Qualification of innovative floating substructures for 10MW wind turbines and water depths greater than 50m

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D 7.4 State-of-the-Art FOWT design practice and guidelines

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Definitions & Abbreviations

AEP	Annual Energy Production
ALS	Accidental Limit State
BEM	Blade Element Momentum Theory
BL	Back Leveraged
BSH	Federal Maritime and Hydrographic Agency of Germany
CAD	Computer-Aided Design
CAPEX	Capital Expenditures
CAPM	Capital Asset Pricing Model
CAR	Construction of All Risks
Cash and PTC LEV	Cash and Production Tax Credit Leveraged
Cash Lev	Cash Leveraged
CFD	Computational Fluid Dynamics
Corp	Corporate
DECEX	Decommissioning Expenditure
DG	Distributed Generation
DLC	Design Load Case
DTS	Draft Technical Specification
EOL	End Of Life
FAST	Fatigue, Aerodynamics, Structures, and Turbulence
FEM	Finite Element Method
FLS	Fatigue Limit State
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode, Effect and Criticality Analysis
FOWT	Floating Offshore Wind Turbine
GESOP	Graphical Environment for Simulation and Optimization
HAZID	Hazards Identification
HAZOP	Hazard and Operability Study
IEA	International Energy Agency
IIF	Institutional Investor Flip
IMU	Inertial Measurement Unit
IPC	Individual Pitch Control
IRR	Internal Rate of Return

kWh	Kilo Watt Hours
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Energy
LES	Large Eddy Simulation
Lidar	Light Detection and Ranging
LRFD	Load and Resistance Factor Design
MATLAB	MATrix LABoratory
MIMO	Multiple Input Multiple Output
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MWh	Mega Watt Hours
NMPC	Nonlinear Model Predictive Controller
O&G	Oil and Gas
O&M	Operation & Maintenance
OC3	Offshore Code Comparison Collaboration
OC4	Offshore Code Comparison Collaboration Continued
OC5	Offshore Code Comparison Collaboration Continued, with Correlation
OPEX	Operational Expenditures
QTF	Quadratic Transfer Function
RANS	Reynolds-Averaged Navier-Stokes
RNA	Rotor Nacelle Assembly
ROI	Return Of Investment
SIF	Strategic Investor Flip
SIMA	Simulation and Engineering Analysis of Marine Operations and Floating Systems
SISO	Single Input Single Output
SLS	Service Limit State
TLP	Tension Leg Platform
TRL	Technology Readiness Level
TSR	Tip Speed Ratio
ULS	Ultimate Limit State
VIV	Vortex Induced Vibrations
VOF	Volume of Fluid
WACC	Weighted Average Cost of Capital
WAMIT	WaveAnalysisMIT

Executive Summary

This report provides an overview of the state-of-the-art design practice of floating wind turbine substructures and the relevant guidelines, which are applied in the design process. It summarizes state-of-the-art practices in the disciplines addressed in the work packages of LIFES50+: Design, experimental practices, numerical simulation practices, industrialization considerations, and LCOE and risk considerations, and can be used as benchmark at the end of the project.
Based on previous research and communication with partners from the consortium of LIFES50+, a general design process was established. This process is based on three key design stages (conceptual, basic and detailed design) and includes categories and topics addressing relevant disciplines to be applied in the first life cycle phase of floating offshore wind turbine (FOWT) substructures (chapter 2). Adding to this overview, specific topics are addressed in detail:

Certification procedures (chapter 3): The scope of this report is in line with the first steps of the certification process (concept, design base and design). The required steps are addressed in detail in this report to provide indication of the tasks that need to be performed and the information that need to be provided to the certification body.
Design of main components (chapter 4): Design and evaluation procedures are described for the main components of the FOWT substructure: environmental conditions, tower and transition piece, controller, floating support structure, mooring and anchoring system and umbilicals / dynamic cables. For the assessment of the controller design, a questionnaire was submitted to contacts in industry and research, addressing topics of feedback control, supervisory control and the safety system. The main findings of this questionnaire are described.
Experimental design practices (chapter 5): The different options for FOWT model tests are summarized and common workflows for model validation and certification are described. Additionally, an overview of available testing facilities is provided.
Numerical simulation design practices (chapter 6): Numerical models for the description of hydrodynamics, aerodynamics, structural dynamics and mooring dynamics of floating offshore wind turbines are described theoretically as well as their application in simulation tools at different design steps.
Industrialization consideration in design practice (chapter 7): Follow-up processes such as standardization, manufacturing, transportation, installation and operation and maintenance that follow the design of the main components are addressed.
LCOE and Risk (chapter 8): Different approaches for LCOE calculation are presented and the necessary components as well as available calculation tools are described. Methods for risk management assessment of FOWT are summarized and the influence of risk on LCOE is addressed.

The presented overall design process can be used as general reference when designing substructures for floating wind turbines but should be regarded as high level overview of the complex procedures performed in the industry. The process presented does not cover all details, but the basic procedures that are performed. Where applicable, reference is made to available summaries and work from the LIFES50+ project regarding work packages.

Contents

1 Introduction

The work package "WP7: FOWT Design practice" aims at the provision of an applicable, recommended design practice in the public deliverable D7.11 for use by industry, research and certification by the end of the LIFES50+ project. This design practice (D7.11) will gather all experiences and generated novel knowledge collected throughout the project. The expected impact of the design practice (D7.11) is to serve as knowledge pool and general reference to further improve and benchmark the design processes in the industry, as well as guidelines and recommended practices provided by certifiers. Also the report is supposed to help identifying areas where future research should be focused on.

This report D7.4 is developed to represent a baseline state-of-the-art summary of the current common FOWT design practice. It is intended to serve as project internal benchmark in order to determine the overall achievements beyond the current state-of-the-art of the LIFES50+ project with respect to the various disciplines addressed in the project. This state-of-the-art report is based on results from previous research projects and available publications. Results from project internal resources (D1.1, D4.4, D6.1, D7.2, D7.3 [generalized information]) were evaluated and a questionnaire sent out to wind turbine manufacturers to outline procedures in the design of the wind turbine controller.

1.1 Report structure

This report presents an overview of the state-of-the-art process and the applied methods of the design practice of floating wind turbines, focussing on the floating support structure (tower, hull, moorings and dynamic cable) and the controller. A general design procedure focussing on the early design and closely linked to the scope of LIFES50+ is derived and presented in chapter 2. The process and steps of the certification of a floating wind turbine project is presented in chapter 3, providing in detail the requirements of a project from a certification body's point of view. Following this, chapters 4 to 8 present state-of-the-art summaries for the various design-related disciplines addressed in the work packages of LIFES50+. First, the state-of-the-art of the design of main FOWT components is presented in chapter 4, focusing on wind turbine controller and support structure, followed by a review of currently applied experimental practices. Next, a summary of currently applied numerical design methods is provided, currently regarded industrialization considerations are discussed, and finally the current practice of cost and risk analysis for FOWTs is outlined.

2 State-of-the-art design procedure

The goal of this chapter is to summarize the state-of-the-art design procedure for floating offshore wind energy systems that is applied in research and industry, taking into account requirements by recognized class societies outlined in standards, guidelines and recommended practices. Building on this, a high level definition of a design process is provided, based on three key design stages. This definition constitutes a general overview of necessary actions, procedures and methods applied in the design of a FOWT system up to a technology readiness level TRL 4.

The chapter is split into two parts. The first part summarizes previous research projects that address the overall design process of FOWT systems. Based on these past efforts on the classification and differentiation between different design steps, the second part defines design stages of the design process of FOWT systems. For each of the stages, the different available models, tools and methods to be applied are identified, based on work previous to LIFES50+. As a result, the design process is split into three main stages: conceptual design, basic design and detailed design.

2.1 Design process of substructures for FOWT systems: review

Various research and demonstration projects have dealt and are dealing with application of design processes of FOWT systems (e.g. INNWIND.EU, HiPRWind, DeepWind, FLOATGEN, AFOSP, WindFloat, GustoMSC, Fukushima FORWARD, GOTO FOWT, INFLOW, MARINA Platform, H2OCEAN, TROPOS, OceaNET). Early projects in the field focussed on feasibility studies and technology demonstration with three key design steps: (1) simulation of substructure, (2) tank testing and (3) coupled simulation (Roddier, et al., 2010). More recent projects put their focus on the process of finding an optimal design, e.g. (Sandner, et al., 2014).

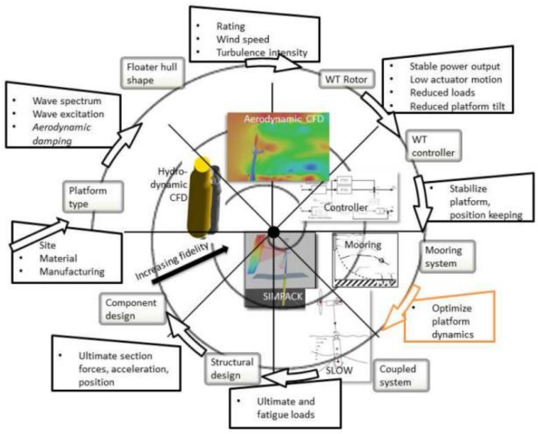


Figure 1: FOWT design process from (Beyer, et al., 2014)

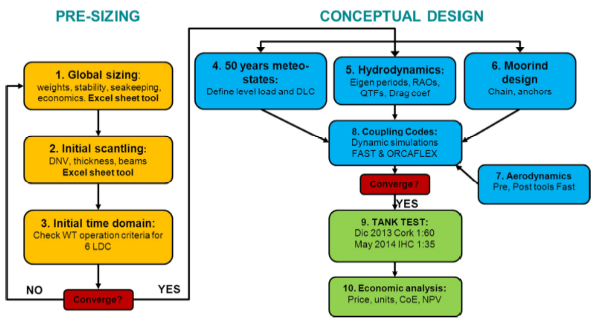


Figure 2: FOWT design process from (Aguirre, et al., 2013)

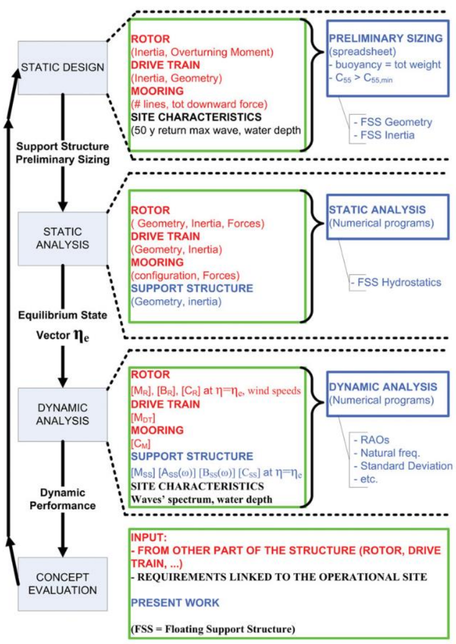


Figure 3: FOWT design process from (Collu, et al., 2014)

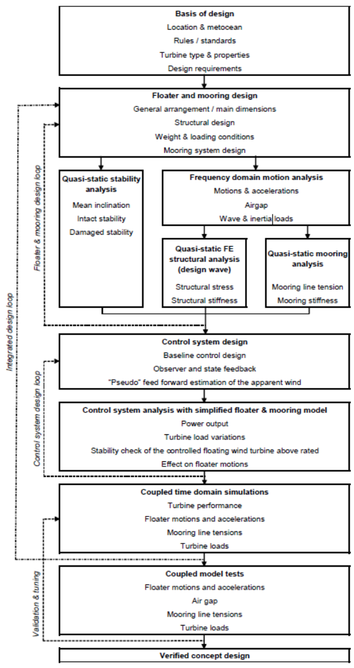
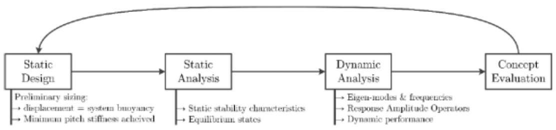


Figure 4: FOWT design process from (Huijs, et al., 2013)



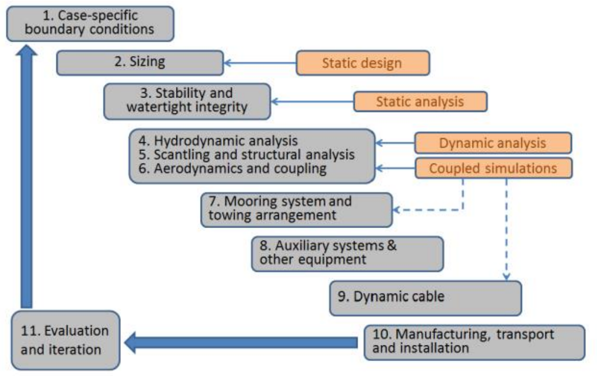


Figure 5: Generic conceptual design process in the off-shore oil and gas industry from D4.4 (Borg, et al., 2015)

Figure 6: Design Steps used in D7.3 (Berque, et al., 2015)

A general representation of the design process of floating substructures can be described by a design spiral that is based on to the ideas presented in common floating offshore references (Chakrabarti, 2005). This has been applied by (Beyer, et al., 2014) and (Azcona, et al., 2013), see also Figure 1, and shows the importance of continuous iteration loops between varying levels of the fidelity of the design in order to find an optimal design.

(Huijs, et al., 2013) also provided an overview of their design procedure, introducing more detailed steps in the pre-design as well as including an early stage control system design loop (Figure 4). (Aguirre, et al., 2013) presented the design process applied for the NAUTILUS semi-submersible sub-structure (Figure 2). (Collu, et al., 2014) determined four essential design steps: "*preliminary sizing, static analysis, dynamic analysis of the structure and, summarising all previous steps, the concept evaluation*" (Figure 3).

Design processes were also addressed in previous deliverables of LIFES50+. An overview of a con-ceptual design process is described in deliverable D4.4, see Figure 5. For the non-public deliverable D7.3 (Berque, et al., 2015), design steps of floating offshore substructures were defined according to Figure 6.

2.2 Design process of substructures for FOWT systems: the state-of-the-art

A general view on the abovementioned projects and reports as well as internal communication in LIFES50+ allows deriving the following general procedure for the design of FOWT substructures, if the selection of the substructure type is already established (see e.g. (Butterfield, et al., 2007)). Also early in the design process, the **corrosion protection** needs to be defined as this fixes the lifetime of the system.

The first step of the design process is typically a **spreadsheet design or pre-sizing** considering only very basic representation of the wind turbine by implementation of deterministic loads (i.e. extreme loads). For this, basic information needs to be available with respect to the environmental conditions at site (at this stage of the technology, the design process is usually individual for each considered loca-tion, as no classification of the environmental conditions comparable to the wind turbine classification for FOWT substructures is available) as well as the wind turbine and the type of substructure to be used. Typically at this stage neither the exact metocean data nor the exact wind turbine type is known, therefore often information beyond this limited basic information is not even available. The goal of this simple sizing step is to ensure basic criteria like stability and determine preliminary values for dimensions and characteristic quantities of the floater and mooring lines as well as the estimated cost of the system. This sizing procedure is based significantly on experience from conventional floating offshore designs. A more detailed description and load cases to be considered can be found in (Huijs, et al., 2013), (Chakrabarti, 2005). It shall be mentioned that these early design criteria, such as design platform heel at rated wind speed or assumptions regarding the wind turbine thrust, height and mass, may have significant influence in later design stages and need to be selected carefully and adjusted once additional information from later stages or regarding the site and wind turbine is available.

Following the pre-sizing, **motion characteristics** are determined through consideration of frequency responses of the system and quasi-static simulations that focus on stability and mooring lines. Also, once a basic internal structural layout is determined, a **structural analysis** is performed by applying pressure mapping in combination with finite element analysis. At this design stage, the **wind turbine system** (i.e. both tower and rotor-nacelle-assembly) is considered as rigid body with a very simple representation of wind loads acting on the rotor (e.g. point force resembling maximum thrust at tower top). If the tower flexibility is regarded to have an important influence on natural periods, which is true for some designs, it may also be considered at this stage.

A first design of the wind turbine **controller** has been mentioned (Huijs, et al., 2013), (Lemmer, et al., 2015)) as a relevant topic to be addressed early in the design using a simplified model of the floater, turbine and the mooring lines. This becomes of interest as soon as the dynamic behaviour of the system is considered. The early inclusion of control system design is considered as important to ensure overall stability (through mitigation of negative damping effects (Sandner, et al., 2015) as well as to determine the closed-loop eigenfrequencies of the system and the overall closed-loop dynamics. The design of the controller requires representative masses and a description of the external forces (i.e. wind and wave) and the coupling of the components of the FOWT system. Based on this, a nonlinear multibody system can be defined with which the controller can be optimized taking into account selected operational points. See also chapter 4.3 for more detailed information on the state-of-the-art design of the controller.

The design of mooring lines can be performed independent from the rest of the structure by application of higher level numerical models at each design stage. This means designing quasi-static mooring lines in a first step and later dynamic and decoupled from the substructure model.

Fully coupled time domain simulations are performed after the conceptual design of floater, mooring system and controller. These are based on a set of design load cases (DLCs) for both ultimate limit state (ULS) and fatigue limit state (FLS) considered crucial to the designer. For example, in LIFES50+ these design driving load cases were selected as a subset from the existing list of DLCs presented in (DNV-GL, 2013). These are provided in deliverable D7.2 and are the ULS DLCs 1.1, 1.4, 1.6, 2.3a, 6.1, 6.2, 9.1, 9.2, 10.1 as well as a simplified version of the FLS DLC 1.2. Environmental conditions are usually not available directly from the site but are derived from other sources leaving the design basis to be somewhat generic. Nonlinear effects like vortex induced motion or slow drift should be investigated, depending on the considered substructure. The resulting loads and motions are compared to the strengths and deflection/acceleration limits of the structure at selected points and adjustments of system properties and dimensions are implemented as necessary. Following this, an iteration loop repeating previous design steps is possible in order to tune the simpler models and arrive at an improved conceptual design.

