400-1 code.

The following external conditions are to be treated: offshore wind characteristics, waves and currents, sea-ice, tidal ranges, earthquakes, ship impact and lightning. The joint probability function of these conditions is the rational basis for developing a limited number of rational design load cases.

The intention is not to give the full theoretical background for definitions, but to give support to compare the different standards and regulations used in wind and offshore industry.

Following Standards/Regulations are used:

- IEC 61400-1, ed. 2, “Wind Turbine Generator Systems, Part1 – Safety Requirements” [1]
- Draft IEC 61400-1, ed. 3, “Wind Turbine Generator Systems, Part1 – Safety Requirements” [2]
- ISO/DIS 19901-1 “Petroleum and natural gas industries — Specific requirements for offshore structures — Part 1: Metocean design and operating conditions”, 2002 [3]
- American Petroleum Institute, “Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design”, API Recommended Practice 2A-WSD, 21st Edition 2000 [4]
- Germanischer Lloyd, Rules for Classification and Construction, III Offshore Technology, 2 “Offshore Installations”, Edition 1999 [5]
- Germanischer Lloyd, Rules and Regulations, IV Non Marine Technology, Part 2 “Regulations for the Certification of Offshore Wind Energy Conversion Systems”, Edition 1999 [6]
- DS 472, “Loads and Safety of Wind Turbine Construction”, 1st edition May 1992 and amendment September 2000. [7]
- Danish Energy Agency, “Recommendation for technical approval of offshore wind turbines”, December 2001. [8]
- Norwegian Technology Center (NTC), NORSOK Standard N-003, “Actions and action effects”, Rev. 1, Feb. 1999. [9]
- DNV, Classification notes No. 30.5, “Environmental conditions and environmental loads”, March 1993 [10]

4.2.2 Deliverable D2: Guidelines for identifying, measuring and modelling of external conditions (67)

The scope of this report is to provide recommendations for the selection of external conditions to be used in the design of turbines at offshore sites. The report is part of the EU-project “Recommendations for design of offshore wind turbines”. Offshore wind turbines are subjected to oceanographic, meteorological, geological and electrical conditions, which may affect their loading, durability and operation. In the report the main load driving environmental conditions are considered, their main parameters analysed and recommendations are given for their use. The conditions analysed in depth are wind speed, waves and currents. Additional notes for sea ice, ice cover, water depth variation etc. are given. Requirements regarding the site assessment and the parameters to be analysed are drawn up. Special focus is set to the description of the sea state and its application to offshore wind turbines. Shallow water effects and their influence in the load analysis as well as in the combination of the external conditions are discussed. Finally the methods for the combination of external conditions used in offshore wind turbine industry are shown and discussed. Recommendations are given on the application of the different methods.

4.2.3 Re-calculation of std(U) (56)

Based on a measured data set this document gives a proposal for a relation between std. dev. of longitudinal turbulence.

4.2.4 Recommendations for design of offshore wind turbines External Conditions (82)

The EU funded project “Recommendations for the Design of Offshore Wind Turbines” (RECOFF) was initiated to supply support for the development of the required new procedures for the design and certification of offshore wind turbines and to support the development of new standards. One scope is to supply information for the selection of most appropriate models to be used in regulations which could apply for the design of offshore wind turbines. In previous work an overview and analysis of existing regulations and standards was performed. Further data from measurements in the North Sea as well as literature was analyzed to extract suitable recommendations. This work was directly fed and applied for the development of following standards and guidelines:

- Draft IEC 61400-1, ed. 3, “Wind Turbine Generator Systems, Part1 – Safety Requirements” [1], under development by Working Group 3, TC88 of the International Electrotechnical Commission (IEC), CD to be published 2005.
- Germanischer Lloyd WindEnergie (GL), “Guideline for the Certification of Offshore Wind Turbines”, to be published end 2004.

This paper gives an overview of the findings with respect to external conditions.

4.3 Analysis Methods and Design Load Cases

4.3.1 Wind and wave misalignment effect on fatigue loading (11)

It was investigated whether misalignment of the waves relative to the wind could contribute to significantly higher fatigue loading due to reduced aerodynamic damping of the wave loads. Moderate levels of misalignment were used. It was concluded that with the moderate levels of misalignment simulated, simple collinear wind and waves produce sufficiently similar results while avoiding the complexity of misalignment.

4.3.2 Wind and wave misalignment effect on fatigue loading (11a)

This further report on wind and wave misalignment effects on fatigue loading uses (artificially) extreme levels of misalignment to discover the effects of such conditions. The report demonstrates that large values of misalignment can indeed lead to significantly increase in predicted damage compared to the case of collinear wind and waves.

4.3.3 Tidal level effects on support structure loading (12)

This report investigates the effect of varying tidal level on fatigue loading. The results led to a conclusion that using a water level 10% of the mean tidal range above mean sea level leads to accurate damage equivalent load prediction compared to simulating true varying tidal level.

4.3.4 Mean Water Depth and Support Structure Stiffness Effects on Support Structure Loading (13)

Large mean water depth variations equivalent to site changes were considered. Variation of the support structure stiffness was also investigated. The results show that the choice of support structure natural frequency, in particular, has a large effect on loads associated with displacement of the structure in the direction of the waves.

4.3.5 Tidal current effects on support structure loading (14)

The effect of tidal currents on wind turbine support structures in terms of the effect on fatigue and vortex induced vibrations was studied. The effect of the current due to tidal cycle alone is to cause increases of order 1-2 % in support structure loads at the mud line. The interaction between currents and waves leads to increases of order 1-2 % in support structure applied loads at the mud line. A simple criteria is proposed which may be used to decide when vortex induced vibration need not be considered.

4.3.6 Fatigue Load Parametric Studies; Wave Effects and Simulation Length requirements (15)

This report summarises the results of two studies related to the calculation of fatigue loads for offshore wind turbines. In the first study, the damage equivalent fatigue loads (DELs) resulting from combined wind and wave loading were compared with loads resulting from wind loading alone. The objective to this study was to determine the sensitivity of individual turbine loads to the presence of waves. The results show that a few key load components are predicted to sustain significantly increased damage due to wave action. The second study investigated the effect of simulation length on calculated DELs. In this case, DELs calculated from simulations of between 10 minutes and 6 hours in length were compared, with and without the presence of waves. The results show that the required simulation time varies and is a function of wind speed, the presence of waves and the load component under consideration.