The next step is the validation of the loads and models as well as further assessment of ultimate loads and tuning of hydrodynamic coefficients through **experimental procedures**. Assessment of ultimate loads still necessitates model tests, as state-of-the-art aero-servo-hydro-elastic software tools are not considered to have an adequate confidence level yet in capturing possible highly nonlinear events. Here, high fidelity calculations applying CFD-models represents an option to represent transient combinations of hydro- and aerodynamics and could add to or partially replace experimental tests and shorten testing procedures. However, in order to achieve a certain level of certification of a new design, validation in lab and at full scale is still necessary and therefore experiments remain essential. Additionally, at this point the use of CFD-models (while often being common practise for large O&G platforms already) has only been applied in very few FOWT projects and cannot be regarded as part of the state-of-the-art design process for load validation. Experimental procedures as part of the design process are commonly used only for validation of the design specific simulation models (e.g. a new design for a TLP substructure), not the simulation tools (or the included physical models). It is assumed here that the applied simulation tools for higher level design and their implied physical models have been validated elsewhere/prior to the considered design process. A more extensive inclusion of experiments in design loops is also possible (if, for example, wave tanks are easily accessible). Overall, experimental tests ensure that the numerical models were setup correctly and the design generally does not show any unexpected dynamic behaviour due to neglected physical effects. Also they serve as an additional proof-of-concept for the selected design and improve confidence of all involved parties.

Once the scaled model is validated in the lab, the conceptual design can be regarded as verified and the detailed design is initiated, followed by validation and demonstration of the system at **full scale** in real environment conditions. Some projects have also validated smaller scaled prototypes in real environmental conditions before performing full scale prototype tests (Utsunomiya, et al., 2009).

The installation of a full scale prototype will also require certification of the design and consequently, certifiers need to be involved latest at this stage. The requirements from certification combined with the resulting needs from the project advancing towards realization, at this stage, the focus will be shifted towards defining in increasing detail the follow-up phases of the project: manufacturing and installation processes, maintenance, decommissioning, general logistics, health and safety as well as environmental and legislation aspects.

On the simulation side, all simulations necessary in order to reach certification of the design are performed (i.e. the full list of DLCs presented in guidelines). The load case table to be simulated for determining the design loads requires a detailed design basis based on reliable metocean and geotechnical data from measurements and/or hindcast data, providing at site data for all relevant environmental parameters describing wind, waves, currents and soil conditions (see also chapter 3.3.3.1). Additionally, the detailed design of the separate components of the substructure and secondary steel is initiated.

In parallel to the technical design of the system, LCOE and LCA as well as risk, safety and functionality analyses are performed continuously with increasing level of detail from the beginning to ensure the economic viability of the design. While LCOE and LCA considerations are not necessary from a certification point of view, the determination of risk, safety and functionality needs to be documented for certification of the design.

From the abovementioned description, a simplified high-level design process can be derived that is linked to LIFES50+ and presented in Figure 7. Three stages are proposed describing tasks that are generally performed until certification of the design. Seven task categories (*Design basis, numerical design, experiments, LCOE & LCA and risk, safety and functionality*) provide a better overview of the work flow. Some of the categories are intentionally linked to correlated work packages in LIFES50+: *numerical design*: WP1 & WP4, *LCOE*: WP2, *experiments*: WP3, *manufacturing and deployment*: WP5, *risk, safety and functionality*: WP6. The input necessary for each of the stages is summed up in the category *design basis*. Another category called *certification* was added in order to show which stage of the certification process can be reached at the regarded design stage. If a further classification seemed feasible, it was accounted for as well. This is in particular the case for the numerical design category in the first design stage. There, a first design loop is performed including different fidelities of numerical tools. Also, the mooring line design is performed separately in this category. For each of the categories exemplary outputs are provided (sometimes linked to subclasses, if applicable). These outputs can be used as input in the stage-internal design loop or as input to the next stage. Note that while iterations and loops within and between stages are expected, they have not been included for simplicity. A schedule of the design process is included in order to show possible overlaps between design stages. Tasks that need to be performed before the presented design process are the selection of one preferred substructure concept, as well as the requirements for the corrosion protection system performance, which influences the fatigue lifetime of the system. Detailed protection methods will be addressed in the detailed design phase.

The scope of the presented design process can be defined as follows:

- The presented design stages focus only on the design of the system up to a technology readiness level (TRL) 4 - that means “TRL 4 - technology validated in lab”. It is acknowledged in this work that a major part of the effort of an industrial FOWT project will be performed in the disciplines of logistics, manufacturing, installation, operation, maintenance and decommissioning procedures.
- Only support structures of FOWTs are considered in LIFES50+. That means that the design of the rotor-nacelle-assembly is considered to be provided by the turbine manufacturer before the design of the substructure. The wind turbine controller as well as the turbine tower are considered to be adjustable and are thus included in the described process.
- As many steps involved in the design process are running in parallel within each stage and iteratively across stages, a high-level view needs to be applied in order to identify the general stages of design. The structure of design stages is sorted in a sequential order (steps that have to be finished first are mentioned first). E.g. wind turbine controller design is included at an earlier design stage than the detailed design because the final design of secondary steel structures cannot be finished before the system loads are established and fixed.
- The process is one simplified high-level view on the design process of FOWT substructures without explicitly outlining step-by-step procedures at each stage. It is highlighted here that industrial procedures are more complex and detailed than presented here; also different design philosophies exist which deviate from the presented process. However, the provided procedure can be used as general reference when working on FOWT substructure systems.

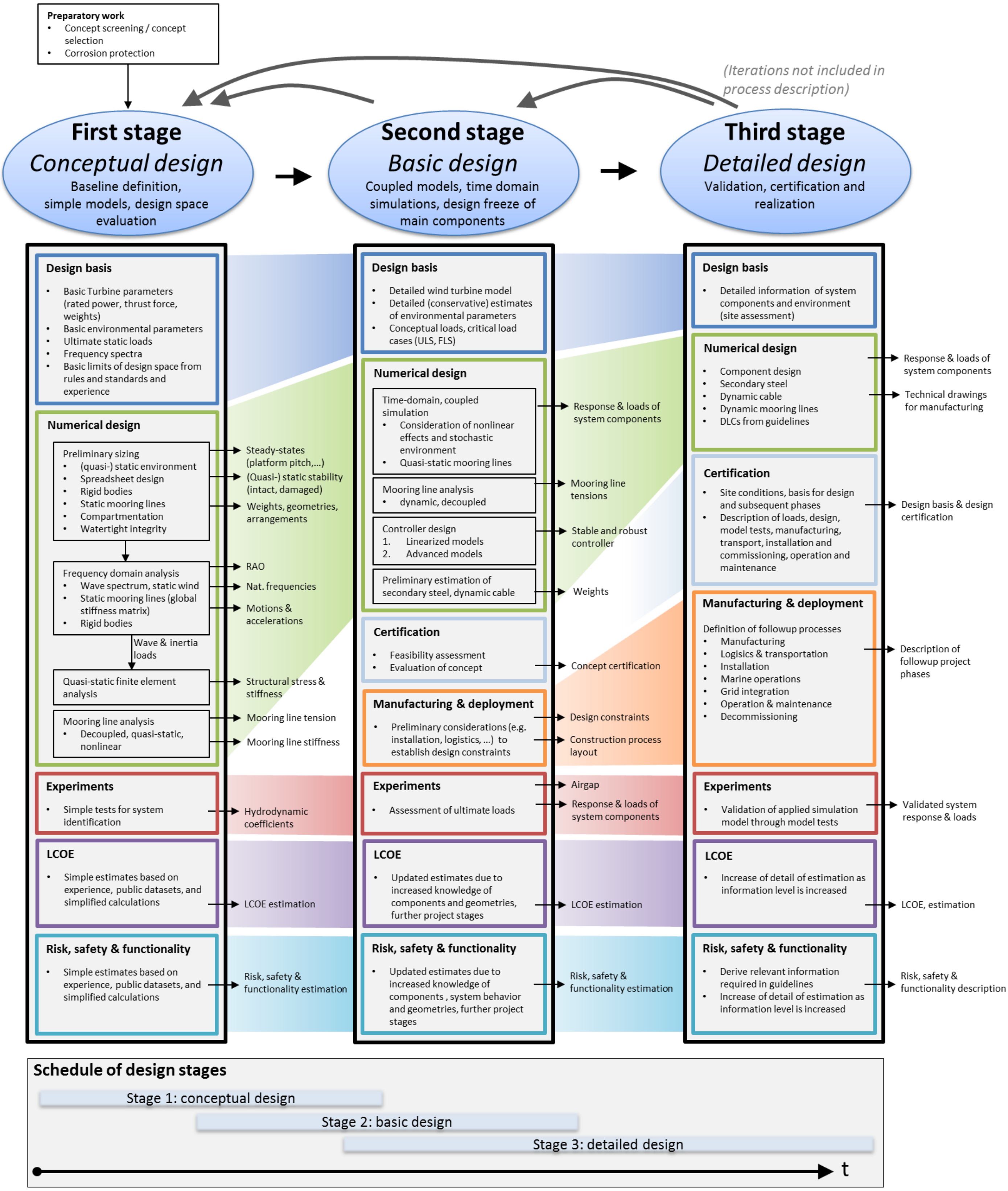


Figure 7: State-of-the-art design process

3 Certification procedures

This particular chapter focuses on how the certification can support in the concept, design basis and design phases of the floating wind turbines' support structures. The rotor nacelle assembly is assumed to be already type designed and approved. With regards to the design standards and codes, the deliverable D7.1 gives an overview of different standards currently available in the market (see Table 1). Since DNV-OS-J103 (DNV-GL, 2013), a DNV GL standard is used for the design of the concepts within the LIFES50+ project, this chapter will mention the requirements from a certification point of view based on DNV GL service documents.

Table 1 Reviewed guidelines and standard in D7.1 "Review of FOWT guidelines and design practice"

Topic	DNV-OS-J103	IEC 61400-3-2	GL 2012	ABS #195	Class NK
Safety Philosophy and design principles	Yes	No	Yes	Yes	Yes
Site conditions, loads and response	Yes	Yes	Yes	Yes	IEC 61400-1, IEC 61400-3
Structural design	Yes	Yes	Yes	Yes	Yes
Materials and corrosion protection	Yes	ISO 19904-1, ISO 20340	Yes	"Industry standards"	Yes
Floating stability	Yes	Yes	Yes	Yes	Yes
Station-keeping	Yes	Yes	GL Rules of Offshore Technology, GL Rules for Material and Welding	API RP 2T, API RP 2SK	API RP 2SK
Design of anchor foundations	Yes	No	GL Rules of Offshore Technology, GL Rules for Material and Welding	API RP 2T, API RP 2SK	No
Mechanical system	Yes	Yes	Yes	Yes	Rules for the Survey and Construction of Steel Ships: Part D and Part H
Cable design	Yes	No	Yes	No	No
Control system	Yes	Yes	Yes	No	No
Transport and installation	Yes	Yes	Yes	No	Yes
In-service inspection, maintenance and monitoring	Yes	Yes	Yes	No	Yes
Guidance for coupled analysis	Yes	No	No	Yes	No

3.1 Project assets and phases

Among the assets in an offshore wind farm, the LIFES50+ project focuses on the floating wind turbine support structures.

The following assets can be considered as part of the floating wind farms:

- Floating wind turbines and their support structures
- Substation including topside and support structure
- Power cables
- Control station

Dividing the project into different assets enables the certification body to offer certification service for each of them separately. More information about each asset is found in DNVGL-SE-0073.

The life-cycles phases can be defined as following:

Figure 8: Life-cycles phases

From the certification point of view, a project can be broken down further into:

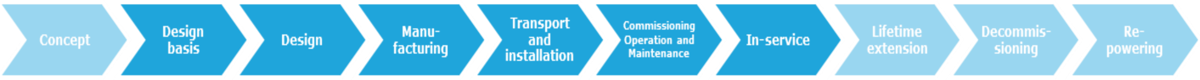


Figure 9: Project certification's phases

The six main certification phases (Design Basis, Design, Manufacturing, Transport and Installation, Commissioning, Operation and Maintenance, and In-Service) are marked in darker color. The others marked in brighter color are normally considered as optional for certification.

The targets of certification activity in each phase are:

1. **Concept**: Evaluation of the concept feasibility and of the assumptions made for the preliminary design. The scope of work is agreed between the certification body and the designer and typically includes: evaluation of the general feasibility of the concept, identification of novelty and risk in the design, evaluation of the preliminary design, verification of the methodology used during the design.
2. **Design Basis**: Evaluation of the site conditions, design independent parameters and basis for design (design dependent parameters). The site conditions' investigations which are considered as part of the Design Basis can start before the Detailed Design. While the site conditions are considered relatively "standard independent", the Design Basis is dependent on the Design and the standards have to be selected. For this reason, there is a split between site conditions and Design Basis in the IEC certification scheme.
3. **Design**: Evaluation of the integrated load analysis and of the final design. In (IEC61400-22) the integrated load analysis is a separate phase while in (DNVGL-SE-0190, 2015) this is part of the Design phase.
4. **Manufacturing**: Surveillance of the fabrication process and products as well as follow-up on the assumptions made during the design phase.
5. **Transport and Installation**: Monitoring during the transport and installation.
6. **Commissioning**: Evaluation of the commissioning handbooks and on-site inspections.
7. **In-Service**: Periodic on-site inspections after the start of the project.
8. **Lifetime extension**: Evaluation the possibility of prolonging the lifetime of an ongoing project considering the initial design assumptions.
9. **Decommissioning**: Evaluation of the decommissioning handbooks and on-site inspections of the removal process.
10. **Repowering**: Evaluation the upgrading of an existing wind farm by a more efficient turbine type.

During the life cycle of the project, the certification phases can be arranged according to the Figure 10 below based on the project certification scheme according to (DNVGL-SE-0190).

The LIFES50+ project defines three design stages which are conceptual design, basic design and detailed design. They are also illustrated in Figure 10. It is expected that the third stage (detailed design) starts in parallel with the Design Basis certification phase in order to reduce the planning time.

Wind power plant phase	Development			Construction		Operation and Maintenance		Lifetime extension	Decommission-ing	Re-powering
Phase no.	0	I	II	III	IV	V	VI	VII	VIII	IX
Certification phase	Concept	Design basis	Design	Manu-facturing	Transport and installation	Commissioning Operation and Maintenance	In-service	Lifetime extension	Decommis-sioning	Re-powering
Short description of the certification activity	Plausibility check of the wind power plant concept.	Design basis covers the site conditions and the basis for design and subsequent phases.	Design covers the steps necessary to achieve final design approval. This includes a site-specific design approval of the power plant.	Manufacturing covers the surveillance during manufacturing of the project related assets.	Transport and installation covers the surveillance during transport and installation of the project related assets.	Commissioning involves all follow-up evaluation and on-site inspections during the implementation of the project. Operation and maintenance relates to the concepts and manuals to be approved.	In-service involves follow-up evaluation and periodic on-site inspections after start of operation and the power plant life-time.	Lifetime extension determines the remaining lifetime beyond the design lifetime of the plant.	Decommisioning contains the planning and execution of the de-commissioning and wind power plant removal.	Re-powering covers the renewal and re-installation of wind power plant at a former power plant site.
Major design stages suggested in the LIFES50+ project	**First stage** *Conceptual design* → **Second stage** *Basic design* → **Third stage** *Detailed design*									

Figure 10: Certification phases

3.2 Standards and Project certification

The following IEC and DNV GL's documents can support the investors, designers and manufacturers in developing the project:

Service specification (Description of the scope of work) used for floating wind projects	
IEC61400-22:2010	Wind Turbines – Part 22: Conformity testing and certification
DNVGL-SE-0073:2014	Project certification of wind farms according to IEC 61400-22, Ed.1
DNVGL-SE-0422	Certification of floating wind turbines (planned published 2016)
Standards (Technical requirements) used for floating wind projects	
DNV-OS-J103:2013	Design of Floating Wind Turbine Structures
DNV-OS-J101:2014	Design of Offshore Wind Turbine Structures
IEC61400-3-2	Design requirements for floating offshore wind turbines (draft technical specification (DTS); standard to be published)
IEC61400-3:2009	Design requirements for offshore wind turbines
DNC-OS-C101:2014	Design of Offshore Steel Structures, General (LRFD Method)
DNV-OS-C106:2014	Structural Design of Deep Draught Floating Units (LRFD Method)
DNV-OS-C105:2015	Structural design of TLPs - LRFD method
DNV-OS-C502:2012	Offshore concrete structure
DNV-OS-E301:2014	Position Mooring
DNV-OS-E302:2008	Offshore Mooring Chain
DNV-OS-E303:2013	Offshore fibre ropes
DNV-OS-E304:2013	Details regarding steel wire ropes for mooring lines
DNV-OS-D101:2014	Marine and Machinery Systems and Equipment
DNV-OS-H101:2011	Marine Operations, General
DNV-OS-H102:2012	Marine Operations, Design & Fabrication
DNV-OS-H201:2014	Lifting appliances used in subsea operations
DNV-OS-H203:2012	Transit and Positioning of Mobile Offshore Units
DNV-OS-H204:2013	Offshore Installation Operations
DNV-OS-H205:2014	Lifting Operations
DNV-OS-H206:2014	Sub Sea Operations
Recommended Practice (methods and ways to fulfill the requirements in the standards) used for floating wind projects	
DNV-RP-C205:2014	Environmental Conditions and Environmental Loads
DNV-RP-F205:2010	Global performance analysis of deep water floating structures
DNVGL-RP-0416	Corrosion protection of offshore wind turbines (planned published 2016)
DNV-RP-H103	Modelling and Analysis of Marine Operations (2014)
Other useful documents for offshore wind certification	
DNV-RP-A203	Technology Qualification
DNVGL-SE-0436	Shop approval in renewable energy (planned published 2016)
DNVGL-SE-0263	Certification of lifetime extension of wind turbines (planned published 2016)
GL-IV-2	Rules and guidelines – IV Industrial services –Part 2: Guideline for the cer-

	tification of offshore wind turbines
DNVGL-SE-0124	Certification of grid code compliance (planned published 2016)
DNVGL-ST-0145	Offshore substations (planned published 2016)
DNVGL-ST-0262	Lifetime extension of wind turbines (planned published 2016)
DNVGL-ST-0359	Subsea power cables (planned published 2016)
DNVGL-RP-0360	Subsea power cables in shallow water (planned published 2016)
DNV-OS-C501:2012	Composite components

Besides DNV GL and IEC standards, there are also other standards from other certification bodies. A detailed comparison of the current standards was made in the deliverable D7.1 of the project LIFES50+. Project certification is a third party service that is relevant for the development of floating wind turbines.

There are two main project certification schemes: the one according to IEC and another according to DNV GL. At the moment these are the only two certification schemes which cover the full project certification based on the authors' understanding. Other certification bodies have issued standards, which mainly include technical requirements i.e. similar to (DNV-GL, 2013). These standards however refer to (IEC61400-22) with regards to the certification scheme. (ABS#195) covers the classification of the floater and states that "*ABS will not review or be responsible for the accuracy of the RNA type certificate*" and requires that the RNA is required to have a type (ABS#195, 2013) certificate in accordance with (IEC61400-22). (BV-NI-572, 2015) of Bureau Veritas mentions that the note "*does not cover top structure, i.e. tower, rotor, blades and nacelle design*" and recognizes the certification scheme according to (IEC61400-22). Similarly, the (NK-Guidelines) focus mainly on the floater's design. More information about the standards can be found in the deliverable D7.1 of the project LIFES50+.

The project certification scheme according to IEC 61400-22 specified in (DNVGL-SE-0073, 2014) is similar to the DNV GL one according to (DNVGL-SE-0190, 2015). The DNV GL project certification scheme however addresses a larger number of topics varying from the beginning (development phase) to the end of the wind farm's life (repowering phase).

The scope of the review as well as the requirements for each phase are described more in detail below.

3.3 Requirements from a certification point of view

3.3.1 Concept

The review of the concept is an optional certification stage which assists the developers in evaluating the feasibility of the technology under development. The scope is defined based on the agreement between the certification body and the developer. The certification body reviews that the methods and principles are according to the standards, that the concept will work and the assumptions made will be demonstrated. The following topics are normally considered as relevant for review:

1. Site conditions: The feasibility evaluation can be carried out for a generic site, according to site conditions defined by the designer. For the project LIFES50+ these metocean conditions are given in the deliverable D7.2.

2. Wind turbines and floating support structures:
   - Safety class
   - Station keeping redundancy
   - Turbine's characteristics
   - Control system of the turbine
   - Design lifetime
3. Standards, guidelines considered for the design
4. Loads and structure design
   - Preliminary loads and load analysis if applicable at this stage
   - Software validation if applicable at this stage
   - Floating stability
   - Support structure's preliminary design
   - Mooring preliminary design
   - Anchor preliminary design
   - Structural checks (ULS, FLS, ALS) of the design
5. Model test information if applicable at this stage
6. Transport, installation concept
7. Mechanical systems

The conceptual design is reviewed to identify the potential showstoppers and to support the development at later stages. Floating wind turbine concepts are considered as a novel technology which is typically associated with high risks and high cost. A concept carefully evaluated at early stages may save cost and lower the risk at the later phases.

3.3.2 Prototype Certification

In certain cases it may be useful to have a prototype before developing a large scale project, e.g. Hywind Demo and WindFloat first prototype. A prototype may also be built to develop the wind turbine's type certified design, which will be used for different projects. The type certified design normally considers conservative loads so that the design loads can cover the loads from a specific project.

Depending on the national requirements, the support structure of a prototype might be subjected to certification before being installed.

A Prototype Certificate is valid for 3 years, counting from the final date of the successful safety and function test. The certificate can be extended for another 3 years.

The Design Basis shall contain:

- Site conditions
- Wind turbines and support structures
- Codes, standards and requirements
- Model test

The Design Assessment of the support structure will cover following items:

- Extreme load analysis
- Fatigue load analysis for the intended operation time
- Floating stability
- Model testing

- Structural integrity of the support structures
- Station keeping system

A manufacturing survey of the support structure should be performed at least for the floating body and the station keeping system.

Before the testing operation, the test plan (measurements, safety and function test) will be agreed with the certification body.

3.3.3 Detailed Design: Design Basis and Design

This corresponds to the phases I and II of the IEC certification scheme as per Figure 10: Certification phases. The verification activity is to evaluate whether the site conditions, design basis and design fulfil the requirements defined by the respective standards.

The Design Basis and Design shall contain following items:

a) Site conditions
b) Wind turbines and support structures
c) Codes, standards and requirements
d) Loads and structure design
e) Model test
f) Manufacturing, transport, installation and commissioning
g) Operation and maintenance

3.3.3.1 Site conditions

International and national requirements are to be considered. Concerning the site conditions, the IEC 61400-3 including 61400-1 are normally applied. For the offshore projects in Germany, requirements of the Federal Maritime and Hydrographic Agency of Germany (BSH) shall be applied.

Following items are included in the site conditions:

- Environmental normal and extreme conditions: wind speeds
- Turbulence intensity
- Wave heights, wave periods
- Correlation of wind, waves and current
- Water depth
- Tide
- Current
- Soil conditions including seabed topography
- Others: earthquake, ice, marine growth, air density, temperature

The list of site conditions' items can be found in IEC 61400-3 Appendix A.

Please note that this section and the list in appendix are developed primarily for bottom fixed foundations and some changes may be needed for floating condition, in order to fulfil the requirements in DNV-OS-J103.

Not only the design values but also the measurement data and methods shall be specified. If the measurement campaigns are not carried out by an accredited institution, DNV GL will also review:

- Test and calibration methods
- Equipment
- Measurement traceability
- Assurance of the quality of test and calibration results
- Reporting of results

Normally, long term metocean (measurement) data at the exact project site is not available for offshore projects. Concerning the wind, typically this limitation is addressed by using different sources of measurements either from the hindcast or from nearby locations and by analyzing the correlation; it is possible to extrapolate the data in time as well as in space. In the final data, it is important to show that the long term variation of the climate during the lifetime of the project is included. Concerning the oceanographic conditions, normally a hindcast study is carried out. The hindcast covers often a period of 20 years or longer. As part of the validation, the hindcast model should be able to capture the extreme values measured as well as the long term trend of the relevant parameters (wave, current, water level). For the floating structures, the wave periods can play a more important role (for both FLS and ULS loads) than for the bottom fixed structures. In general, the extreme values corresponding to different recurrence periods are deduced by extrapolation which depends strongly on the quality of the data and the extrapolation methods applied. In case the quality of the data or hindcast simulation is not sufficient, safety margin shall be applied as a measure of correction.

The soil conditions are based on soil investigations which shall provide soil data for the geotechnical design. The soil investigations normally comprise the following types of investigation:

- Site geological survey to find out whether the subsoil conditions are homogenous
- In-situ testing such as cone penetration tests (CPT) or standard penetration test (SPT), pressiometer tests and diatometer tests
- Soil and rock sampling with static laboratory testing
- Topography survey of the soil surface
- Geophysical investigations to correlate with borings and in-situ testing
- Shear wave velocity measurements for assessment of maximum shear modulus
- Cyclic laboratory testing if applicable by national requirements

The extent and content of the soil investigations depends on the foundation type which is detailed in DNVGL-ST-0126.

3.3.3.2 Wind turbines and support structures: general information

The Design Basis shall contain the items as listed in the concept phase but shall provide enough information for the detailed design of the support structures and foundations. They are:

- Safety class
- Station keeping redundancy
- Turbine’s characteristics
- Control system of the turbine
- Design lifetime

The rotor nacelle assembly is part of the input for the load simulation.

The materials and assembly methods (welding, bolt, grout) shall be specified.

Normally, in order to avoid resonance coming from the rotor nacelle's components (e.g. 1P/3P vibration) the turbine manufacturer has restriction on the frequency range, which the support structures design shall fulfill.

The corrosion protection strategy shall be detailed:

- Coating,
- Cathodic protection
- The assumed corrosion allowances

It is expected that the split of responsibility between different partners (developer, turbine manufacturer, foundation designer) are clearly defined at this stage.

3.3.3.3 Codes, standards and requirements

The following standards have been used in the LIFES50+ project:

- Design of Floating Wind Turbine Structures (DNV-OS-J103)
- Design of Offshore Wind Turbine Structures (DNV-OS-J101)
- IEC 61400-3
- IEC 61400-1
- Offshore Concrete Structures (DNV-OS-C502)
- Position Mooring (DNV-OS-E301)
- Corrosion protection of offshore wind turbines (DNVGL-RP-0416)

Further standards due to local requirements (e.g. BSH standards for offshore projects in Germany) shall be applied.

3.3.3.4 Loads and structure design

The following load input parameters shall be specified:

- Design values for wind conditions
- Design values for sea states, wave heights, crest elevations, directional scatter, fetch, sea level
- Design values for combination of wind and wave conditions. In particular also misalignments between wind, wave and currents
- Design values for water levels and seabed levels
- Design values for soil stiffness, soil strength
- Damping:
  - Wave damping
  - Viscous damping
  - Aerodynamic damping
  - Structural damping
  - Slosher dampers, tuned mass dampers etc.
  - Station keeping damping
  - Soil damping
- Selection of wave theory and hydrodynamic load calculation methodology
- Response analyses

- Load combinations (Design Load Cases)
- Duration of simulation as well as number of simulations
- Load factors and load reduction factors
- Material safety factors
- Design lifetime of structures
- Clustering methodology for large wind farms, if applicable
- Comparison of RNA loads from the Type Certified Design versus project loads

The load calculation procedure of an offshore wind farm project can be described according to the figure below. For the floating wind turbine, the response amplitude operator (RAO) functions are additional input for the simulation. The full structural dynamics of the rotor nacelle assembly, support structures including foundation shall be implemented in the simulation code.

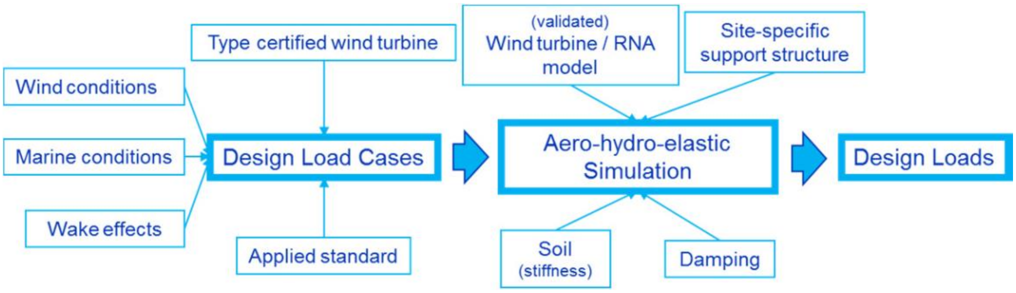


Figure 11: Load simulations

As part of the verification process, the certification body performs an independent load analysis in order to validate the model and the design loads. This independent analysis focuses on the critical load cases. Dynamic behavior and natural frequency shall be checked in this step.

The load and material factors depend strongly on the safety class considered and shall be decided from the early stages of design. The safety class depends on whether the structure is manned or unmanned. Likely, the floating wind turbines are the large ones (5 MW to 10 MW) which in case of failure will lead to high economic loss. Considering high safety class means the design is more robust but requires high capital cost (CAPEX). The robustness in turn allows a better reliability which means lower operational cost (OPEX). Similarly, a manned design requires higher safety factors and hence is more costly in term of CAPEX. However, it allows prolonged presence of the technical staff during the maintenance which might be beneficial in reducing the operational cost (OPEX) of the project. For the station keeping system, another variable that influences the safety factors is its redundancy and shall be considered from early stages of the project. Reference is made to DNV-OS-J103, Section 2.

Due to high effort in calculation time, the load calculations are normally only carried out for some selected locations in the wind farm. Hence, the clustering strategy shall be specified to demonstrate how the design loads can cover all the designs in the wind farm. This is preferably to be done at the design basis stage, if not before the end of the design phase.

The floating stability is to be considered in the design phase. This is different from a bottom fixed structure where floating stability may only be relevant during the transport and installation phase. The floating stability shall be verified for different conditions: towing, positioning, ballasting, installation and in-service condition. Reference is made to DNV-OS-J103, section 10. For the static floating stability, the following information shall be made available:

- Stability criteria and standards which they are based on
- Weights and centre of gravity, including how they are determined (hand calculation, FEM or inclining test)
- Tank parameters and free surface corrections
- Loading conditions
- Ballast material
- List of openings (for access, power umbilicals, etc)
- Hydrostatic curves and cross curves
- Draughts, Height of metacenter (KM), Metacentric Height (GM), pull force of towing boats in different conditions
- Righting arm (GZ) curve
- Maximum vertical centre of gravity (VCG) curve

There is sometimes a need to verify the stability by hydrodynamic simulation (dynamic stability). While it is quite straight forward to check the predefined stability criteria by hand calculation (static stability), it is more complicated to verify the floating stability by simulation. Damping and wave periods are very important for such analysis and shall be carefully determined. The (DNV-RP-H103, 2014) provides guidance on this kind of analysis.

The support structure is to be verified for different limit states (ULS, FLS, ALS and Service Limit State (SLS)) according to the design basis and in compliance with DNV-OS-J103 and other standards if required. It covers both in-service analysis and transitional stages (transport, installation). The following evaluation activities are conducted:

- Review of the detailed structural design reports, design drawings and manufacturing specifications for detailed structural design. For the analysis using FEM, the input and output files might be requested to be checked by the certification body.
- Review of geotechnical design including soil preparation, tolerances, drivability and scour protection for ULS, SLS and if relevant ALS.

For the critical structural components, independent structural analysis shall be carried out.

In principle, the design is approved by drawings, which are a means of communication between the designers and the manufacturers. For this reason, it shall be ensured that the level of detail in the drawings is sufficient and the main assumptions of the design calculations can be found in the drawings.

Regarding the power cables, the relevant codes for analysis and design of dynamic power cables shall be considered as required in DNV-OS-J103.

3.3.3.5 Model tests

Model tests are carried out for different purposes:

- Validation of the load simulation tools or support the theoretical calculations
- Verify theoretical methods or models
- Determination of the input parameters such as damping, RAO functions

DNV-OS-J103 requires the following:

"*Model tests shall be carried out to validate software used in design, to check effects which are known not to be adequately covered by the software, and to check the structure if unforeseen phenomena should occur. The tests shall be as realistic as possible with respect to scaling of wind, wave and current loading, considering issues such as scaling laws and inadequate model test basins*."

DNV GL considers that for novel designs, or unproven applications of design where limited, or no direct experience exists, relevant analyses and model testing shall be performed to demonstrate the acceptable level of safety. This is a requirement in the detailed design phase and is for both in-service and transitional stages (transport, installation). The exact scope of the model tests depends on the maturity of the design, application methods as well as on the applied simulation software.

The model tests' documents shall contain the following information:

- Scaling approach (e.g. Froude scaling)
- Scale ratio (not lower than 1:60)
- Test plan including decay, extreme, and wind and wave combination tests
- Tank/basin size (length, width, depth)
- Wind generation equipment (wind field size, wind tunnel dimensions, etc.)
- Test wave conditions (wave period, height, shape, spectrum)
- Scaled wind conditions (wind speeds, turbulence intensity, wind filed quality)
- Sensor positions and dimensions to be measured
- Calibration protocols
- Comparison measurements with simulation data for selected test cases

A final report validating the numerical tool and/or to calibrate the hydrodynamic model shall be prepared and reviewed by the certification body.

3.3.3.6 Manufacturing, transport, installation and commissioning

During this stage, assumptions on manufacturing, transport, installation and commissioning are made by the designers, which shall be checked and followed up at the later phase. This includes:

- Standards, codes and additional requirements
- Specifications and tolerances
- Limiting environmental conditions
- Manufacturing requirements and quality assurance systems
- Methods and loads of relevance for transport and installation
- Requirements for transport, installation (incl. loading) and commissioning manuals
- Quality assurance systems for the installation contractors

3.3.3.7 Operation and maintenance

At least following information shall be stated as part of the Design Basis and Design phase:

- Inspection scope and frequency
- Target lifetime of components, systems and structures
- Requirements for service and maintenance manuals
- Requirements for the condition monitoring system.

3.3.4 Manufacturing

The main activities of the manufacturing surveillance are illustrated as following:

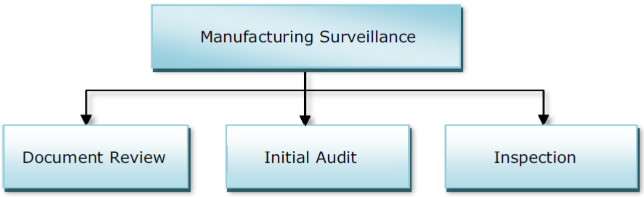


Figure 12: Main activities of manufacturing surveillance

Initial audit and inspection can be classified as on-site activity. The audit's purpose is to check the ability of the shop floor to perform the production of the components according to the expected quality. The scope of the inspection is decided in considering the results of the audits.

Concerning the steel support structures and foundation, the points that normally need to be considered by the certification body are:

- Compliance with quality plan requirements
- Incoming goods inspection
- Welding procedures specification and welding procedures qualification
- Welder qualifications
- Construction drawings versus reviewed drawings
- Visual inspection of on-going jobs
- Repair work
- Corrosion protection systems
- Witnessing of non-destructive testing and review of its documentation
- Visual inspection of finished structures before shipping
- Documentation review.

For the concrete support structure, additional points to be considered are:

- Formwork, reinforcing steel, embedment prior to concrete casting
- Preparations for casting, use of correct materials, construction joints, grouting of ducts, curing conditions etc.

It can be assumed that the manufacturing surveillance of the station keeping system (e.g. mooring and anchors) is covered in the certification of the used equipment and is not included in the project certification.

3.3.5 Transport and Installation

As part of the project certification DNV GL shall perform:

- Review of the transport and installation documentation
- Surveillance of transport and installation

It is important that the method statements for transport and installation manuals are made available to and reviewed by the certification body before the activity starts.