4.3.7 Simulation Length Requirements for Offshore Fatigue Load Calculations (15a)

This further report on simulation length requirements for fatigue load calculation concludes that 10-minute simulations are as adequate for wind and waves as they are for wind only.

4.3.8 ’Lumping’ of Fatigue Load Cases (16)

An investigation was carried out to determine the minimum number of load cases required to calculate the fatigue loading of offshore wind turbines whilst maintaining acceptable accuracy. It was concluded that a single pair of appropriately calculated mean values of significant wave height and mean zero crossing period is sufficient to accurately calculate the fatigue loading.

4.3.9 ’Lumping’ of Fatigue Load Cases (16a)

This further report on 'Lumping' of fatigue load cases was motivated by the concern that the original investigation was not broad enough in terms of potential shallower water sites and variation support structure stiffnesses. The conclusion is however the same with 1 mean value of significant wave height and mean zero crossing period sufficient per wind speed.

4.3.10 Deliverable D3, Collated sensitivity studies (27)

Basically a collection the documents 4.3.1 through 4.3.9, for which separate abstracts are provided.

4.3.11 Extrapolation Including Wave Loads; Replacing the Distribution of H_S by a Suitable Percentile (19)

In this note extremes of offshore wind turbine response in terms of overturning moment and base shear during normal operation are regarded. The aim is to justify that, without significant loss of accuracy, it is possible in the extreme evaluation procedure to substitute the distribution of the significant wave height, H_S, conditional on the mean wind speed at hub height by a deterministic number determined as a suitable percentile of the conditional H_S-distribution. Because a specific simplified case study is examined a systematic sensitivity study should be carried out in order to support the conclusions drawn herein. A first estimate for the percentile of the conditional H_S-distribution is suggested. Since wave loads contribute differently to the overturning moment and the base shear, it is expected that the most feasible percentile will not be identical for both reactions. However the sensitivity of the extreme approximation to the choice of the percentile is small for the overturning moment, as it is by far dominated by the wind loads. Thus choosing the same percentile for both reactions may be acceptable.

4.3.12 The Influence of the Dependency of Mean Wind Speeds on the Extreme Response of Wind Turbines in the Operational Range (40)

The estimation of the extreme response during operation of a wind turbine is usually based on the assumption that the 10-minute extreme responses are mutually independent. This is not strictly true. The turbulent response is approximately independent, however the 10-minute mean wind speed, and thereby the average standard deviation of turbulence is not. Due to the correlation assuming independency must lead to conservative estimates of the extreme response. In this note it is however demonstrated that the assumption of independency is generally a good approximation when extreme response of long return periods is considered, which is the typical case. The note starts out with a section in which the general formula for the distribution of the extreme response is given. In the succeeding section it is shown that asymptotically, that is, for the extreme of many 10-minute periods, the dependency has no influence. After that section a detailed analysis is made in order to quantify, for a specific turbine, at what number of 10-minute periods the asymptotic result may become useful. It turns out that for return periods larger than about 24 hours dependency has no importance. Finally another approach to the problem, based on discretisation of the mean wind speed distribution is presented and compared with the general case.

4.3.13 Extreme Response During Operation; Comparing the use of an extreme turbulence model and proper extrapolation (85)

The CDV for the 3rd Ed. of the IEC 61400-1 standard proposes two load cases aimed at the examination of rare extreme response events experienced in a wind turbine during operation, that is, load effects of average recurrence period of say 50 years. These may be determined by extrapolation of the distribution of more frequently occurring extreme load effects. This is the idea behind design load case (DLC) 1.1, which considers the extrapolation of load effects.

DLC 1.3, on the other hand, considers mainly extrapolation of climate parameters followed by only partial extrapolation of load effects. This note discusses the differences in the framework of and DLC 1.1 and 1.3 and exemplifies the differences in the approach of the two load cases. The analysis of this note leads to the following conclusions:

1. Even for fixed turbulence intensity, the process formed by the largest response in each 10-min. period is stochastic with large – though rare – specimens. Thus, the variability of extreme load effects is due both to variability in the climate parameters *and* variability in extreme load effects conditional on fixed climate parameters.
2. Consequently, the load case DLC 1.3 will yield non-conservative estimates of the rare extreme load effects.
3. Since the variability of extreme load effects conditional on fixed climate parameters is often predominant, non-conservatisms in the range from 10% to 40% may occur.
4. It must be appreciated that the degree of non-conservatism depends on the concrete type of structure, i.e. control, regarded. This is most crucial for the distribution assumed for the extreme response events.
5. In *general* terms, DLC 1.3 cannot not provide an extreme turbulence that will yield the correct rare extreme response for all possible wind turbine structures.

In all examples the IA climate defined in the CDV for the 3rd Ed. of the IEC 61400-1 standard is regarded

4.3.14 Investigation into IEC Offshore draft standard Design Load Case (DLC) 1.1 (59)

DLC 1.1 concerns a new load calculation method for offshore wind turbine design and certification. This is load extrapolation using statistical methods to make estimates of 50-year extreme loads. This load case specifically concentrates on the power production regime of the offshore wind turbine. Multiple power production simulations are run at a range of external conditions. Large numbers of extreme load values are obtained. Probability distributions are fitted to these results. These fitted distributions are then weighted and summed to give an overall response function for each load. 50-year return values can then be obtained from these response functions.

The objectives of this study were:

- To carry out statistical load extrapolation methods in as accurate and clear way as possible
- Attempt to show valid short cuts to a more practical yet satisfactorily accurate load calculation procedure.
- In doing this, to back up the findings of Po Wen Chen's thesis [1]
- From the conclusions of this work, aid in recommendations for the new offshore IEC standard Design Load Case 1.1 methods

[1] Cheng, P.W., A Reliability Based Design Methodology for Extreme Responses of Offshore Wind Turbines, PhD thesis, Delft University of Technology, 2002.

4.3.15 Deliverables D4 & D5: Collated Sensitivity Studies II: focus on draft load cases (70)

Garrad Hassan is responsible for leading the activities required for Work Package 2 (WP2) of the RECOFF project. This work package has the title "Analysis Methods" according to the original project proposal but has been re-named "Computational Tools" following discussion at the project kick-off meeting held on 5-6 February 2001. Originally it was proposed that there would be Deliverables D4 and D5. However, it has since been agreed that these should be amalgamated into one single Deliverable, D4. This Deliverable continues in the vein of Deliverable D3, being a collation of number of sensitivity studies. However, the studies contained in D4, performed towards the end of the project, tend to focus on individual load cases from the draft standard. This is partly due to developments in the IEC Working Group 3 responsible for writing the offshore standard. The work in this deliverable reflects the state of the draft IEC 61400-3 document as of 30/08/2004. There is a certain overlap with RECOFF doc. No. 59 (see abstract 4.3.14). Of relevance here is the Deliverable D1 (see abstract 4.2.1), which reviews the state of the art of existing guidelines and codes in terms of external conditions.

4.3.16 Draft IEC 61400-3, Annex C, (informative), Shallow water hydrodynamics and breaking waves (35)

This document was one of the first drafts for an annex to the current draft of the IEC 61400-3 standard for offshore wind turbines. The text gives a collection on known guidelines for shallow water hydrodynamics and breaking waves.

4.3.17 Draft Annex C for draft standard prepared by IEC-TC88-WG03 (64)

Based on document 35 and further developed (abstract 4.3.16).

4.3.18 Draft Annex D for draft standard prepared by IEC-TC88-WG03 (63)

This document provides a draft for the for an annex to the current draft of the IEC 61400-3 standard for offshore wind turbines. The text gives a collection on known guidelines for how to compute various wave loads when first the wave kinematic have been established. This proposal is naturally related to the proposal in RECOFF doc. 64, see abstract 4.3.17.

4.3.19 Additional loads, boat impact; other maintenance loads (69)

This document provides a proposal regarding additional loads, boat impact and other maintenance loads relevant for offshore turbine design. The document has contributed to the current draft of the IEC 61400-3 standard for offshore wind turbines.

4.3.20 Spatially average of turbulence intensity inside large wind turbine arrays (68)

For large wind farms it is necessary to re-evaluate the concept of "ambient" turbulence intensity. In the interior of the wind farm, the standard deviation of turbulent wind speed fluctuations will be composed by a horizontal average of fluctuations, and a component representing the well defined, nearer wakes. In earlier works, a model for the impact on fatigue loading of increased turbulence in wind turbine arrays was presented. The spatially *averaged* component termed “ambient" or average wind farm turbulence is an important component of the fatigue model and is treated in further details in here.

4.3.21 Presentation of the DLC table proposed for the IEC 61400-3 standard (72)

This document provides, in brief, the motivations that have led to the present draft of the DLC for the IEC 61400-3. Based on the text in the draft standard further comments are added to clarify the aim and origin of the specific load cases, which are almost all derived from the DLCs of the IEC 61400-1 FDIS. The DLC table is not the result of the work carried out in the RECOFF project alone, but the project has made significant contributions.

4.3.22 Effect of Waves On Ultimate Loads Produced by IEC load cases DLC 1.4 & 1.5 (60)

This report summarises the results of an investigation to determine the effect of waves on the extreme loads experienced by offshore wind turbines and the significance of phasing between the transient wind events and waves. The study was carried out using the conditions described by the Design Load Cases 1.4 and 1.5 as stated in the draft IEC offshore standard. Many of the extremes of load components for DLC 1.4 varied significantly with the phase difference between wind transient and wave cycle. Extreme wind shear is less severe for the turbine overall than the extreme coherent gust with direction change. For DLC 1.5, the phase difference between wave cycle and shear transient is less of an issue as the two forms of loading interact little.

4.3.23 Study of DLC 1.4 and DLC 1.5 (62)

Background document for document no. 60, see abstract 4.3.22.

4.3.24 Approximate Maximum Value Distribution for Narrow Banded Gaussian Processes with Linearly Varying Mean Value (84)

A simple non-stationary Gaussian process $u(t)$ obtained as the sum of a stationary narrow banded zero mean Gaussian process $\xi(t)$ with std. dev. σ added to a linearly increasing function of time $m(t)$ is considered. Thus the process $u(t)$ is a narrow banded Gaussian process with linearly increasing mean value function $m(t)$. The results obtained are also valid for a similar process with linearly decreasing mean value function. It is the distribution of the global maximum value, within a given period of time, of such processes that is the subject here. Under the assumption of narrow bandedness the local maximum values of the process $\xi(t)$ are approximately Rayleigh distributed. In order to keep the following derivation simple the distribution is assumed purely Rayleigh. This means that the proof becomes heuristic. At the end of the note the implications of this simplification is discussed. The results are useful when considering the influence of linear trends in turbulence on the distribution of 10-minute maximum responses, which in turn are of interest in extrapolation of extreme response during normal operation.

4.3.25 Peak Factors for the Sum Process of two Independent Stationary Gaussian Processes, Some Analytical Results (58)

This note derives an approximate expression for the peak factor of the sum process of two Gaussian processes. The expression gives the peak factor in terms of the peak factors and variances of the two Gaussian processes. The note has relevance when considering weighted safety factors.

4.3.26 Derivation of tower top acceleration due to hydrodynamic loading (61)

The hydrodynamic loads acting on the support structure of an offshore wind turbine are able to affect loading of the rotor-nacelle assembly only indirectly as a consequence of dynamic vibration of the support structure. This indirect influence of the hydrodynamic loads on the rotor-nacelle assembly is in general small, and possibly negligible depending primarily on the dynamic characteristics of the support structure and the water depth. Although the dynamic vibration of the support structure will affect the tower top structural velocity and therefore the aerodynamic loading acting on the rotor, the more important effect is that associated with the tower top acceleration and therefore the inertial loading. This is the subject of this document.

4.3.27 Approximate tower top acceleration (42)

This document comments on document 61 (abstract 4.3.26). The present document offers a slightly different formula for the approximate assessment of the contribution from hydrodynamic loading to the standard deviation of tower top acceleration.