The documentation review covers:

- Overview of the wind farm
- Technical specifications for transport and installation (dimensions, weights, centres of gravity, dimensions of the installation vessels)
- Weather windows for transport and installation in compliance with the Design Basis and Design phases
- Arrangement of the equipment (lifting, upending tools)
- Description of the procedures including working steps
- Description of the required protection measures
- Description of the quality control required by the Design

The surveillance activity covers:

- Identification of the relevant components
- Inspection of components to be transported or installed
- Monitoring of weather windows in compliance with the described procedures
- Monitoring of methodology, sequences and important working steps
- Checking of damage after the transport or installation

3.3.6 Commissioning

Following activities are performed during for the commissioning:

- Review of commissioning manual
- Commissioning surveillance
- Inspection of installations and review of commissioning records.

3.3.7 In-Service : Operation and maintenance

The operation manual shall be reviewed by the certification body. The following items should be described in the manual:

- Project specific requirements
- General operation description of the wind farm
- Description of the supervisory control and data acquisition
- Specification of operation activities to be carried out
- Description of emergency cases and actions
- Description of power back-up installations
- Telecommunication procedures

- Access possibilities and the associated weather conditions
- Handling and resetting of faults
- Personnel safety requirements

For the maintenance of the project's assets, the review of the maintenance manual and the inspection plan for the periodic monitoring inspections shall be carried out.

3.3.8 Lifetime extension

A wind farm is normally designed for 20 years. Requirements for the lifetime extension can be found in DNVGL-SE-0263 and DNVGL-ST-0262.
DNV GL suggests four methods for lifetime extension as summarized as following. The requirements are different for each method.

Method	Practical part	Analytical part (generic)	Analytical part(specific)	Reliability analysis
Lifetime extension inspection (LEI)	X			
Simplified approach	X	X		
Detailed approach	X	X	X	
Probabilistic approach	X	X	X	X

Table 2: Methods for lifetime extension

3.3.9 Decommissioning

Decommissioning is an optional certification module and is expected to be easier to obtain for floating wind turbines than for the bottom-fixed structures. The degree of deconstruction is not a fixed parameter and depends on the project specific conditions (state-of-the-asset, law requirement, and economic situations). Hence, the degree of deconstruction will be specified in the beginning. The steps to be certified are:

- Decommissioning and deconstruction concept
- Decommissioning
- Deconstruction
- Transport

The documentation for each step shall be reviewed before starting of the activity. The decommissioning of power cables shall be considered according to DNVGL-RP-0360.

3.3.10 Repowering

Repowering can be done by substitution of whole or part of the wind turbines including or not including the support structure. This allows the use of more suitable or more efficient turbines for the project site after sufficient environmental data have been collected during the course of the project. The certification process is considered to be similar to that of a new wind farm. Possible impacts of the old wind farm on the new wind farm shall be considered such as consolidation of the soil, re-evaluation of the site data with better measurements, change of seabed morphology due to the old wind farm.

4 Design of main components of FOWT Systems

4.1 Environmental conditions

Environmental conditions need to be established/assessed and updated in various detail levels throughout the design process. While early design generally focusses more on extreme environmental conditions, fatigue analysis and a more detailed description of the environment are included later in the design process. Environmental assessment in later design stages is usually linked to DNV-OS-J101/103, DNV-RP-C205, and IEC61400-1/3 or other recognized standards. For analysis of environmental data, common statistical data analysis tools can be applied (e.g. MATLAB, Scilab, R, MS Excel).

In order to establish conditions for early assessment of loads with less detail than those described in the before mentioned codes, simplifications of the environmental conditions can be applied. Thus for the first design stage, the consideration of conservative estimates for extreme values of environmental conditions as well as the use of commonly used wind and wave frequency spectra is regarded as sufficient.

In the second design stage, a higher detail level of environmental conditions is required for the basic design. First, a subset of considered design driving load cases involving detailed environmental conditions is selected for evaluation to reach a basic design of the overall system. For the definition of the selected load cases, hindcast and other modelled data of the environmental conditions can be collected while previously initialized measurement campaigns to collect in situ data are evaluated. This includes environment of wind (wind speeds, turbulence intensity, air density, temperature, etc.) and ocean (wave heights, periods, wave spectrum, current speeds, water level, marine growth, bathymetry, soil conditions, etc.), see Table 3. It generally includes reference to available environmental datasets in order to specify relevant design load cases. Sources for reference are, for example, publically available in-situ data from meteorological stations (met masts, weather buoys, etc.) positioned close to the considered site, long term hindcast data or regional climate reports that can be referred to. These can deliver information on the wind and ocean environment in various detail levels. Opposed to the conceptual design phase, not only maximum values are considered, but also information of statistics of the parameters needs to be derived (e.g. 90th percentile turbulence intensity, wave period ranges, wind wave misalignment).This requires evaluation of combined statistics (occurrence probability distributions) of various parameters (e.g. wind-wave) which are usually based on available scatter plots. If data is not available for one of the environmental parameters available, conservative values can be applied from mentioned guidelines or by estimates. An exemplary definition of such a “generic design basis” is the design basis defined in deliverable D7.2 “Design Basis” (Krieger, et al., 2015). This can also be used as baseline for a concept certification step.

For detailed design and certification, conservative values can be used for all load cases required by the certification body. It is more common, however, to set up a detailed measurement campaign in order to realize a more accurate and cost effective design. This requires long term measurements (typically some years) of the environment at the considered site. The duration of such a campaign needs to be selected so that the probability distributions of environmental parameters are converged sufficiently and representative for the selected site and so that collected data can be used for calibration of hindcast models. Due to the necessary length of these measurement campaigns it is likely that they will be initiated earlier than the design of the FOWT system. Environmental parameters of interest are, for example, wind speed at hub height, wind shear, turbulence intensity, wind, wave and current direction, wave height, wave period, current profile, and soil conditions. Due to the high costs of floating met masts, buoys equipped with lidar wind measurement devices present a more cost effective solution that could become more common in the future (Bischoff, et al., 2014). The evaluation of measurement campaigns enable a detailed statistical evaluation of the environment which is necessary for definition of fatigue load cases and provides a base for data extrapolation for the definition of ultimate load cases (see also chapter 3.3). If a windfarm is developed, additional conditions relevant for each of the wind turbines, respectively clusters, need to be specified and considered (e.g. effective turbulence intensity in wake position).

Table 3: Basic design parameters from deliverable D1.1 (Gomez, et al., 2015)

Notation: DNV-0S-J101 Sec3	
Wind	EWM (B503)
Waves	ESS (3.3.4.7)
Current	ECS
Water level	MSL
	EWLR
Soil Conditions	
Others	Water tempera-ture (3.8.3.1)
	Marine growth DNV-RP-C205 6.7.4.2

4.2 Tower and transition piece

The initial tower design is typically based on the design of fixed bottom offshore structures or onshore structures, which is at first important to provide tower mass and inertia for the first design of the sub-structure. However due to the additional substructure motions of a FOWT and thus the resulting higher extreme and fatigue loads (Fulton, 2007) the tower needs to be re-qualified. In case analysis yields that the original tower cannot sustain the increased loads without major redesign including tower internals, a new tower design may be required. In addition typically the flange at the tower bottom needs re-design to connect to the transition piece or directly to the substructure, depending on the concept.

In order to evaluate the tower design a coupled model of the FOWT is needed at an early design stage. A high priority is given to the modal analysis of the tower which gives the eigenfrequencies and eigenmodes of the tower. As presented in (Larsen, et al., 2007) the eigenfrequencies change and new vibration modes appear compared to fixed bottom when the tower is mounted on a floating structure, which has got further consequences for the controller design. It is noticed that this behaviour varies between the different types of substructure concepts and has to be checked individually. The tower design may be further modified and adapted during the later design steps and corresponding iteration loops.

For the design of the tower it is especially important that the tower structural properties are designed in a way that its natural periods are not excited by the rotor and blades (1P, 3P frequencies). Furthermore in the offshore environment the tower must not be excited by waves and corresponding wave spectra as well as the resulting substructure motions. Several design standards are common and similar to fixed bottom structures. Figure 13 shows an overview of excitation frequencies for a generic 5 MW variable speed turbine which is derived from the chosen design in (Jonkman, et al., 2009). The placement of the first tower eigenfrequency may lie below the rotor frequency which is then called soft-soft design (1). This design is mostly not feasible due to material properties. A placement of the tower frequency in the rotor frequency range (2) is questionable since it will then be very close to the excitation. More common is to put the tower eigenfrequency between the rotor and blade passing frequency (3). This is called "soft-stiff" design. If the tower mode lies above the blade passing frequency it is called "stiff-stiff".

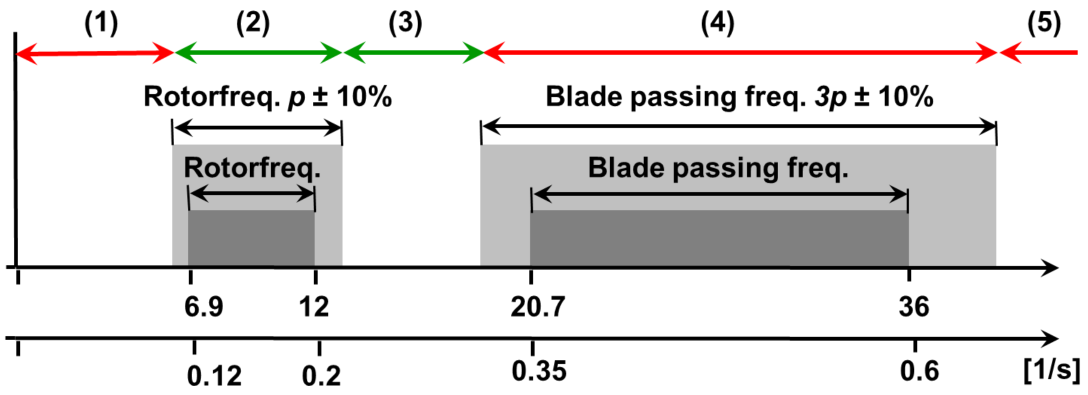


Figure 13: Excitation frequencies of a wind turbine rotor

Special attention in terms of loads is considered to be given at the transition piece, i.e. the connection of substructure to tower. Global loads, including wind turbine loads resulting in high bending moments and high fatigue loads, are expected to be of high importance at the transition piece or in areas close to the transition piece. For this reason and due to the possibility, that the transition piece has got a complicated architecture, it is usually analysed with a detailed FEM model.

A further element which may be relevant with regard to the transition piece is the electrical interface, including cable characteristics (minimum bending radius, electromagnetic-compatibility requirements, overlengths, etc.) and lightning protection system. Also material compatibilities, assembly and support requirements as well as health and safety requirements are to be considered.

4.3 Controller

In LIFES50+ deliverable D7.3, (Berque, et al., 2015) the design procedure of the controller has been addressed and the feedback by the four designers in form of a questionnaire evaluated. The questionnaire rates the importance of different design stages on the overall design and performance.

The importance of the modelling of aerodynamics and coupling effects in the design process is rated as the upper middle range. The impact of the control strategy has been rated as rather low by some designers although it is difficult to boil down the impact of the controller on cost of energy. This is in contrast to the common view that the controller is rather critical since it can lead to instability of the whole system. It is a general perception of the research community that the impact of the controller and the design process of the controller depend significantly on the chosen substructure type. Thus, its design and assessment with high-fidelity simulation tools should have a priority in order to reduce risk in the design process. Some designers have tested different control strategies in a wave basin in order to reduce risk and uncertainty. Others, however, have rated the control strategy as rather low.

4.3.1 Introduction

Whereas different control strategies have been employed in former wind turbine concepts, modern wind turbines are operated at a variable speed with an optimal tip-speed ratio for optimal power production up to the rated rotor speed. At this point the power is commonly limited by turning the blade pitch towards feather such that the turbine produces a constant power for wind speeds between rated wind speed and cut-out wind speed. See (Burton, et al., 2011) for more details.

For floating wind turbines especially this above-rated control is critical since the pitching of the blades can de-stabilize the floating wind turbine system as elaborated in Section 4.3.1.4.

In the following, variable speed control in region 2 is addressed before the design process of the blade pitch controller is analysed. Finally, the supervisory control and safety system is topic of Section 4.3.1.3.

4.3.1.1 Variable speed control

From cut-in wind speed to rated wind speed the rotor speed varies in order to allow for an optimal power production. Thus, the optimal tip-speed ratio TSR is tracked by controlling the rotor speed Ω with the generator torque at all operating wind speeds v_0.

$$TSR = \frac{\Omega R}{v_0}. \quad (1)$$

Here, the rotor characteristics determine the optimal TSR. Usually, this conventional control concept from onshore and fixed-bottom wind turbines is not changed for floating substructures. No negative damping effect arises for below-rated wind speeds since the trust is increasing with increasing wind.

4.3.1.2 Blade-pitch control

From rated wind speed to cut-out wind speed, the generator torque is held constant (for onshore wind turbines the generator torque is changed to have power constant) and the rotor speed is regulated with the collective blade pitch angle. A PI-controller is the standard way: the rotor speed error and its integral multiplied by the corresponding proportional and integral gains gives the blade pitch angle. The blade pitch angle as actuated variable results in an aerodynamic thrust and torque, which depends on the highly nonlinear aerodynamic rotor properties. In order to keep the closed-loop system dynamics constant throughout all operating points above rated conditions, a method called "gain scheduling" is necessary. See Figure 14 for a rough sketch of a simple PI-controller, which is the basis for state-of-the-art multi-MW blade-pitch controllers.

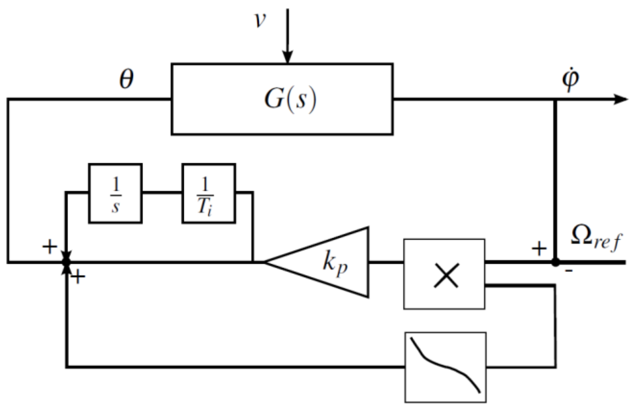


Figure 14 – Wind turbine model G(s) in closed loop with blade-pitch controller including gain scheduling function.

Thus, the blade pitch control design requires the structural and aerodynamic rotor properties, but also the overall system information to analyse the coupled system stability and allow for an optimized control. This means that the data for a state-of-the-art simulation model like FAST (Jonkman, et al., 2005) must be available together with environmental conditions to optimize for disturbance rejection.

For an optimal design process, the hull and the mooring system (especially elements important for the overall dynamics like heave plates) could benefit from considering the controller during the design and not just in the final stage after the floater design is established. The system eigenmodes, such as the coupled platform pitch, tower fore-aft and flapwise blade modes, can significantly influence the operational loads and should thus be optimized for the whole coupled system for reduced fatigue loads.

4.3.1.3 Supervisory control

Supervisory control is responsible for the activation of control regions and safety conditions for failures. Designers may choose to set limits on e.g. RNA acceleration, inclination connected primarily to sea states that would also stop the turbine. Such maximum operational sea state limits may be incorporated into supervisory loops. Due to the larger platform motions, the rotor-effective wind speed can, especially at low wind speeds, vary not due to the absolute but the relative wind speed. This might lead to the fact that switching regimes have to be adjusted.

4.3.1.4 Specifics for floating wind turbines

The controller has a significant impact on the system dynamics. The contradicting goals of stabilizing power for above-rated wind speeds and minimizing platform motion are a key challenge, as has been reported repeatedly in the literature. A too aggressively tuned blade-pitch controller results in unstable platform behaviour. This is due to a non-negative phase zero of floating platforms, which limits the bandwidth of the blade pitch controller. A good explanation of this “negative damping” problem is given in (Veen, et al., 2012). For an uncoupled adaptation of the controller the bandwidth of the PI-controller can be reduced in order not to excite the platform modes, see (Jonkman, 2008). Another method for a de-coupled tuning of the gains is given in (Larsen, et al., 2007). The different methods have been applied and compared by (Fleming, et al., 2014) and (Savenije, et al., 2014). A study on the integrated design of the hull shape of the floating platform including the controller has been made in (Sandner, et al., 2014). It shows that an optimization of the platform and the mooring system should not happen without the blade pitch controller since it significantly alters the operational natural frequencies and mode shapes.

As mentioned before, two control goals hold at the same time and therefore multiple-input-multiple-output (MIMO) strategies have been investigated. First, with only one actuated variable as the blade pitch angle and conventional single-input-single-output (SISO) controller design, see (Fischer, 2012) but also with additional actuators to stabilize the tower have been implemented in (Lackner, et al., 2011). Other multivariable controllers have been developed by (Lemmer, et al., 2015), (Christiansen, 2013) and (Luo, et al., 2011) mostly using all or the most relevant system states as controller input. An extensive study on individual pitch control (IPC) for floating wind turbines can be found in the thesis (Namik, 2012). Recently, also the inclusion of disturbance preview for floating wind turbines has been studied, see Section 4.3.4 for more details. A nonlinear model-predictive controller (NMPC) with Lidar (Light detection and ranging) wind measurements is presented in (Schlipf, et al., 2013) and extended for IPC in (Raach, et al., 2014). A model development and linear model predictive control design can be found in (Lindeberg, 2009).

The design process of the controller for floating wind turbines usually takes place in practice after the main dimensions of the platform and the mooring system have been determined and the wind turbine blade characteristics are available. The most critical control region is the region above rated wind speeds, where the blade pitch controller is active to keep the rotor speed constant. A strong coupling of the rotor dynamics with the whole system is present here. The dynamics including the controller and the closed feedback loop of rotor speed to blade pitch angle is referred to as “closed-loop dynamics”. Therefore, it might be advisable to look at the blade-pitch controller at early design stages already. Below rated wind speeds the generator torque is the actuated variable to control the rotor speed for optimal power production. The switching between these main regions can also have a significant impact on the loads. The model data necessary for the stages of controller design are listed in Table 4.

4.3.2 State-of-the-art design process of blade pitch controller

The focus of this section is the blade pitch controller as this one is crucial for FOWT. The common state-of-the art for the design process is depicted in Figure 15 and later in Section 4.3.3 commented with the responses of a questionnaire that has been sent out by the LIFES50+ task members.