4.3.28 Frequency Domain Analysis of Offshore Wind Turbines (81)

The design of offshore wind farms is a great challenge. The dynamics of the individual wind turbines differ because of different water depths and soil conditions and the environmental conditions are described by a huge amount of metocean parameters. It is a hard job to identify the most critical loaded wind turbine and the number of load cases to be assessed is enormous. Since a frequency domain tool allows for quick parameter studies and fatigue analyses it is very desirable to apply a combined time/frequency domain approach. The use of a time domain tool is then focused on the most critical load cases only. Specific topics of a frequency domain tool are discussed in this report, such as the required linear model, the rotational coupling between the rotor, drive train and the tower, and the determination of the loads.

4.3.29 Deliverable D4/D5: Verification Simulations of DLC 1.2 and 6.1 a,b,c (90)

To verify wheter a large number of simulations performed by Garrad Hassan for the development of design load cases for offshore wind turbines, the RecOff partners compared a limited number of load cases on the basis of the statistics, power spectral density and 1 Hz fatigue equivalent loads. The results show that the DLC 1.2 compare quite well the DLC 6.1 a-c show significant differences. These differences are due to different assumptions made by the individual partners for the simulations. Overall we have reasonable confidence that the results prepared by GH are typical for the off shore environment. Due to lack of time no second round of simulations has been performed.

4.3.30 HAWC Load Simulation of Generic 5MW Offshore Wind Turbine Model (87)

This report contains the result of a HAWC load simulation of a 5 MW wind turbine. The turbine data is fabricated for the purpose of comparing different codes for simulation of wind turbine load. The report relates to doc. 90, see abstract 4.3.29.

4.3.31 Final report from CRESS on test calculations (88)

Within the framework of the RECOFF project, CRES involved mainly in to the work package No2. The purpose of this work package was to identify the applicability of the existing methods and load models to the offshore wind turbines. Therefore, CRES collected all relative information concerning offshore structures simulation and especially the offshore wind turbines, and modified the aeroelastic code GAST of the National Technical University of Athens (NTUA) for offshore analysis. Moreover, it was decided by the partners to conduct a set of load calculations for an offshore wind turbine in order to ascertain possible failings in the description of the design load cases, which are presented in the draft version of the IEC 61400-3 standard. The load cases were proposed by ECN and agreed among the partners of the project. These cases were selected according to the working draft of the IEC 61400-3 standard (version October 2003). One load case for normal power production and three load cases for standstill conditions were selected. The subject of the present report is the calculation of the static and dynamic operational loads of an offshore wind turbine according to the IEC specifications. For this purpose, a generic 5MW wind turbine with pitch-variable speed control is considered and Garrad Hassan and Partners provided all necessary data.

Modeling includes modal analysis and performance for the entire operational range along with assessment of the controller in transient response. The report relates to doc. 90, see abstract 4.3.29.

4.4 Structural Reliability Methods and Safety Factor Calibration

4.4.1 Deliverable D9: Partial Safety Factors for Extreme Load Effects in Wind Turbines (6)

Deliverable D9 has been reduced to cover the evaluation of structural reliabilities of onshore turbines, thus providing a review of some general aspects of structural reliability of wind turbines and providing a reference case for offshore turbines. Overlapping with Deliverable D7 proposals for new partial safety factors are made. Procedures that can be proposed for probabilistic design of offshore wind turbines can be found in documents 73 and 76, i.e. abstracts 4.4.6 and 4.8.2, respectively. Taking up the results provided in this report, Deliverable D7 treats the offshore case. This report presents the results of a simplified probabilistic safety factor calibration. Proposals for future safety factors are also given. Present safety factors have been adopted from existing structural design codes ranging over many different types of structures and a wider set of load cases than relevant to wind turbine engineering. The work presented here offers a wind turbine specific calibration leading to optimal safety factors. The following issues have been dealt with:

- extreme loads and extreme loads during normal operation (i.e. currently not fatigue loads),
- differentiation of safety factors with respect to load and response model uncertainties,
- statistical simulation uncertainties, and
- weighting of safety factors with respect to the ratio of aerodynamic loads to gravity loads in a given cross-section.

Thus this report provides basic understanding of onshore wind turbine structural reliability. It is important to note that soil resistance is not treated. This is a specifically difficult issue. Both the reliability of extrapolated normal operation events (where few turbines are at risk) and storm events are considered. Finally a comparison between standards different civil engineering standards and wind turbine standards is made.

4.4.2 Note: updated safety level evaluations relative to the background document for Partial Safety Factors in the 3rd Ed. of IEC 61400-1: Wind Turbine Generator Systems: Safety Requirements (77)

A note on the reliability of wind turbines subject to extrapolated normal operational loads. Has subsequently be incorporated in into document 6, see abstract 4.4.1.

4.4.3 Deliverable D7: Partial Safety Factors and Characteristic Values for Combined Extreme Wind and Wave Load Effects (71)

The concerted action of wind and wave loads on offshore wind turbines is a subject that has drawn much attention over the past years. The load combination problem of wind and waves is present in the case of fatigue loads, in the case of extrapolation of operational response, and in the case of the extreme storm event. The present paper discusses only the extreme storm event. The load combination problem involves the determination of the characteristic loads and safety factors. In wind engineering and offshore engineering, respectively, well established practices for the definition of characteristic values and the choice of safety factors for wind and wave loads separately exist. The main aim of the present paper is to investigate the possibility of making a simple merger of these existing practices into a possibly conservative design rule for the combined action of wind and waves. The paper considers a simplified probabilistic model that serves the purpose of illustration thereby giving an understanding of how the merging can possibly be solved and finally gives first guidance on the choice of characteristic values and safety factors. Under the assumptions made herein, it is made probable, that is, it is not falsified, that such a combination rule can be established. Moreover, as an important and useful result, it turns out, still under the assumptions made, that it is possible to choose the same safety factor for wind and wave loads, whereby the combination problem simplifies considerably. The method of analysis has been probabilistic calibration including storm profiles. The case study of a mono pile structure in non-shelter deep waters of North Sea type implying drag-dominated wave loads is regarded and focus is put on load safety factors. The results point at the possibility of applying the same safety factor, namely 1.35 as recommended by both ISO and IEC standards, to 50-year return period values of both wind and wave loads and their combination, whereby the load combination problem simplifies greatly with respect to choice of safety factors. This simplification rests on the requirement that the expected 10-minute maximum aerodynamic response is combined with the expected 3-hour maximum hydrodynamic response. The great advantage of this result is that one may retain the well-known design practices of wind engineering and offshore engineering using the standard reference periods. On the other hand this has its consequences. The difference in reference periods imposes a problem on the evaluation of the combined response generated by the wind and wave loads. The paper presents a method to evaluate the combined response; both by use of pseudo random dynamical simulations and by use of deterministic, static, and dynamically equivalent combined steady wind and wave heights. Summarised the methods reads:

1. Determine 50-year return period wind and wave load climate parameters.
2. If they are not already 10-min based climate parameters for wind and 3-hour based climate parameters for waves then transform them to become so.
3. Make 1-hour response simulations with formal climate parameters obtained by formal transformation of the 10-min wind data and 3-hour wave data to parameters that, when used in a 1-hour simulation, will reproduce the 10-min max wind load/response and the 3-hour max wave load/response. Formulas for the transformations are provided.
4. Make two deterministic computations with steady wind and a regular non-linear wave. One computation with the expected gust in 10 minutes combined with a reduced companion wave height, and a computation with 3-hour max wave height combined with a reduced companion gust. A formula is provided.
5. Finally apply the load safety factor 1.35

It is underlined that other assumptions than those behind the models applied herein may lead to different results. Because the case study has, within the limits of available uncertainty model information, been carefully selected and because the outcome of a simple parametric study indicates that the results are relatively robust to changes in the assumptions for the load uncertainty model it is expected that the proposed choice of safety factors, return periods and reference periods for the characteristic storm event are not generally invalid. Further it is expected that the results regarding safety factors will be valid both for load effect and load code formats, as long as the assumptions made are not violated. The usability of generalised probabilistic methods on the basis of which site-specific characteristic values and partial safety factors may be derived, provided sufficient climate data is present, is briefly discussed. This document is an extended version of document 37 and related documents are: 38, 54, 55, 56, 57, 65 and 86.

4.4.4 Load Combination in a Storm Event (38)

The adequateness of regarding solely purely aerodynamic and purely hydrodynamic load effects when dealing with the load combination problem reported in document 37 (or the updated version 70) has been questioned. This note aims at demonstrating the influence of the lack of temporal coincidence of gusts and extreme waves on the calibration of safety factors for different relative contributions of the aerodynamic and hydrodynamic load effects. The assumptions are by and large the same as in the document 71. It is shown that the effect is small.

4.4.5 Storm Profiles for Wind Loads (89)

One of the load cases considered in wind turbine design is the ultimate load generated by extreme winds. Per definition the expected maximum response to the mean wind and associated turbulence intensity of 50-year return period is considered as the ultimate load. Because storms have longer duration than 10-minutes the maximum response during storms is on the average larger than that implied by the described idealised definition of the extreme event. This note makes an attempt at evaluating how much larger the maximum response in a storm is on the average relative to the idealised extreme event. Because this note is related to offshore turbines only the response in the support structure, i.e. tower, substruc-ture, and foundation is considered. Though wind turbines may idle in the storm event we re-gard only turbines in stand still. It is assumed that the response experienced in the support structure of an idling turbine is not radically different from that of a parked turbine making the analysis here valid for an idling turbine too. It is found the storm maximum response is about 6% higher than the peak 10-min maximum repsonse.

4.4.6 Deliverable D6: Structural reliability methods applicable for offshore wind turbines, a short review (73)

A number of methods have been developed for use in the oil and gas sector. These are shortly listed. A review report on these methods applicability for the oil and gas sector has been have found an evaluated Thge review thorough and gives further references. The findings in that review are found to be valid for offshore wind turbines as well. Therefore a separate review is not presented here. However, the applicability of the ‘extrpolation method’ has been extensively investigated in the RECOFF project, see RECOFF docs. 85, 70 (deliverable 4+5), 19 and many others. Also the ‘contour line method’ has been considered, see RECOFF doc 85.

4.4.7 Examples of Fatigue Lifetime and Reliability Evaluation of Larger Wind Turbine Components (25)

This report regards the lifetime distribution of larger wind turbine components in a generic turbine that has real life dimensions. Because the distribution of lifetimes is directly linked to the reliability calculations of reliabilities and partial load safety factors under specific assumptions about uncertainty sources are considered as they are of anticipated to be of general interest to potential readers too. Three components were considered: hub, main shaft, and main frame. They showed to have significantly different levels of safety. These differences are expected to result partly from the fact that different manufactures that have contributed with the design of the components may have different design strategies, partly from the fact that in any turbine not all components are designed fully to the limit. Thus any turbine design has a bottleneck, which then can be one of the components considered the work reported here. However the safety of the shaft seemed to be very low, implying that other reasons than the bottleneck-argument may exist. These have not been uncovered during the course of the project. The reason that the considered frame has very high reliability can be that the design strategy implies very conservative assessment of design loads. So, the main result is, as the investigation in document no. 24 (abstract 4.5.2) confirms, that large differences in design practise and standards exists. This makes it difficult to make clear proposals on fatigue load and material safety factors and fatigue models. Making a final decision is up standardisation committees.

4.4.8 The accuracy of wind turbine design codes derived from VEWTDC results (17)

The results of analyses with the major European wind turbine simulation codes have been compared with measurements on three different turbines. For the purpose of defining partial safety factors or for structural reliability calculations the accuracy and spread of the codes has to be described. Based on the outcome of the VEWTDC project some estimates of accuracy and spread of the design code results have been made. More information and results from the project are available at: http://www.ecn.nl/unit_de/wind/vewtdc/index.html.

4.5 Structural integrity

4.5.1 Corrosion Protection for Offshore Wind Turbines (34)

OWTS are exposed to a marine climate. Corrosion protection is thus to be taken into account by the selection of suitable materials and appropriate coatings and protective films, plus regular inspection. The assessment of mechanical and electrical components shall take into account not only the integrity but also the influence of corrosion on functioning, e.g. jamming of rusted joints or failure of sensors. In particular, freedom from corrosion is assumed for fatigue calculations. Analogous considerations are to be applied as regards the possibility of erosion, particularly for the rotor blades. OWTS components are exposed to aggressive environmental conditions and not easily accessible. Because of the operational conditions, in many cases repeated protective coating is not possible. Special importance therefore attaches to the design, choice of material and corrosion protection measures.