First, a linear model is derived based on the structural data of the mooring system and the FOWT, the hydrodynamic model data and the aerodynamic model data. With the environmental conditions giving the relevant production load cases a linear model can be set up and used for analyses. This is essential for the system understanding with all zeros and poles, the mode shapes, open-loop transfer functions, etc.

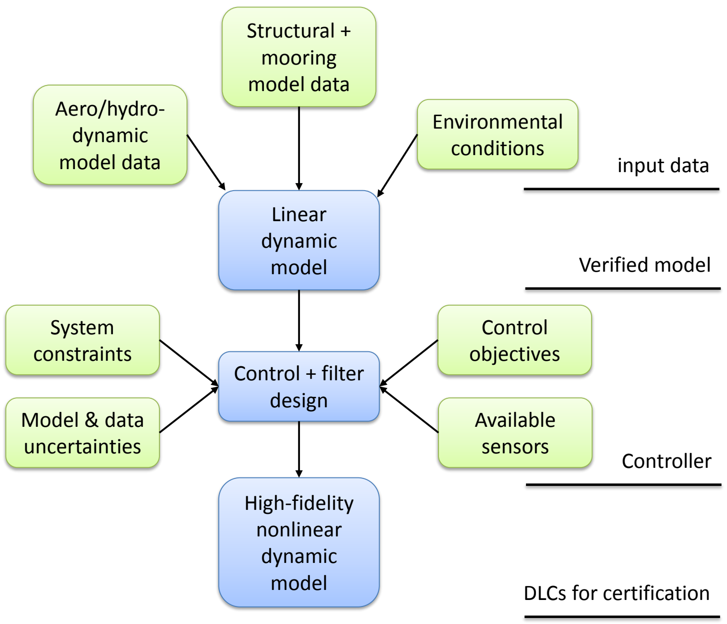


Figure 15 - Controller design process scheme.

Having derived the linear model the control objectives, together with the available system sensors to be used for control allow the definition of the control scheme to be employed. With the constraints of the system, e.g. maximum allowable excursions, maximum actuator power consumption, fatigue lifetime, etc. and the model uncertainties the linear model might be scaled and the necessary robustness quantified.

The control design is then, depending on the selected scheme, as outlined in Section 4.3.1.4, developed in an iterative procedure. For an assessment of the robustness models of higher fidelity need to be used with the relevant environmental conditions.

For certification, the controller has to be incorporated in a sufficiently accurate model that has been adjusted based on the results of experiments. A number of load cases with site-specific conditions needs to be run starting with system-identification cases such as deterministic wind and wave cases up to stochastic conditions for the assessment of realistic environmental loads.

For an improved planning of the controller design process, the necessary data and the sensors are subject to the next sections.

4.3.2.1 Model parameters necessary for control design

In this section the model parameters that are necessary for different levels of control design are outlined. Table 4 shows model parameters with a given priority. This is done since it is of high importance to design the controller at an early design stage, and at least to a preliminary detail to ensure the controller does not introduce any de-stabilizing dynamic system behaviour that would lead to excessive and unrealistic loads above rated operating conditions. This is to allow an optimization of design loads including the controller with realistic environmental conditions. Also, for the designer of the floating platform it is necessary to have data of an as high as possible accuracy to calculate and optimize the floating foundation with the mooring system. With the rough model parameters of priority 1, it is possible to define a functional controller for preliminary load calculations. It is noted that the parameters of priority 1 are a very reduced subset of the one with the highest impact on the system dynamics and the coupling with the controller. In more detailed design stages, more details have to be investigated such as effects from yawed inflow, aeroelastic stability, 3D gyroscopic effects and others.

For the detailed controller, and especially for the certification, it is necessary to have a state-of-the-art dynamic model available.

Table 4 – Necessary FOWT model parameters for control design.

Parameter	Discipline	Necessary mainly for	Priority
Aerodynamic coefficients (power and thrust)	Aerodynamics	Conceptual blade-pitch controller	1
Drivetrain mass, inertia	Structural dynamics	Conceptual blade-pitch controller	1
Platform surge/pitch eigenfrequency	Hydro/structural dynamics	Conceptual blade-pitch controller	1
Platform surge/pitch damping	Hydrodynamics	Conceptual blade-pitch controller	1
Aerodynamic coefficients	Aerodynamics	Variable speed controller	1
Platform mass/inertia	Structural dynamics	Blade-pitch controller	1
Platform hydrodynamic coefficients	Hydrodynamics	Blade-pitch controller	
Quasi-static mooring lines	Structural dynamics	Blade-pitch controller	1
Wind turbine mass/inertia	Structural dynamics	Blade-pitch controller	1
Tower elastics	Structural dynamics	Blade-pitch controller	1
Blade elastics	Structural dynamics	Blade-pitch controller	2
Blade polars	Aerodynamics	Blade-pitch controller	2
Nonlinear time-domain model	Multi-disciplinary	Supervisory control	1
Environmental condi-	Meteorology/		

tions	hydrodynamics

4.3.2.2 Required sensors

Common sensors for the control of variable-speed blade pitch-controlled wind turbines are the actual rotor speed, or generator speed and the blade pitch angle. For the tower damper loop it is also recommended to use the tower fore-aft acceleration signal as control input. This signal is commonly available from the inertial measurement unit (IMU) installed in the nacelle. Further sensors, like remote sensing of the wind with LiDARs or wave scanning devices like radar is required if advanced predictive control for load reductions is utilized. If fatigue loads are critical these look-ahead feedforward control strategies can mitigate the loads induced by incoming waves or gusts, see e.g. (Schlipf, et al., 2015).

4.3.2.3 Required actuators

For modern multi-MW wind turbines the only actuators are the three blade-pitch angles and the generator torque. The blade pitch actuators can be independent of each other to allow for individual pitch control (IPC). This accounts for azimuth-dependent wind loads and reduces the blade and tower-top fatigue loads. For further fatigue-load reduction additional actuators, like tuned mass-dampers can be used. This is shown, e.g. in (Lackner, et al., 2011).

4.3.3 Questionnaire to designers of existing prototypes

The LIFES50+ consortium received responses to a questionnaire designed by USTUTT from Statoil (Hywind spar), Gicon (Gicon-SOF TLP), NREL (WindFloat semi-sub), Alstom (Pelastar-TLP) and the University of Maine (VolturnUS semi-sub).

In general, the closed loop controller design is dependent on the platform design. So usually the controller for FOWT is different from the onshore controller, but for special designs such as TLPs the controller design stays the same or is close to the onshore design. Most of the developers classify their controller as a combination of SISO-loops, whereby different design methodologies are applied.

As control inputs typically collective pitch and generator torque are used. One designer added additional control inputs for global motion stability purposes, which depend on the substructure type, and made thoughts on individual pitch actions for load purposes, which however are not yet implemented. The standard sensors mainly used are the generator speed or rotor speed, respectively and the tower acceleration. Also the platform inclination is used by two designers. One designer tested also the use of more, additional sensors depending on the platform type without further specifying them in the questionnaire. For the design of the collective pitch controller itself, most of the designers did not adopt a method from literature except one for establishing a baseline in performance.

For testing the controller usually a fully coupled simulation model is used, where wind and wave loads are considered simultaneously. One designer indicated the use of a quasi-coupled model, where a substructure super-element is added in order to consider wave loads, which are, however, not corresponding to the instantaneous wave loads.

The supervisory control design is not different to the onshore design as far as specified by the developers. Only one designer introduced more operation modes for special conditions, such as drifting ice. Important design driving conditions seen by the designers are the tower loads and maximum rotor speed and more specifically the 50-year storm as well as drifting ice.

The safety system doesn't usually differ from the onshore version. However, the designers make their thoughts about special emergency procedures and shutdown procedures, which are related to the floater motions. The design driving conditions for the safety design are the same as for the above mentioned supervisory control.

Finally, the developers gave their comments on questions which they would like to be answered from an R&D perspective with respect to controller design for FOWT. A common problem identified by the designers is the question, what the design drivers and the control implications of the various floating concepts (spar, semi-submersible, TLP) are. Further problems are related, for instance, to physical constraints on controller performance or to the robustness of the control design with respect to environmental or system uncertainties and changes.

Thus, the control design for current prototypes differs typically from the one for common fixed-bottom onshore turbines. The complexity of the work also suggests incorporating the control design in early design stages already.

4.3.4 Outlook: Prospects of advanced control

It might be necessary to take advantage of the controller for reducing fatigue or even extreme loads. In this case additional sensors and actuators can help to achieve this load reduction. As described above, active or semi-active mass dampers can reduce the tower motion and tower loads. Such tower-dampers can help to reduce fore-aft and side-side fatigue loads. This is already a common technology for modern turbines. See (Lackner, et al., 2011) for an application to floating turbines. Measuring the wind speed ahead of the turbine with LiDARs allows for feedforward control, which detects gusts before they hit the turbine. Additional sensors allow the feedback of additional signals besides the rotor speed. With these MIMO procedures for example the tower-top velocity can be controlled to increase the tower damping ("tower feedback control"). A number of these methods have been evaluated for fixed-bottom offshore wind turbines in (Fischer, 2012). If large loads occur at high wind speeds the operating range can be extended in order to allow the blade pitch controller to be active in those conditions for load reduction.

4.4 Floating support structure

In general a lot of know-how of the conventional offshore industry such as the oil and gas industry as well as the shipbuilding industry is adopted. However wind-specific experience is accumulating and dedicated design procedures are developed, which for instance address the needs of higher quantities.

4.4.1 Classification of Concept

One possible way to classify concept designs for floating offshore substructure is presented here. Basically it consists of three concept designs, each combining elements of the three criteria for hydrostatic stability, which are: ballast-stabilised, waterplane-stabilised and mooring-stabilised. A more detailed look into this criteria is given in (Borg, et al., 2015). The three concept designs are:

1. Spar: A long, cylindrical structure with large draught, which is ballast stabilised and thus gains its stability by having the centre of gravity lower than the centre of buoyancy. (James, et al., 2015)
2. Semi-Submersible platform: Buoyancy stabilised substructure which floats semi-submerged on the surface of the ocean whilst anchored to the seabed with catenary mooring lines. (James, et al., 2015)
3. Tension leg platform (TLP): A semi-submerged buoyant structure, anchored to the seabed with tensioned mooring lines, which provide stability. (James, et al., 2015)

Each of the designs has strengths and weaknesses summarized in (James, et al., 2015), which are often dependent on specific site conditions. The designs have their origin in the oil and gas industry, but must be adapted to the needs of the floating offshore wind industry. For example the offshore wind industry requires higher quantities but smaller structures compared to the oil and gas industry, which impacts on the design, fabrication, installation, and operational characteristics of the structures (James, et al., 2015).

Figure 16: Overview of support structure Concepts (DNV GL, 2015)

4.4.2 Sizing

Sizing plays a significant role in the concept design from the beginning of the project, which means that decisions taken and options chosen early in the design are going to be key parameters during the entire project. The first step of the design process is typically a spreadsheet design or pre-sizing. The goal of this first sizing step is to ensure basic criteria such as stability and determine preliminary values for dimensions and characteristic quantities of the floater and mooring lines as well as the estimated cost of the system (Matha, et al., 2016). Main drivers for this initial sizing are the site conditions (metocean), turbine weight and inertias plus thrust, as well as the limitation of static heel. The heave and pitch periods are used as acceptance criteria based on simplified analyses on the relationship between motions and natural periods. Other requirements that typically apply are draft limitations and other assembly site limitations (logistic and supply chain). In the first-sizing phase it is primarily designed for extreme driven ULS; FLS are included in the later design stages.

An important part of the sizing procedure is the weight estimation. Hereby the mass as well as centre of gravity and inertia are determined for each subsystem and components (RNA, tower, transition piece, ballast etc.). This is already essential during the pre-design process, since a variation from the forecast weight would greatly impact motion behaviour as well as transport and installation contracts, load out procedure, etc. Establishing a weight control procedure is seen helpful in order to ensure that the weight of every item is kept within allowable margins. The structural weight is a large cost driver and minimising the amount of steel or concrete used in the substructure is seen as a key consideration (James, et al., 2015).

A high priority in this design step is the basic cost evaluation. Besides the already mentioned amount of used material, other parameters influence the cost, which are the construction method, load out operation, accessibility, operation and maintenance procedure as well as decommissioning costs.

Further elements of sizing include compartmentation, ballast tanks, and a basic dynamic response analysis, which is performed in order to ensure that platform dynamic modes are sufficiently separated from the excitation force periods such as waves and rotor frequency.

At the end a 3D CAD model of the concept is developed, which can be used for visualization and as design verification throughout the project.

4.4.3 Stability and Watertight Integrity

The well-established practice and tools in stability and watertight integrity has been adopted from other maritime activities (e.g. offshore oil and gas). However offshore possible uncertainty lies in potentially different requirements of national authorities.

In general the substructure stability should be ensured during the in service phase as well as the pre-service including load out, transportation and installation. Often the substructure manufacturer designs the substructure with limiting the angles (e.g. heel angle) in order to be able to use standard wind turbines. However the intact stability requirements of distinct substructure concepts varies. Intact stability requirements are given in DNV-OS-J103 (DNV-GL, 2013). Besides the intact stability, damage stability is to be considered, which is typically depending on national requirements. In standards used for the design, e.g. DNV-OS-J103 and IEC61400-3-2, damage stability would not be required, if the structure is unmanned and there is no harm to human life and environment. Damage conditions are established on the base of experience as well as water basin test campaigns. Typical damage conditions are the compartment flooding or a broken cable of a TLP. One criterion for these damage stability requirements is a limited heeling angle.

4.4.4 Structural Analysis

The structural analysis starts with determining an initial structural layout. This includes a check of the local strength, which is often dominated by hydrostatic loads. The structural layout is then checked against global design loads, which are derived from static and dynamic simulations (ULS, ALS and FLS). In order to define the load cases offshore standards and rules as well as metocean conditions are used as guidance and input respectively. For the calculation of the design loads a wide range of tools are applied, ranging from in-house tools mainly used for the initial structural layout to commercial tools, including HydroD, Wadam, Sima, 3DFloat, Ansys Aqwa, Orcaflex, and Nastran. The turbine loads are typically obtained by running an aero-elastic code, e.g. FAST, Bladed, SIMA or equivalent. More information about numerical tools is provided in chapter 6.

Having compared the acting loads to the strengths of the structure further adjustments of the system is identified. Possible hotspots lay in the parts close to the tower deck junction where high bending moment and fatigue loads occur. Other stress hotspots occur possibly in the structural transitions. Frames are added as needed in order to optimise the trade-off between minimising steel or concrete weight and reducing the complexity and cost of construction.

Finally, depending on the substructure concept, buckling may be relevant for small areas only (predominantly when high in-plane loads are present, e.g. due to hydrostatic pressure as well as bending loads from turbine, waves etc.) and does not need to be checked throughout the whole structure.

4.4.5 Hydrodynamic analysis

The evaluation of hydrodynamic loads is tackled by considering two types of methodologies. On one hand computational models are used, on the other hand more complex water tank test campaigns are run in order to validate the computational results as well as to calibrate the parameters in the computational hydrodynamic models. In the computational analysis the Morison equation is usually applied for slender structures. Hereby current and wave loads can be calculated. The coefficients in the Morison equation are typically adjusted by model tank test results, potential theory and finally results from CFD calculations.

For non-slender structures with large volumes software based on the potential theory such as Ansys Aqwa and WAMIT is used. With this method 1st order forces on oscillating bodies (Froude-Krylov, radiation, diffraction) can be computed. Viscous effects are not included inherently, but can be artificially implemented. 2nd order wave forces can also be considered in a potential theory model; however often these wave excitations are calculated by means of Newmann's approximation or quadratic transfer functions (QTF).

To a certain extent CFD simulations can be used to evaluate the drag behaviour of the floating substructure in current only conditions.

4.5 Mooring and anchoring system

4.5.1 Cost reduction potential

There is potential in reducing costs through improved design with respect to mooring and anchoring system and their installation. A study by (James, et al., 2015) provides some insight into identification and prioritization of most critical technical challenges in floating offshore wind. A ranking is made for various technical challenges and the mooring-, anchoring system and their installation is scored as medium, resulting in medium cost reduction potential. Opportunities for potential research initiatives for cost reduction are, e.g. a better understanding of loads and limitations, advanced materials with low weight and costs, lifetime asset integrity for over 25 years, optimisation of the installation process. Other studies assuming estimates for possible reductions in LCOE for wave and tidal mooring system are given in (LCICG, 2012). The report states 40% LCOE reduction by 2020 for tidal energy and 50% for wave energy devices. Synergies between the technologies floating wind, wave and tidal energy may help to increase efficiency and improve deployability.

4.5.2 Mooring Configurations

Two types of mooring configuration are most common. On one side catenary lines are usually used for spar-buoy and semi-submersible foundations permitting both station-keeping and substructure motion. A taut-leg mooring system is used with tension leg platforms (TLP) providing restoring force through axial stretching. An overview of different concepts is given in (James, et al., 2015) and shown in Figure 17.

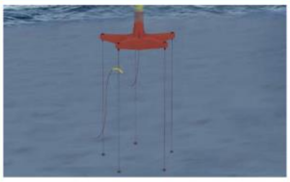
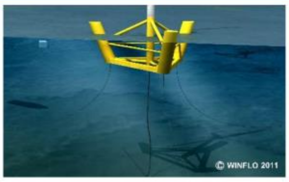
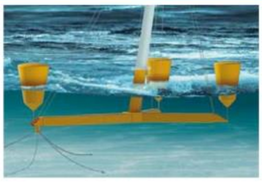
Taut-leg	Catenary	Semi-taut
		
Example: Glosten PelaStar	*Example: DCNS SeaReed*	*Example: Aerodyn Nezzy*
• Synthetic fibres or wire which use the buoyancy of the floater and firm anchor to the seabed to maintain high tension for floater stability	• Long steel chains and/or wires whose weight and curved shape holds the floating platform in place. Lower section of mooring chain rests on the seafloor, supporting the anchor and acting as a counterweight in stormy conditions	• Synthetic fibres or wires usually incorporated with a turret system, where a single point on the floater is connected to a turret with several semi-taut mooring lines connecting to the seabed
• Small footprint	• Large footprint	• Medium footprint
• Vertical loading at anchoring point	• Horizontal loading at anchoring point	• Loading typically at ~45 degrees to anchoring point
• Large loads placed on the anchors – requires anchors which can withstand large vertical forces	• Long mooring lines, partly resting on the seabed, reduce loads on the anchors	• Medium loads on the anchors
• Very limited horizontal movement	• Some degree of horizontal movement	• Limited horizontal movement, but full structure can swivel around the turret connection
• High tension limits floater motion (pitch/roll/heave) to maintain excellent stability	• Weight of mooring lines limits floater motion, but greater freedom of movement than taut-leg	• Single connection point makes the platform susceptible to wave induced motion
• Challenging installation procedure	• Relatively simple installation procedure	• Relatively simple installation procedure
• Minimal disruption to the seabed (small footprint)	• Lower section of chain rests on the seabed, resulting in more disruption (large footprint)	• Low level of disruption (medium footprint)

Figure 17 Overview of mooring configurations according to (James, et al., 2015)

Possible mooring arrangements are demonstrated in Figure 18.