4.5.2 Deliverable D8: Comparison of international offshore regulations with regard to the achieved bearing capacity of structural members (24)

The Germanischer Lloyd WindEnergie GmbH has undertaken a dyadic study to present the safety levels respectively the bearing capacity achieved by the ultimate limit state (ULS) and fatigue (FAT) design of (welded) steel structures on basis of some selected international standards. The first part is dealing with the achieved safety levels according to API RP 2A-LRFD, ISO/CD 19902, Germanischer Lloyd Offshore Wind Energy, Danish Approval Scheme for Wind Turbines, and IEC 61400-1. The components considered are tubular members and tubular joints (X-type). The second part is dealing with the differences in tower (and foundation) shell design according to ISO 19902 and Eurocode 3. Both ultimate limit state (ULS) and fatigue (FAT) design are accounted for. The components considered are (welded) steel structures such as tubular members.

4.5.3 Review of existing design methods using analytical and numerical tools for integrated design procedures for offshore turbines (23)

The title of this note is taken directly from task 1 of work package 3. The title is somewhat confusing. Strictly speaking the review according to this title can be reduced to nothing, as it does not make much sense to talk about analytical or numerical tools for integrated design *procedures*. To the author's knowledge nobody has this far (i.e. by the end of the RECOFF project) made an attempt to build up numerical or analytical tools that could undertake a complete design of an offshore turbine. However, many attempts have been made to formulate more or less complete design procedures. Furthermore work has been made, or is in progress, to develop numerical tools for integrated response simulation of OWTs subject to combined loading, typically wind and wave loads. This note will try to provide a very short overview of the status of the different design procedures and integrated response simulation tools developed so far.

4.5.4 Probable inconsistency load case 6.1 (30)

This note is about a possible inconsistency between the stochastic 6.1a load case and the deterministic load cases 6.1b and 6.1c as proposed in the draft IEC 61400-3 standard. The deterministic wave height in load case 6.1b and 6.1c is based on a 3 hour stationary sea state. However in wind energy engineering it is common practise to perform several 10 minute simulations for every stochastic load case. For the stochastic load case 6.1a this would mean that the simulation time is less than 3 hours. Thus the most probable maximum wave height found in the stochastic simulation will be smaller than the selected wave height in the in load case 6.1b and 6.1c. Thus issue is also dealt with in RECOFF docs. 71 and 55, se abstracts 4.4.3 and 4.5.9, respectively.

4.5.5 On the calculation of combined wind and wave loads (example DLC 6.1) (33)

One major problem in establishing the design environmental conditions for offshore wind turbines is the combination of the external conditions to derive design loads. Contrary to offshore structures where wave loads usually dominate loading, offshore wind turbines support structures may equally be loaded by wind, wave and sea ice forces while currents are of minor importance in shallow waters. The document investigates the proper simulation period for the response to combined wind and wave loads. This issue is also dealt with in RECOFF docs. 71 and 55, se abstracts 4.4.3 and 4.5.9, respectively.

4.5.6 Combined Characteristic Extreme Loads (86)

The idea is to establish, under some simplifying assumptions, one or more deterministic load cases that will approximately produce a response in the support structure equal to the expected extreme response due to random loads during a storm. One may say that the discussed methods are equivalent static methods. When defining characteristic values for a deterministic method, which is typically time independent, care must be taken that the combination of the wind and wave loads is properly modelled. The scenario is, in accordance with the proposed design load cases 6.1a-c for the IEC 61400-3 draft standard, that there is no phase shift between storm peak wind and peak wave climate parameters like the mean wind speed U and the significant wave height H_s, and further that they are statistically dependent. Thus it is in the following implicitly understood that everything is conditional on U and H_s taking some value. On the other hand the instantaneous values of wind speed and surface elevation are assumed statistically independent. Of course the scenario rests on some presumptions that are never met in reality. However, in most cases the presumptions lead to conservative designs. The document discusses existing methods, and proposes a new method. For a treatment of the general case refer to e.g. Cheng, P.W.: *A Reliability Based Design Methodology for Extreme Response of Offshore Wind Turbines*, which has further references. The note is related to document 71, where the new result presented in the present document has been further developed in document, see abstract 4.4.3.

4.5.7 Memo on The Algorithm Behind DLC 6.1 (54)

The memo lists briefly the steps to go through in order to complete response calculations meeting with requirements of proposed design load case 6.1 in the draft 61400-3 standard.

4.5.8 Memo Concerning DLC 6.1 (57)

A contribution to the general discussion of the form of the proposed design load case (DLC) 6.1. The discussion pinpoints a few issues: the importance of distinguishing between design loads and design load *effects*, the conservatism implied by the proposed DLC i.e. its non-site-specific nature, and its potentially too simplistic format.

4.5.9 Transformation of Climate Data Between Different Reference Time Periods (55)

This note discusses possible ways of transforming climate data for wind and wave data from one reference period to another. The focus is on the storm situation. Transformation from 10 minutes to 1 hour or 3 hours and vice versa is considered. These periods are the typical basic reference periods. Both transformation between real measurable climate data and transformation between formal data, that is data that will ensure different formal computational schemes result in the same loads, are considered. These transformations are specifically relevant for the application of the extreme storm design load case 6.1 proposed in the IEC 61400-3 draft standard. Related RECOFF docs. are 33 and 30, see abstracts 4.5.5 and 4.5.4, respectively.

4.5.10 Calculation methods for DLC6.x (65)

It is expected that the calculated loads resulting from the DLC 6.x proposed in the current IEC 61400-3 draft will be strongly influenced by structural dynamics, and therefore the modelling techniques to be used will have to take account of the stochastic nature of the wind and wave loading. Due to the relatively shallow water depths in which wind turbines are being installed, the non-linear nature of the waves must also be accounted for as this has a significant influence on the design loads of the support structure. This document describes three possible calculation methods that take account of these effects, and discusses the advantages and disadvantages of each. It is offered as a basis for further discussion. Each of the methods is based on time-domain solutions.

4.5.11 Design of Concrete Structures for Offshore Wind Turbines, a paper (50)

This document describes the use of concrete for support structures of offshore wind turbines. It presents as well an overview of international standards and guidelines for the design and construction of concrete structures with special consideration of the requirements for offshore wind turbines. The standards that have been compared are in particular the Eurocode 2, DIN 1045 Edition 2001 and 1988, DS 411 Edition 1999, ACI 318-02, as well as the Germanischer Lloyd “Regulations for the Certification of Offshore Wind Energy Conversion System” and DNV Standard “Offshore Concrete Structures”.

4.6 Operation and maintenance

4.6.1 Labour Safety and Health and Safety (28)

As part of the Recoff project RECommendations for OFFshore wind turbines, Task 6 has been defined with the objective to investigate if aspects like licensing, health and safety, and labour safety have influence on the design of the turbines. In other words: are there any regulations that determine e.g. the turbine design, or limit certain design solutions? To answer this question, the process for obtaining permits is briefly described in Chapter 2. In Annex A and B, tow examples of offshore wind farms and their licensing aspects are given; one for a Dutch wind farm and one for a Danish wind farm. In Chapter 3, an inventory has been made of the types of work that need to be carried out in the various stages of an offshore wind project. Each type of work has classified as “new” for offshore wind applications, or “existing” in other branches of offshore industry. In the latter case, health and safety procedures can be easily adopted. Furthermore, Chapter 3 presents the existing and missing health and safety information for the different types of work and it presents the national and international authorities for health and safety. Finally, in Chapter 4, the new types of work, which are specific for large application of offshore wind energy, will be discussed in more detail with special attention to the health and safety aspects.

4.6.2 Optimisation of the O&M costs to lower the energy costs (74)

A Probabilistic O&M Cost Optimisation model is presented, with which the operation and maintenance strategy of offshore wind farms can be improved. Basis for the application of this model is an extensive analysis of the fault detection and repair cycle offshore. A calculation model has been added.

4.6.3 Deliverable D10:Proposal for standardisation/interface for data-collection (75)

A generic database has been proposed in which O&M information of offshore windfarms can be gathered, processed and presented. The database should be organised, used and maintained by the windfarm owners. An international approach of countries around the North Sea seems most yielding.

4.7 Presentations and Miscellaneous

4.7.1 Offshore certification (5)

Siting of wind turbines on land is a growing problem in northern Europe due to the fact that windy places are becoming scarce and that noise and visual impact reduce their acceptance. All these problems are taken care of when offshore siting is considered. However, offshore siting is not free from any problems and restrictions most of which were addressed in a JOULE 1 project carried out by Germanischer Lloyd and Garrad Hassan & Partners Ltd.. A more in-depth study on the feasibility of offshore wind turbines in the German coastal waters was recently performed by a large group of industrial partners. This document discusses offshore certification procedures. This paper is an EWEC paper.

4.7.2 Load Analysis and Certification of Offshore Wind Turbines (31)

This paper presents the general way through the load analysis for offshore wind turbine certification. An overview of the state of the art considering the external conditions for the load assumptions is given. A critical review, based on performed certifications, of the different load cases to be considered and their application for load analysis is performed. A comparison between the loads of generic designed onshore turbines to the loads for generic and site specific offshore designs is performed. The influence of wave loading and of the different dynamic behaviour of the substructure on machinery components is analysed. For the tower and foundation, a generic approach is not possible, a detailed knowledge of the site conditions, such as water depth ranges, soil conditions, wave scatter diagrams, extreme wind and wave conditions and currents among other things are necessary. Often detailed data is not available or aspects like wind and wave correlation are not existent. In the paper some simple theoretical methods used for solving these problems are discussed. Problems regarding the realistic representation of extreme storm loading on an offshore wind turbine are drawn up and possible solutions are presented. The paper was presented at EWEC 2003, Jun 16-19. Madrid, Spain.

4.7.3 An offshore wind turbine model (2)

A single degree of freedom frequency domain model for an offshore wind turbine is presented. The model aims at modelling the base shear force and the overturning moment, that is, the model focuses on the foundation of the offshore turbine. The model is motivated by the need for a simple model in assessing weighed partial safety factors to be applied to extreme response which is due more than one environmental load. Moreover it is demonstrated how the model can come into play in site specific calibration of partial safety factors. Presented orally at EWEC 2001, Copenhagen, Denmark July 2001.

4.7.4 Wind conditions for offshore wind turbine design, RECOFF, comparison of Standards and Regulations (32)

This paper was presented at the 3rd IEA experts meeting on wind conditions for turbine design. The paper relates to RECOFF doc. 26, see abstract 4.2.1.

4.7.5 Response Extrapolation for Offshore Wind Turbines (43)

The same issue as document 19, see abstract 4.3.11. Paper for poster presentation at EWEC 2003.

4.7.6 Response Extrapolation for Offshore Wind Turbines (66)

The poster corresponding to document no. 43, see abstract 4.7.5.

4.7.7 Safety Factors and Model Uncertainty (44)

PowerPoint presentation given at an expert meeting of the IEA Annex 11, Risø National Laboratory, 2002. The presentation is very early relative to document (6) to which the reader is referred, see abstract 4.4.1.

4.7.8 Calibration of Partial Safety Factors for Extreme Loads on Wind Turbines (41)

This paper gives a short presentation of the work that has been carried out in order to make a proposal for partial load and material safety factors for the currently ongoing revision of the IEC 61400-1 standard. The aim has been to derive a set of corresponding consistent load and material partial safety factors for the extreme load cases for wind turbines. In this paper only the standstill load case is considered. To attain the aim a simplistic probabilistic calibration procedure has been applied. The most important result of the work is discussed herein. It concerns the proposal of equal minimum material safety factors for all materials. Oral Presentation at EWEC 2003, Madrid, Spain, July 2003. For a more detailed discussion of the issues, see document 6; abstract 4.4.1.

4.7.9 Udvikling inden for offshore standardisering og relateret udviklingsarbejde (45)

PowerPoint presentation at Dansk Vindenergi's conference, 2003, in Danish. The presentation discussed important design load issues for offshore turbines not covered sufficiently accurate at that time.

4.7.10 Fatigue and extreme loads in wind farm clusters - and need for measurements (46)

PowerPoint presentation at ENDOW workshop, Risø March 7-8 2002. The presentation discusses the measurements that would be needed to support or further investigate the contemporary models for loads and energy yield.