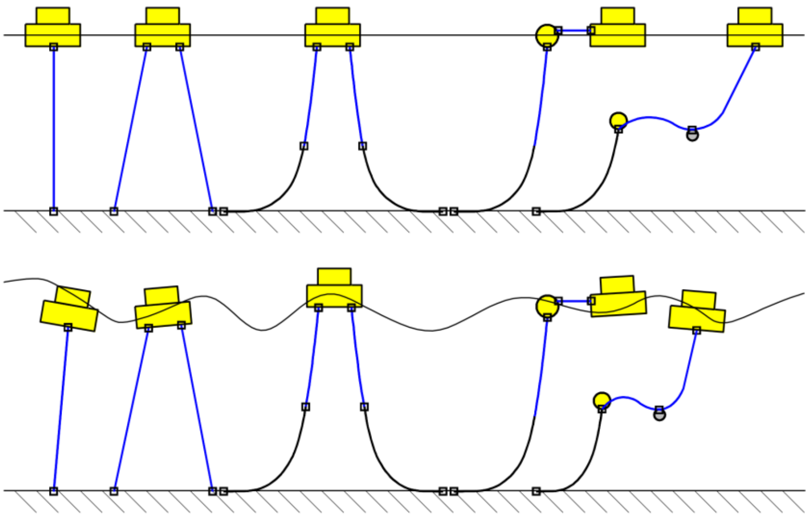
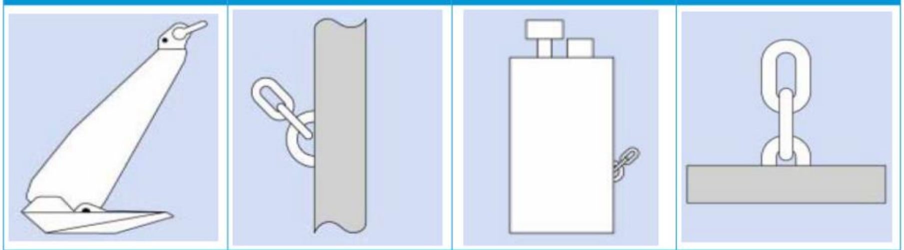


Figure 18 Possible mooring arrangements (Weller, et al., 2013)

4.5.3 Anchoring configurations

The type of installed anchoring system depends on the mooring system, seabed conditions at the site and the required holding capacity. Drag-embedded anchors are usually installed with catenary mooring lines. Drive piles, suction piles or gravity anchors are preferred for taut-leg mooring lines to handle the high vertical loading. The holding capacity can be influenced by the size of the anchor and also depends on the seabed condition. Sands and hard clay result in higher holding capacity than soft clay. If the soil condition does not permit drilling, gravity based anchors may be beneficial. An overview of different anchoring systems is given by (James, et al., 2015) and shown in Figure 19.



Drag-embedded	Driven pile	Suction pile	Gravity anchor
• Best suited to cohesive sediments, though not too stiff to impede penetration	• Applicable in a wide range of seabed conditions	• Application constrained by appropriate seabed conditions - not suitable in loose sandy soils or stiff soils where penetration is difficult	• Requires medium to hard soil conditions
• Horizontal loading	• Vertical or horizontal loading	• Vertical or horizontal loading	• Usually vertical loading, but horizontal also applicable
• Simple installation process	• Noise impact during installation (requires hammer piling)	• Relatively simple installation, less invasive than other methods	• Large size and weight can increase installation costs
• Recoverable during decommissioning	• Difficult to remove upon decommissioning	• Easy removal during decommissioning	• Difficult to remove upon decommissioning

Figure 19 Overview of anchoring configurations according to (James, et al., 2015)

4.5.4 Relevant standards and guidelines

A detailed list of standards and guidelines that may be relevant for design of mooring and anchoring system is given in (Weller, et al., 2013) and is included in Figure 20. Additional, DNV-OS-C105 Structural Design of TLPs (LRFD Method) by Det Norske Veritas from 2011 may be relevant.

Guideline	Publication Date
Det Norske Veritas	
Position Mooring: DNV-OS-E301	2010
Offshore Mooring Chain: DNV-OS-E302	2009
Offshore Fibre Ropes: DNV-OS-E303	2013
Offshore Mooring Steel Wire Ropes: DNV-OS-E304	2009
Design and Installation of Fluke Anchors: DNV-RP-E301	2012
Design and Installation of Plate Anchors in Clay: DNV-RP-E302	2002
Geotechnical Design and Installation of Suction Anchors in Clay: DNV-RP-E303	2005
Environmental Conditions and Environmental Loads: DNV-RP-C205	2010
Design of Floating Wind Turbine Structures: DNV-OS-J103	2013
Certification of Tidal and Wave Energy Converters: DNV-OSS-312	2012
Det Norske Veritas and Carbon Trust	
Guidelines on design and operation of wave energy converters	2005
Bureau Veritas	
Classification of Mooring Systems for Permanent Offshore Units. NR 493 DT R02 E	2012
Certification of fibre ropes for deepwater offshore services. 2nd edition. NI 432 DTO R01E	2007
Rules for the Classification of Offshore Loading and Offloading Buoys NR 494 DT R02 E	2006
International Standards Organisation	
Petroleum and natural gas industries -- Specific requirements for offshore structures -- Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units: ISO19901-7:2013	2013
Shipbuilding and marine structures -- Mooring winches: ISO3730:2012	2012
Fibre ropes for offshore stationkeeping: Polyester: ISO18692:2007	2007
Fibre ropes for offshore stationkeeping: High modulus polyethylene (HMPE): ISO/TS14909:2012	2012
Ships and marine technology -- Stud-link anchor chains: ISO1704:2008	2008
American Petroleum Institute	
Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring: API RP 2SM *(amended version)*	2007
Mooring Chain. API Spec 2F	1997
American Bureau of Standards	
Guidance Notes on the Application of Fiber Rope for Offshore Mooring	2011
Guidelines for the purchasing and testing of SPM hawsers	2000
Standards Norway	
Marine fish farms - Requirements for site survey, risk analyses, design, dimensioning, production, installation and operation: NS 9415:2009	2009

Figure 20 Offshore guidelines which may be relevant for design of mooring and anchoring system (Weller, et al., 2013)

4.6 Umbilicals / dynamic cable

Umbilicals are designed based on all movements and loads expected from wind and ocean environment and design situations are derived so that both ultimate and fatigue limit states are considered. FOWTs are generally installed in environments with high energy density, and in comparison to other floating devices in rather shallow water, which positions major parts of umbilicals into the wave zone. This means a highly dynamic operational environment which needs to be considered in the design process. Cable failure modes include fatigue and extreme loads and, especially for FOWT systems, the potential for effects such as hockling and kinking is increased. The consideration of a new environment demands special care in the design and was investigated by (Marta, et al., 2015). They found that extreme bending and fatigue loads due to cyclic bending loads were design driving bending loads. They also found that the design itself can have an impact on the loads that need to be endured. In another study. (Thies, et al., 2011) analysed umbilicals for marine energy applications and found that for a lazy wave configuration, fatigue failure of the conductor as a major topic to be addressed in the design.

In general, different geometric configurations for the attachment of umbilicals are possible for floating structures (Figure 21). An important criteria for the decision on the geometric configuration is the water depth. The Fukushima FORWARD project uses riser cables in order to connect the wind turbine to the substation (Figure 22).

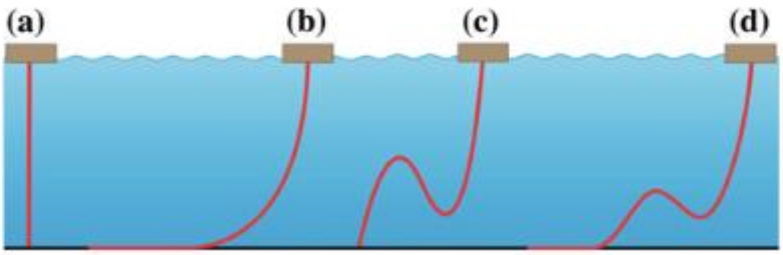


Figure 21: Examples of riser geometric configurations. (a) vertical riser, (b) catenary riser, (c) steep-wave riser, (d) lazy wave riser (Neto, et al., 2014)

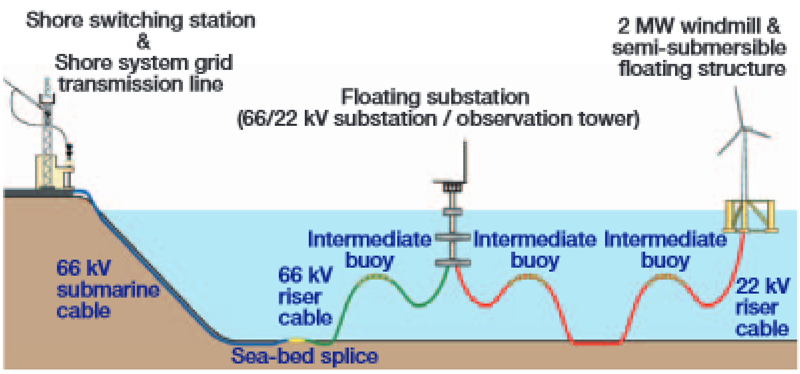


Figure 22: Transmission and substation system (Fujii, et al., 2013)

An exemplary design of umbilicals and the surrounding power transmission system, as shown in the figure above, can be found in (Fujii, et al., 2013), where the design for the Fukushima FORWARD project is presented. There, a design loop is established for riser cables based on environmental conditions, floating structure and riser characteristics including riser shape selection, static, dynamic and ultimately fatigue analysis (Figure 23). Relevant design parameters are for example cable cross section, length, weight, tension, bending radius and distance from hull. The attachment of dynamic cable to main structure also needs to be addressed. The inclusion of a robust condition monitoring system could further support effective planning of maintenance procedures and thus reduce operational expenditures.

The design of umbilicals (or dynamic cable, riser cables) can be performed according to standards ISO13628-5 and API SP 17j (see: ISO 13628-2). It should include consideration of both installation and in-service conditions. Also the influence on the performance of the FOWT support structure needs to be evaluated. Further instructions can be found in (Bai, et al., 2005). Numerical tools that are able to perform analysis and design of umbilicals are Ansys mechanical, Orcaflex and Windopt (see D7.3, D4.4 of the LIFES50+ project).

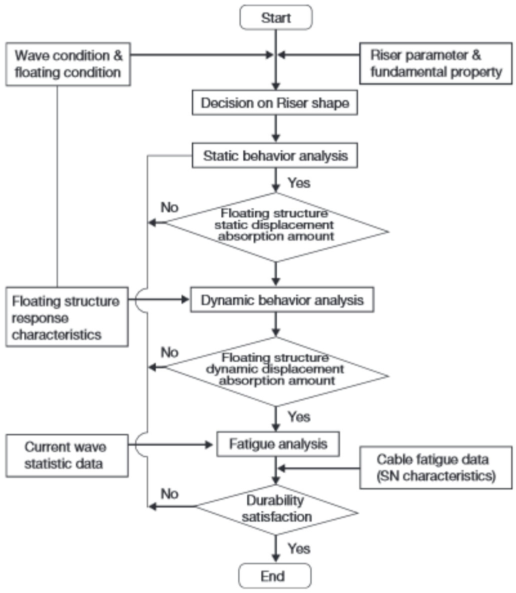


Figure 23: Design process of riser cable (Fujii, et al., 2013)

While important in terms of overall cost, the design of umbilicals is not considered to significantly influence the design of the FOWT support structure and controller and hence is considered to be addressed in detail in the third design stage. However, due to the added complexity in the environment compared to past experience, development of the technologies are expected to gain in importance as the FOWT industry evolves, which could be developed by exploitation of synergies with adjacent technologies such as floating tidal and wave energy converters. (James, et al., 2015).

5 Experimental design practices

Experimental testing of floating wind turbine models can have various objectives. Numerous numerical simulation tools for calculating motion and dynamics of FOWTs are available. Many existing codes of the offshore and oil & gas industry provide approved and validated routines describing the dynamics and loading from waves and currents to floating structures. But they lack a sufficient consideration of the aerodynamic loads on the rotor caused by turbulent wind, complex rotor aerodynamics and an own control system on top of the structure, as well as a structural model capable of modelling the large deflections as e.g. experienced by rotor blades. This introduces a non-linear loading source to the entire system. Additionally, the influence of second order hydrodynamics and mooring line behaviour is not always modelled in sufficient detail. Although, simulation models are continuously improving, there is still an uncertainty, also due to the number of available tools, their different fidelities and the critical load cases they are able to represent numerically. Work package 4 of LIFES50+ addresses some important aspects of these issues. Figure 24 illustrates the different options available for FOWT model tests together with the objectives for the tests.

Currently many research programs like OC3/OC4 (Robertson, et al., 2013) compare the results of different simulation codes, and in the latest phase (OC5) also with measurement data from model tests to improve the reliability of simulations. Model tests give hydrodynamic coefficients, which can then improve the modelling capabilities of simulation models, especially simpler ones. Consequently, model tests can help to improve simulation software with the goal of reducing the need for experiments. On the other hand if little experience of simulation technology is available model tests can also replace extensive simulation studies during the design. For the certification of a design a model test might be required. An important aspect of model tests is risk reduction and the increase of the concept maturity and the technology readiness level (TRL). Test results often help to increase dissemination activities of a prototype.

An extensive literature study of past floating wind model tests can be found in (Müller, et al., 2014).

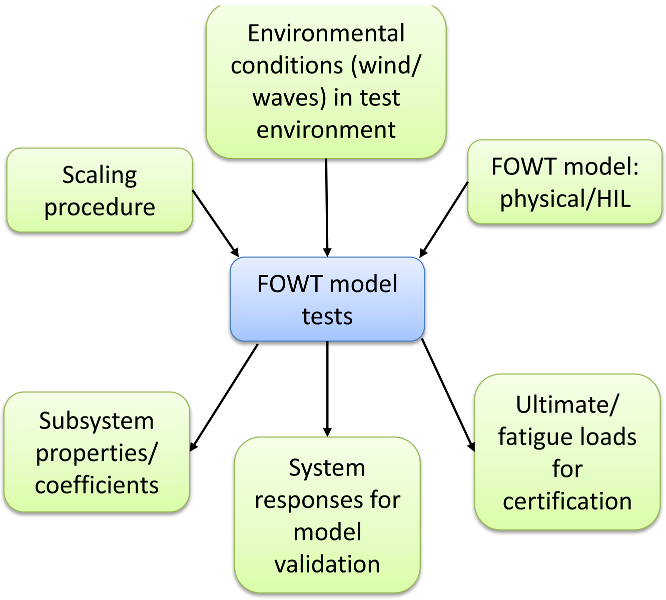


Figure 24 – Model tests alternatives and objectives.

LIFES50+ deliverable D7.3 (Berque, et al., 2015) states in its gap analysis that there is a need from the designers involved in the project to reduce test durations for a streamlined design process. Another designer mentions that the assessment of survival conditions is a core objective of the model tests. Generally, the derivation of drag (and added-mass) coefficients from physical tests has also been mentioned as an important goal of experimental testing.

5.1 Overview of testing facilities

Facilities which have already proven their capability of testing floating wind turbine models are listed in Table 5 with their capabilities for wind and wave modelling. It is noted that the table lists the facilities known to the authors and the ones that have been used by the consortium members already. There is not guarantee for completeness.

Table 5 – Selection of facilities for experimental testing of floating wind turbines.

Place	Institution	Wind	Waves
Copenhagen/DK	DHI	Open wind generator (by DTU)	Regular/irregular, directional
Nantes/FR	Ecole Centrale de	Open wind generator	Regular/irregular, di-

	Nantes		rectional
Edinburgh/UK	FloWave	-	Circular, waves, current
Hamburg/GER	HSVA	-	
Wageningen/NL	Marin	Open wind generator	Regular/irregular, directional
Trondheim/NO	Marintek	Hardware-in-the-loop and open wind generator	Regular/irregular, directional
La Seyne/FR	Oceanide	Max. 5m/s	Regular/irregular, current
Cork/IRE	University of Cork, COER	-	Regular/irregular
Maine/USA	University of Maine	Closed wind generator	
Santander	Cantabria Coastal and Ocean Basin - IHC	Portable wind generator	Regular/irregular, directional, currents
Madrid	Canal de Experiencias Hidrodinámicas de El Pardo - CEHIPAR	-	Regular/irregular, directional

5.2 Numerical model validation

One important objective of model tests is the validation of simulation models. Past modelling efforts suggest that dynamic similarity in a model is best achieved by adopting Froude number based hydrodynamic scaling and Lock number based aero-elastic similitude. All major rotor outputs should scale consistently with the Froude scaling of the floating structure so that coupling between above-water and in-water driven dynamics is consistent at test and full scales. Unique airfoil design at model scale is necessary to achieve Froude consistent outputs and overcome the low Reynolds numbers (below 100,000) present in model tests. Data collection tethering has caused past problems and can be eliminated by the use of a wireless data acquisition system.