4.7.11 Background for ”effective” turbulence model (47)

PowerPoint presentation of the model assumptions for the “effective” turbulence model. The topics dealt with are

- Contemporary uncertainty in predicting fatigue?
- Various load measurements
- What parameters affect fatigue loading?
- How do different cross-sectional forces react to wake conditions?
- Equivalent load in 1, 2 and multiple wakes
- What parameters effect fatigue loading?
- A most surprising observation
- What parameters must be expected to influence fatigue loading?
- Is wake-turbulence just … turbulence?
- General response-modelling

4.7.12 Extrapolation of extreme wind loads during normal operation (48)

In most cases extreme wind load on civil engineering structures coincides with extreme wind conditions. However, for wind turbines extreme loading may occur during normal operation with 5-25 m/s wind and therefore a central issue is to correctly predict the expectance value of the largest extreme load during normal operation. On basis of accurate input of statistics of the wind, aeroelastic simulation tools and mathematical models for the load distributions conditioned on mean wind speed, turbulence and trends in the time series, the unconditional distribution of extremes for the operating wind turbine is derived. Poster presented at EWEC 2003, Madrid, Spain, July 2003.

4.7.13 Vindlaster på offshorevindmøller (49)

PowerPoint presentation given at Dansk Vandteknisk Selskabs Møde i Nysted, 2003, in Danish. The main message of the presentation is that wind farms – especially offshore – generate the design driving wind loads themselves. That is, both fatigue and extrapolated loads are dominated by the wakes. Thus it is often the wind climate internally in the wind farms, and not the surrounding climate that drives the design.

4.7.14 Wave Spectrums and Forces For the Design Load Cases 1.2 & 6.1a,b,c of the 61400-3 IEC Standard (51)

PowerPoint presentation of status of CRESS work with load simulation for the DLCs 1.2 and 6.x from the draft IEC 61400-3 standard.

4.7.15 Partial Safety Factors and Characteristic Values for Combined Extreme Wind and Wave Load Effects (37)

Paper presented at Special Topic Conference, TU Delft 2004. An updated version of this paper is given in document (71), see abstract 4.4.3.

4.7.16 Partial Safety Factors and Characteristic Values for Combined Extreme Wind and Wave Load Effects, PowerPoint presentation (52)

PowerPoint presentation at EAWE Special Topic Conference, TU Delft, 19-21 April 2004. The presentation relates to document 37, see abstract 4.7.15. An extended version is given in document 53, see abstract 4.7.17.

4.7.17 Partial Safety Factors and Characteristic Values for Combined Extreme Wind and Wave Load Effects, an extension of document no. 52 (53).

PowerPoint presentation relating to document 37, see abstract 4.7.15.

4.7.18 Extreme structural loads at non-extreme mean wind speeds (80)

Paper based on RECOFF doc. 85, see abstract 4.3.13. The paper was given as poster presentation at EWEC 2004, London, UK, November 2004.

4.7.19 Extreme structural loads at non-extreme mean wind speeds, Poster (83)

Poster related to RECOFF doc. 80, see abstract 4.7.18.

4.8 Documents not funded by the RECOFF project but presented at meetings

4.8.1 Modelling of severe joint wave and wind climates (29)

For design of wind turbines for offshore locations, it is necessary to consider combination of loads that occur simultaneously. For design against an ultimate limit state, it will be necessary to carry out the design for the largest combined load that occurs in the design life of the wind turbine. Loads that occur simultaneously and are to be combined may consist of wind load, wave load, current load, and ice load. For illustration, it suffices to consider the combination of just two such simultaneous loads. Wind load and wave load can be used as an example for this purpose. The wind load and the wave load originate from two concurrent load processes, namely a wind load process and a wave load process. These load processes will be mutually dependent or correlated as a result of the fact that they to a great extent have the same cause: The stronger the wind, the higher are the waves.

4.8.2 Optimised and Balanced Structural and System Reliability of Offshore Wind Turbines, An account (76)

The reliability of wind turbines against wind loads does not depend on the strength of the turbine structure and the wind climate alone. A wind turbine is equipped with a control/safety system that, among many other things, is supposed to bring the turbine into a load-reducing mode if the wind speed rises above some predefined level, typically known as the cut-out wind speed. The control/safety system is also supposed to bring the turbine to calm in case of accidental events like over-speed. Thus the reliability of a turbine against wind loads clearly depends also on the reliability of the control/safety system. The over-all aim of the project has been to establish an account of the knowledge about the balance between the importance of the wind turbine control and safety system on the one hand and the wind turbines structure on the other hand for the structural failures of wind turbines and possibly judged what would be the situation of offshore turbines. To deal with these issues the project has dealt with

- The formulation of a general framework for the assessment of the structural reliability of wind turbines including the reliability of the control and safety system. The framework also gives the frame for reliability-based cost-optimisation of design.

- An account of the state-of-the-art in the fields of structural reliability of wind turbines and system analysis of wind turbine control and safety systems.
- An analysis of failure databases for onshore turbines with the aim of investigating the structural and system reliability of existing wind turbines in a few special cases and from the results possibly derive some indication of the balance between structural and system reliabilities of present day offshore turbines.
- The application of structural reliability methods, and cost-optimisation to offshore wind turbines under the assumption that the control and safety system works as required.

Some of the main conclusions of the project are:

- Available data on failures of wind turbines is generally ambiguous. Only databases for onshore turbines in the 1980’s and 1990’s have been available to the project.
- There is a tendency in the databases that there has been a predominance of structural failures that have been caused by malfunctioning of the control and safety system, i.e. an unfavourable unbalance between system and structural reliability.
- A thrifty and scrupulous recording and collection of failure occurrences would really be beneficial for the wind turbine manufacturers, as the failure data serve as an important input for the optimisation of the wind turbine design.
- Cost-optimisation studies based on structural reliability methods, both under the assumption that the control/safety system performs as expected and not, and when fatigue and inspection planning are regarded, exhibit small improvements in gain of the optimal turbines relative to a present-day reference turbine design. This is due to the fact that the optimum is rather flat – a general feature of structural optimisation problems.
- The cost-optimum study shows that there is more money to gain in optimisation of O&M costs. Seeing the small economical gain of the reliability-based cost optimisation in the light of O&M costs and in the light of the accuracy of the uncertainty models used in the structural reliability evaluations carried out in the present report it may be that optimising structural reliability is at the moment premature.
- The application of structural reliability methods, and cost-optimisation to offshore wind turbines require more accurate uncertainty models in order to obtain more reliable results that go beyond what has been achieved in the present report