For the model validation first, steady-state results shall be compared for free-decay tests, waves only, wind only cases and finally combined cases. Results in frequency domain make it possible to assess the resonance frequencies where time-domain results help to understand transients and compare them to simulation models. Especially hydrodynamic coefficients, like added-mass and viscous damping can be well found from model tests.

The validation of simulation tools from measurements increase the reliability of the models and reduce uncertainties in the design. Therefore, model tests with an appropriate level of detail are currently scheduled in the design phase of floating wind turbines.

5.3 Model test results for certification

The test facilities should reproduce, under a reliable scaling methodology, the relevant environmental conditions. The model tests should the relevant load cases for the tested concept and the site. The model test should be able to provide in-depth insight into loads that would be experienced by a full scale system installed offshore (assuming no scaling errors, high accuracy measurement devices, etc.). In the case that detailed model tests with proven reliability are performed, these might be used for certification in the future, additionally to simulation results. An indication that model test results can be part of future certification guidelines has been given by DNV-GL, see (Müller, et al., 2014).

6 Numerical simulation design practices

Numerical models used within the consortium have already been addressed in the public deliverable D4.4 "Overview of the numerical models used in the consortium and their qualification" (Borg, et al., 2015). Additionally, a survey of current design practices in deliverable D7.3 "Survey of FOWT Design Practice and gap analysis" has been conducted and gaps identified (Berque, et al., 2015).

In this chapter, the main outputs of the previous deliverables are gathered and combined with additional publications on numerical modelling of floating offshore wind turbines. In the first part numerical models are described theoretically. The second part summarizes the application of these models in simulation tools used for the design.

6.1 Numerical models

State-of-the-art design practice is based on an integrated analysis considering aerodynamic, hydrodynamic and structural dynamic effects as well as the mooring and control system. The influences can be simulated in a coupled and uncoupled manner. Within the modelling categories different levels of fidelity are available. The designer has to choose between accuracy and costs on the one side and efficiency and speed on the other side. A graph describing this general trend and typical applications of the models is shown below (see Figure 25).

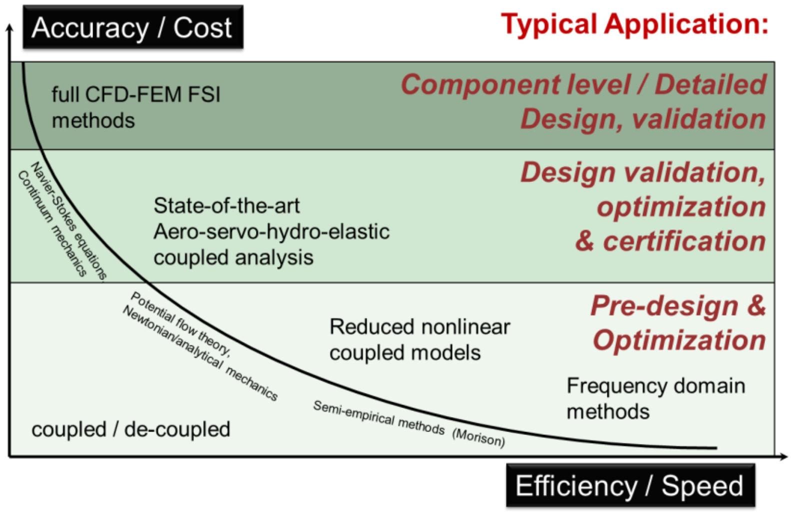


Figure 25 Application of numerical design tool according to efficiency and accuracy

Current studies show that state-of-the-art models cannot capture all relevant effects, especially at extreme conditions and high transient behaviour. Figure 26 demonstrates the probability of occurrence of waves loads on a monopile foundation based on experimental results and numerical models. For high loads there is a deviation between standard tools and measurements. Only advanced tools are capable of reproducing the relevant effects. Thus, there is potential for safety factor reduction and design risks by minimisation of the uncertainties by application of advanced tools.

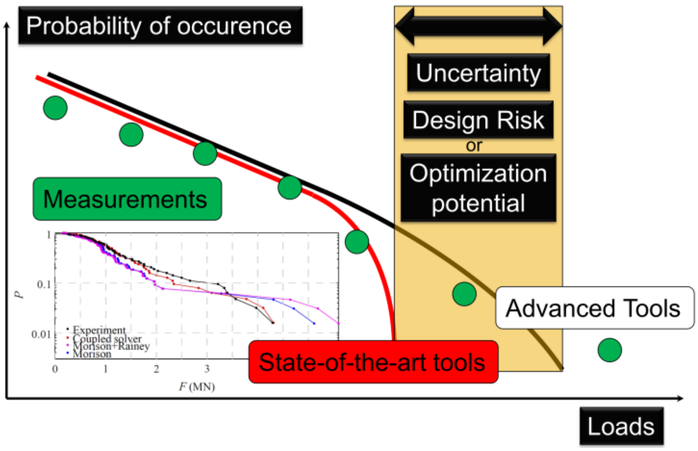


Figure 26 Probability of occurence of wave loads and resulting uncertainty according to (Matha, 2015) and (Signe Schloer, 2014)

Different approaches for computation of aerodynamic and hydrodynamic loads on wind turbines are available. The methods are visualized in Figure 27 and described in the following sections.

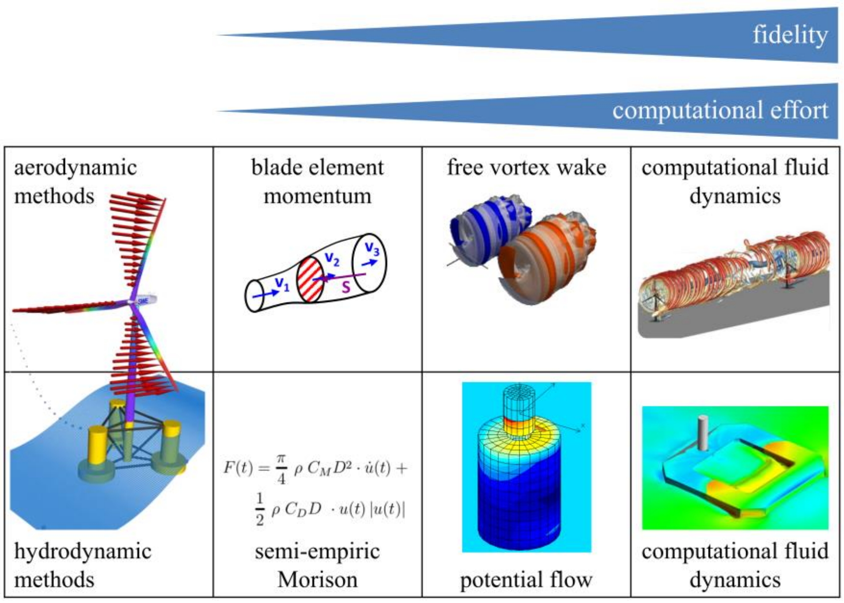


Figure 27 Overview of numerical models for aerodynamics and hydrodynamics (figures USTUTT-SWE, USTUTT-IAG)

6.1.1 Hydrodynamic models

Three major numerical approaches are used for hydrodynamic analysis of floating offshore wind turbines: Semi-empirical, potential flow theory, computational fluid dynamics. Limitations of the described methods are summarized in (Matha, et al., 2011).

Semi-empirical models are based on strip theory and Morison equation (Sarpkaya, et al., 1981). There are applicable for hydrodynamic transparent structures and compact bodies with a diameter D to wavelength λ ratio of less than $D/\lambda < 0.2$. Important hydrodynamic coefficients in Morison equation like drag and inertia are determined empirically via experimental tests. Look-up tables for common structures like cylinders can be found in the literature. Thus, drag and inertia dominated cases can be calculated using Morison equation which also accounts for flow separation. Further corrections are available. Rainey's method, derived from fluid kinetic energy, is an improvement for the inertia term by assuming a non-distorted wave surface. A correction by Lighthill includes a second order correction term to Morison equation and is based on the horizontal gradient of the in-line velocity resulting in variations of the dynamic pressure around a cylinder.

Potential flow theory is used for hydrodynamic non-transparent structures meaning $D/\lambda > 0.2$. One has to distinguish between first, second, etc. order models. The theory is applied for diffraction dominated cases. For first order potential flow theory linear Airy wave theory is used for calculation of wave kinematics. Hydrodynamic properties of the floating foundation, like hydrostatics, added mass contributions, damping form linear wave radiation and incident wave excitation from linear diffraction are computed in a pre-processing step in the frequency domain. The resulting matrices are fed into the hydrodynamic solver together with the wave kinematics and floater motion. Potential flow theory is inviscid and, thus, viscosity is usually added by additional viscous drag term from Morison equation. Free surface memory effects can be considered in the time domain (Jonkman, 2007). Hydrodynamic forces are calculated as lumped forces at a reference point and only rigid bodies can be modelled. Second order potential flow theory accounts for the sum and difference-frequency forces resulting from nonlinearities of real surface waves. Higher order wave theories have to be applied depending on the wave height, period and water depth. A distinction can be made based on (LeMéhauté, 1976) and is demonstrated in. Using higher order potential flow theory permits more accurate modelling of sea states and resulting wave loading but requires more computational effort. The instantaneous floater position and instantaneous water level can be applied. Second-order floating platform forces can be calculated based on three approaches. One can account for only the static mean-drift, calculate mean- and slow-drift terms based an approximation by Newman which is only based on first-order effects or one evaluates the full difference- and summation-frequency quadratic transfer functions (QTF) to get the mean- and slow-drift forces (Jonkman, et al., 2015).

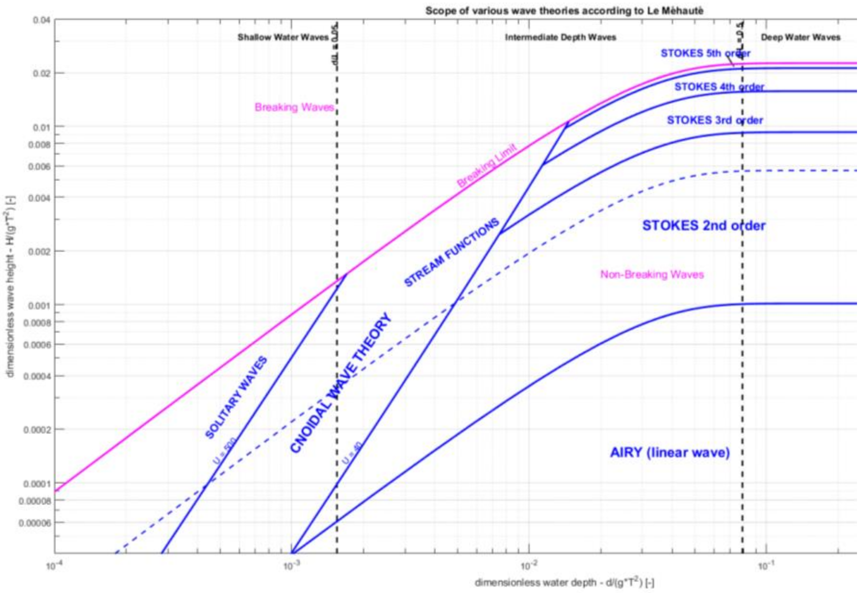


Figure 28 Categorization of wave theories according to (LeMéhauté, 1976)

Computational fluid dynamics (CFD) inherently include all relevant linear and non-linear hydrodynamic effects. However, one has to face significantly higher computational effort compared to semi-empirical and potential flow solutions. Usually, the finite-volume method is applied to solve the Reynolds-Averaged Navier-Stokes (RANS) equations on structured and unstructured grids. The free surface can be represented by the volume of fluid (VOF) approach. Breaking waves can be considered with resulting slamming. Viscous effects are included resulting in vortex separation e.g. at mooring lines and the floater. Current studies by (Beyer, et al., 2015) show the potential of modern CFD techniques for simulation of hydrodynamic loads on floating foundations. Meshless CFD methods are also available using Smoothed Particle Hydrodynamics. CFD can be used to calculate hydrodynamics properties like damping and drag.

Further hydrodynamic effects like marine growth or effects due to filled members can be considered as well (Jonkman, et al., 2015).

6.1.2 Aerodynamic models

Aerodynamics of wind turbines can be calculated by three main approaches, shown in Figure 27. Industry standard is the blade element momentum (BEM) theory which combines both simplicity and computational speed. It is based on the balance of momentum and requires airfoil tables which have to be determined in a pre-processing step via simulation or experiments. Different correction methods can be applied for hub and tip loss, tower effects, dynamic stall, dynamic inflow etc. (Moriarty, et al., 2005).

More advanced methods are based on potential flow solution assuming inviscid, irrotational and incompressible flow. By means of the free vortex wake method the wake of a wind turbine is discretised into vortices that are shed from the rotating blades and that can convect and deform freely in the computational domain. By application of the Biot-Savart law the induction on the rotor and the wake is computed. The method inherently includes tip-loss effects that are considered in BEM via correction. In contrast to BEM, more complex rotor-wake interactions can be easily simulated by free vortex wake methods (Beyer, et al., 2015). The rotor blade is represented by means of a lifting-line or lifting-surface. The aerodynamic properties are included in the computation via airfoil tables.

Computational fluid dynamics for aerodynamics are very advanced but also require very high computational effort. Usually, the finite-volume method is applied to solve the Reynolds-Averaged Navier-Stokes (RANS) equations on structured and unstructured grids. Large eddy simulation (LES) permits detailed modelling of the atmospheric boundary layer. CFD can be used to calculate airfoil tables.

6.1.3 Mooring system models

Mooring lines are modelled via a linear approach based n stiffness and damping matrices. Thus, the linear system behaviour is captured. A quasi-static approach relates the displacement of the mooring lines to the resulting restoring force on the floater in a pre-processing. Inertia and damping of the mooring system are not considered. The catenary equation is based on an equilibrium solution and includes seabed friction, elastic stretching and non-linear geometric restoring. Mooring line forces may also be calculated dynamically by means of a lumped mass and multi-body approach using finite elements. The line inertia and dynamics are included and Morison equation is applied for the instantaneous hydrodynamics forces. Vortex induced vibrations (VIV) may be modelled if the hydrodynamic models account for vortex shedding.

6.1.4 Structural dynamic models

Structural dynamics are accounted for by either rigid bodies or flexible bodies based on a modal representation, multi-body system or finite element approach (see Table 8).

6.2 Verification and validation of numerical tools

Load calculations are done by design codes that are based on numerical models. Within the IEA Wind Task 30 code to code verification has been conducted for a semi-submersible floating platform (OC4 project Phase II). A list of applied simulation tools and used numerical models is shown in Table 6 based on the verification studies within IEA Wind Task 30: OC4 Phase II (Robertson, et al., 2013). The study has been performed in 2013 focusing on simulation of a semi-submersible floating wind turbine system with participants within and outside of the LIFES50+ consortium. As tools develop a recent overview of the tools and their capabilities within the LIFES50+ consortium can be found in **Error! Reference source not found.**.

Table 6: Overview of modelling tools used within IEA Wind Task 30: OC4 Phase II (case: semi-submersible)

Code	Code Developer	OC4 Participant	Structural Dynamics	Aerodynamics	Hydrodynamics	Mooring Model
FAST	NREL	NREL, CENTEC, IST, Goldwind, CSIC	T: Mod/MB P: Rigid	(BEM or GDW)+DS	PF+QD	QS
FAST v8	NREL	NREL	T: Mod/MB P: Rigid	(BEM or GDW)+DS	PF+ME	QS
CHARM3D+ FAST	ABS+NREL	ABS	T: Mod/MB P: Rigid	(BEM or GDW)+DS	PF+ME+(MD+ NA)+(IP+IW)	FE/Dyn
OPASS+ FAST	CENER+ NREL	CENER	T: Mod/MB P: Rigid	(BEM or GDW)+DS	PF+ME	LM/Dyn
UOU+FAST	UOU+NREL	Univ. of Ulsan	T: Mod/MB P: Rigid	(BEM or GDW)+DS	PF+QD	QS
Bladed	GH	GH, CGC, POSTECH	T: Mod/MB P: MB	(BEM or GDW)+DS	ME+(IW+IP)	QS
Bladed Adv Hydro Beta	GH	GH	T: Mod/MB P: MB	(BEM or GDW)+DS	PF+ME+(IW)	QS
OrcaFlex	Orcina	4Subsea	T: FE P: Rigid	BEM, GDW, or FDT	PF+ME	LM/Dyn
HAWC2	Risø-DTU	DTU	T: MB/FE P: MB/FE	(BEM or GDW)+DS	ME	FE/Dyn
hydro-GAST	NTUA	NTUA	T: MB/FE P: MB/FE	BEM or FWV	PF+ME+(IP)	FE/Dyn
Simo+Riflex+ AeroDyn	MARINTEK+ NREL	CeSOS	T: FE P: FE	(BEM or GDW)+DS	PF+ME	FE/Dyn
Riflex-Coupled	MARINTEK	Marintek	T: FE P: Rigid	BEM+FDT	PF+ME+(IW)	FE/Dyn
3Dfloat	IFE-UMB	IFE	T: FE (co-rotated) P: FE	BEM+FDT	ME+(IW)	FE/Dyn
SWT	LMS	LMS-IREC	T: FE+Mod/MB P:FE+Mod/MB	BEM or GDW	ME+(IW)	FE/Dyn
DeepLinesWT	PRINCIPIA-IFPEN	PRINCIPIA	T: FE P: FE	BEM	PF+ME+(IW)	FE/Dyn
SIMPACK+ HydroDyn	SIMPACK	SWE	T: Mod/MB P: Rigid	BEM or GDW	PF+QD	QS
CAsT	Univ. of Tokyo	Univ. of Tokyo	T: FE W: FE	BEM	ME	QS
Wavec2Wire	WavEC	WavEC	T: N/A P: Rigid	N/A	PF+QD	QS
WAMSIM	DHI	DHI	T: N/A P: Rigid	N/A	PF+QD	QS

T = Turbine P = Platform Mod = Modal MB = Multi-Body FE = Finite Element N/A = Not Applicable	BEM = Blade-Element/Momentum GDW = Generalized Dynamic Wake DS = Dynamic Stall FDT = Filtered Dynamic Thrust FWV = Free-Wake Vortex	PF = Potential Flow theory ME = Morison Eq. MD = Mean Drift NA = Newman's Approximation IP = Instantaneous Position IW = Instantaneous Water Level QD = Quadratic Drag	QS = Quasi-static Dyn = Dynamic LM = Lumped Mass

A more recent comparison between numerical tools has been done within the OC5 project with the focus in phase 1b of validating against measurements of monopile wave model tests. The following table summarizes the applied numerical tools (Amy Robertson, 2016).

Table 7 Overview of numerical tools used within IEA Wind Task 30: OC5 phase 1b (case: monopile)

Participant	Code	Wave Model (Reg/Irr)	Wave Elevation	Hydro Model	Structural Model
4Subsea	OrcaFlex	FNPF kinematics	FNPF kinematics	ME	FE, RDS
GE	Samcef Wind Turbines	5th Order Stokes/ Linear Airy	Stretching	ME	FE (TS), RD
DNV GL-ME	Bladed 4.6	6th and 8th Order SF/ Linear Airy	Measured	ME	FE (TS), MD
DNV GL-PF	Bladed 4.6	Linear Airy	Measured	1st Order PF	Rigid
DTU-HAWC2	HAWC2	6th and 8th Order SF/L. Airy & FNPF kinematics	Stretching & FNPF kin.	ME	FE (TS), RDS
DTU-HAWC2-PF	HAWC2	6th and 8th Order SF/L. Airy	Stretching	1st Order PF	FE (TS), RDS
DTU-BEAM	OceanWave3D	FNPF kinematics	FNPF kinematics	ME+Rainey	FE (EB), RD
IFE	3Dfloat	FNPF kinematics	FNPF kinematics	ME	FE (EB), RDS
IFE-CFD	STAR CCM	CFD	CFD-derived	CFD	Rigid
IFP-PRI	DeeplinesWind	3rd Ord. SF/ Linear Airy	Measured	ME	FE
UC-IHC	IH2VOF	FNPF kinematics	FNPF kinematics	ME	Rigid
MARINTEK	RIFLEX	2nd Order Stokes & FNPF kinematics	Measured & FNPF kin.	ME	FE(E-B), RDS, FS
NREL-ME	FAST	2nd Order Stokes & FNPF kinematics	Measured & FNPF kin.	ME	FE (TS), MD
NREL-PF	FAST	2nd Order Stokes	Measured	2nd Order PF	Rigid
NTNU-Lin	FEDEM 7.1	Linear Airy	None	ME	FE (EB), RD
NTNU-Stokes5	FEDEM 7.1	5th Order Stokes	None	ME	FE (EB), RD
NTNU-Stream	FEDEM 7.1	Stream Function	None	ME	FE (EB), RD
PoliMi	POLI-HydroWind	2nd Order Stokes	None	ME	FE (EB), RD
SWE	SIMPACK +HydroDyn	2nd Order Stokes	None	ME	FE (TS), MD
UOU	UOU + FAST	2nd Order Stokes	None	ME	Rigid
WavEC	Wavec2Wire	2nd Order Stokes	Measured	2nd/1st Order PF	Rigid
WMC	FOCUS6 (PHATAS)	FNPF kinematics	FNPF kinematics	ME	FE (TS), MD

Looking at coupled simulation environments also including the controller a recent comparison between simulation codes is included in D4.4 (Borg, et al., 2015). Therein, more information can be found on the tool usage of the LIFES50+ consortium in the design and optimisation process.

Table 8 Overview of tool capabilities within LIFES50+ consortium included in D4.4 (case: floating general)

	Aerodynamics	Hydrodynamics	Structural dynamics	Mooring line dynamics	Controller modelling
WAMIT	N/A	FD PT	RB or Modal	GSM	N/A
AQWA	N/A	FD PT or TD CE+MD	RB or FEM (TD)	GSM or QSM or FEM	N/A
WINDOPT	N/A	FD PT	RB	QSM or FEM	N/A
FAST	(BEM or GDW) + DS + DI	TD ME or TD CE + MD	Modal or MBS	GSM or QSM or FEM	DLL or UD or SM
BLADED	BEM + DS + DI	TD ME or TD CE + MD	Modal or MBS	GSM or QSM or FEM	DLL
OrcaFlex	Coupled to FAST	TD ME or TD CE + MD	Coupled to FAST	GSM or QSM or FEM	Coupled to FAST
3DFloat	BEM + DS + DI	TD ME or TD CE + MD	FEM	GSM or FEM	DLL or UD
Flex5	BEM + DS + DI	TD ME or TD CE + MD	FEM/Modal/Shape	QSM	UD
HAWC2	BEM + DS + DI	TD ME or TD CE + MD	MBS/FEM	GSM or QSM or FEM	DLL or UD
SIMA (SIMO/ RIFLEX)	BEM + DS + DI	TD ME or TD CE + MD	MBS/FEM	GSM or QSM or FEM	DLL or UD
Sesam/ Wadam	N/A	FD PT + ME	RB	GSM	N/A
Simpack	(BEM or GDW) + DS + DI or FVM or CFD	TD ME or TD CE + MD	MBS	GSM or QSM or MBS	DLL
SLOW	ACP	Reduced TD CE or ME	Modal or MBS	GSM or QSM	SM

Aerodynamics
BEM – Blade Element Momentum
GDW – Generalised Dynamic Wake (induction model)
DI – Dynamic Inflow
DS – Dynamic Stall
CFD – Computational Fluid Dynamics
FVM – Free-wake Vortex Model
ACP – Actuator Point Model

Hydrodynamics
FD – Frequency Domain
TD – Time Domain
PT – Potential Flow
CE – Cummins Equation
MD – Morison Drag term
ME – Morison Equation

Structural & mooring line dynamics
RB – Rigid Body
MBS – Multi-Body System formulation
FEM – Finite Element Method
GSM – Global Stiffness Model
QSM – Quasi-Static Model

Controller Modelling
DLL – Dynamic Link Library
UD – User Defined
SM – Simulink-MATLAB interface

6.3 Application of numerical tools in design stages

The numerical tools used in different design stages described in Figure 7: State-of-the-art design process. For stage one (static design and analysis and frequency-domain coupled analysis) and stage two/three (time-domain coupled analysis) a classification is given in Table 9 based on (Borg, et al., 2015)

Table 9 Usage of numerical tools in different design stages

Static design and analysis (stage 1)	**Frequency-domain dynamic analysis (stage 1)**	**Time-domain coupled analysis (stage 2/3)**
In-house parametric tool, WINDPOT	WAMIT, AQWA, WINDOPT, SESAM/WADAM (includes WAMIT)	SLOW, SIMPACK, HAWC2, Flex5, FAST, FAST-Orcaflex, SIMA (SIMO/RIFLEX), 3DFloat, BLADED, CHARM3D+FAST, DeepLinesWT

7 Industrialization considerations in design practice

The desired cost reduction in offshore wind has already been demonstrated in the oil and gas industry, with the move from fixed to floating substructures leading to reduced costs per daily barrel of oil produced. Cost savings were achieved through more standardised designs, optimised fabrication lines, easier assembly, transportation, and installation, and easier decommissioning (James, et al., 2015). In the current state of the floating wind industry, due to the pre-commercial status of the market, the consideration of manufacturability, fabrication constraints, serial production, design complexity reduction, assembly, supply chain, installation, geotechnics, O&M and risk is currently limited, compared with fixed-bottom design (James, et al., 2015); practical experiences of large scale floater projects does not exist to-date. On the current market only single-unit prototypes are existing and the first pre-commercial windfarms are planned in 2017 (Hywind Scotland (Statoil, 2015)) and 2018 (Windfloat Portugal (James, et al., 2015)). Nevertheless substructure designers are considering elements of industrialization in the conception phase which are summarized in the following sub-sections.

7.1 Standardization

One element of industrialization is the standardization of the design, which describes a process which is well defined in terms of methodology, associated risk and incorporation into an overall design process (Matha, et al., 2016). As mentioned above floating wind is at an early stage and therefore the standardization considerations by the designers differ to a large extent. Nevertheless, several specific standards have been developed for floating wind turbines (see (Gujer, et al., 2015)) and many standards and guidelines are available from the oil & gas and the wind turbine industries. A standardized design process is proposed in section 3.

Furthermore the term standardization includes not only a standardized design process, but also a standardized industry production. In this regard a supply chain with standardized components is to be considered important in order to reduce costs. This includes a modular design to unlock the benefits of serial fabrication. Additionally component standardization includes interfaces to wind turbine manufacturers, certifying agencies, fabricators and installation contractors. In respect of component standardization the floating wind industry can profit from the well-established infrastructure and supply chain of the offshore oil & gas industry (James, et al., 2015).

7.2 Manufacturing, Transport and Installation

Manufacturing, transport and installation of FOWTs are seen as having high potential in reducing LCOE. So the design is not only be driven by technical aspects but also logistical aspects which may determine the design to a certain extent. E.g. a design which allows modular construction and assembly is preferred from manufacturing point of view. In this context it is beneficial to determine early in the design process where each part of the substructure will be built and how the transportation and assembly of the system can be performed. In this regard the proximity of suppliers to the port facilities is useful to reduce costs, particularly the costs of transporting components to port for assembly (e.g. turbine, moorings, anchors, electrical cabling) (James, et al., 2015). For the assembly of the FOWT it is furthermore helpful to have a well-defined interface between substructure and WT.

In general the use of special vessels is a big cost driver and should be kept at a minimum level. In this context the capability to fully assembly the FOWT at port is considered as a big advantage for these designs, allowing the use of conventional vessels at moderate day rates. However logistical constraints have to be considered because at many sites the water depth around the harbours and construction sites as well as the shipyard dimensions itself can be a an important limitation (in particular for deep drafted designs such as spar buoys).

7.3 Operation and Maintenance

In general two operation and maintenance strategies exist, applied for either small or major repairs. For small repairs a strategy similar to fixed bottom structures is used, getting turbine access by a crew transfer vessel. For major repairs the maintenance strategy is likely to differ. Dependent on the sub-structure concept the FOWT is towed back to the port using standard tug boats. However the cost of this method, which needs further investigation, are dependent on the distance to port and the weather conditions (James, et al., 2015) as well as the capability of the design to easily detach the mooring and electrical cables.

In order to reduce maintenance efforts to a minimum condition monitoring systems and remote control systems are installed on the substructure and moorings of many concepts (ORE Catapult, 2015). Hence visual inspections can be carried out within larger intervals, which are 5 years on average (James, et al., 2015). In this context a design requirement should be to allow an easy access for inspection and maintenance, so that critical components are reachable and above sea level (James, et al., 2015).

7.4 Materials

According to (James, et al., 2015) the currently dominant material used for FOWT substructure is steel, which is the case for fixed bottom structures as well and where therefore considerable experience already exists. However some substructure designers are using concrete in their concepts, which on one side results in heavier structures than if steel is used in order to match system properties; On the other side concrete can be 10 times cheaper than steel (James, et al., 2015). In the context of industrialization, concrete brings benefits in terms of increased local content, which lowers the transportation costs and allows being more flexible in manufacturing. Furthermore, concrete is less prone to corrosion and therefore seems to be more robust than steel structures. However one of the drawbacks of concrete is less experience in large scale fabrication compared to steel, which has been widely used by the oil & gas industry.

In conclusion both materials, steel and concrete, are expected to be able to exceed the minimum lifetime of 20 years and the choice which material with its related cost benefits is to be used is dependent on the substructure design and must be made following a more detailed analysis.

8 State-of-the-art LCOE and Risk

8.1 LCOE

LCOE is an abbreviation which is in some references defined as “Levelized costs of Energy” and in some others as “Levelized costs of Electricity”. However, the basic meaning of the term is always the same: LCOE are the costs for producing one unit of energy. (Bjerkseter, et al., 2013) Interprets the LCOE as “the minimum discounted price per unit for which energy has to be sold to break even on the total investment”. In most of the references for this subchapter the LCOE is expressed in real 2011 prices in €/MWh but also in £/MWh, €ct/kWh, €/kWh, $/MWh or in NOK/MWh and it is calculated on a post-tax basis. In this report, we will use €/kWh if not stated otherwise. Applied discount rates vary between 10 and 12 percent (SI OCEAN, 2013), (Bjerkseter, et al., 2013). It is noted that the tax rate may be sensitive to the considered region in the world.

According to (Ebenhoch, 2014), the levelized cost of electricity offers a way to compare the cost of energy across the technologies. Nevertheless, comparisons should be made with caution because there are some things that must be taken into account. Firstly, the formula and the calculation of the LCOE differ more or less depending on the reference because as shown below there is no universal formula (Moné, et al., 2015). Secondly, there is few reliable reference LCOE-values, as the technology of floating wind turbines is very young: some developers publish numbers or information based on their own rough estimation instead of measured values from full-scale prototypes (Ebenhoch, 2014). Thirdly, the LCOE is a site-specific value: if the location and the associated parameters (distance to shore, water depth, wind speed, etc.) change, the inputs for the LCOE calculation (CAPEX, OPEX, DECEX and AEP see chapter 8.1.1) change as well (Ebenhoch, 2014).

In the following, three exemplary approaches to calculate the LCOE are presented:

In (Hobohm, et al., 2013) and (Ebenhoch, 2014) the following formula for the LCOE is used:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}} \qquad (2)$$

$LCOE$:	*Levelized costs of electricity in €ct/kWh*
I_0:	*Capital expenditure (CAPEX) in €ct*
A_t:	*Annual operating costs (OPEX) in year t*
M_{el}:	*Produced electricity in the corresponding year in kWh*
i:	*Weighted average cost of capital (WACC) in %*
n:	*Operational lifetime in years*
t:	*Individual year of lifetime (1, 2…n)*

In (Interational Renewable Energy Agency, 2012), (Bjerkseter, et al., 2013) and (Myhr, et al., 2013) the following formula is used:

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \qquad (3)$$

$LCOE$:	*Average lifetime levelized cost of energy generation*
I_t:	*Investment expenses at time t*
M_t:	*Operation and maintenance costs at time t*
E_t:	*Energy generation at time t*
r:	*Evaluation discount rate*
t:	*Time ranging from zero to n*

In contrast to the first formula, here the investments (or capital expenditures) are also offset against the discount rate. The investment expenses correspond to the CAPEX and the operation and maintenance costs correspond to the OPEX in the first formula.

(SI OCEAN, 2013) uses the following formula:

$$LCOE = \frac{SCI + SLD}{87.6 \cdot LF} \cdot \frac{r \cdot (1+r)^n}{(1+r)^n - 1} + \frac{OM}{87.6 \cdot LF} \quad (4)$$

$$SLD = \frac{SDC}{(1+r)^n} \quad (5)$$

$$LF = \frac{AEP}{87.6 \cdot R} \quad (6)$$

LCOE:	*Levelized cost of electricity [c€/kWh]*
SCI:	*Capital cost of the power plant [€/kW]*
SLD:	*Specific levelized decommissioning cost [€/kW]*
SDC:	*Specific decommissioning costs at end of lifetime [€/kW]*
OM:	*Annual O&M costs [€/kW]*
LF:	*Load factor of the facility*
r:	*Discount rate*
n:	*Facility lifetime [year]*
AEP:	*Annual Energy Production [kWh]*
R:	*rated power [MW]*

In this formula, the decommissioning costs are included separately. In the other references the decommissioning costs are embedded in the calculation for the capital expenditures (see 8.1.1.3 DECEX). The capital costs of the power plant correspond to the CAPEX and the annual O&M costs correspond to the OPEX in the first formula.

8.1.1 LCOE Components

For all of the LCOE equations there are four important inputs (Moné, et al., 2015). With capital expenditures (CAPEX), operational expenditures (OPEX) and the annual energy production (AEP), the impact of differences in the design (like a smaller wind turbine) are included in the equation. The financial aspects of the formulas are represented by the fourth important input – the charge rate or more precisely a discount rate like the Weighted Average Cost of Capital (WACC). In many of the references, there is another important input in the LCOE equations. Decommissioning costs (DECEX) either are offset in the CAPEX or are embedded separately as can be seen in Equation (4).

The three factors of expenses (CAPEX, OPEX, DECEX) do not occur at the same time. They are allocated to different life stages of a project.

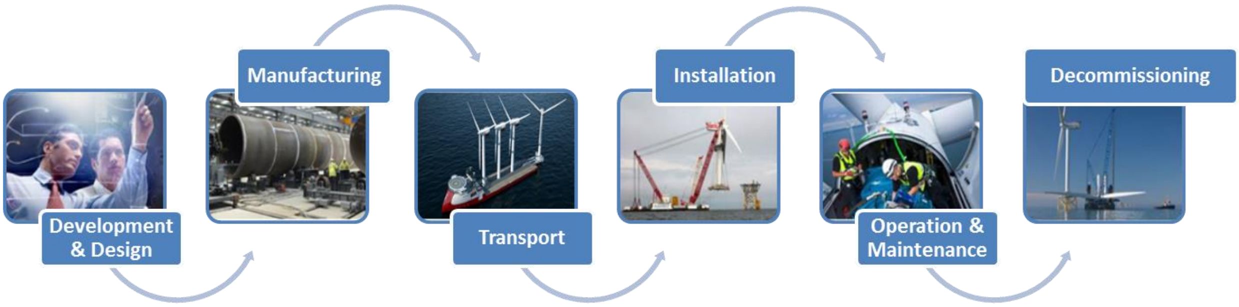


Figure 29: Lifestages (provided by IREC)

In Figure 29, the different life stages of a floating offshore wind farm are presented. CAPEX occur in the first four stages Development and Design, Manufacturing, Transport and Installation. OPEX comes up in the Operating and Maintenance phase and DECEX in the Decommissioning phase.

8.1.1.1 CAPEX

Capital expenditures (CAPEX) occur mostly at the beginning of a project and they contain not only the costs of the separate components, but also costs for project management, manufacturing and installation as well as grid connection. (Ebenhoch, 2014).

The following components can be included in the CAPEX calculation (Ebenhoch, 2014):

- Project consenting and development
- Project management
- Construction phase insurance cover from start of construction until operation start (Construction all risks (CAR), Third party insurance)
- Turbine costs (supply of the nacelle and its sub-systems, the blades and hub and the electrical systems to the point of connection to the array cables, delivery to the nearest port to supplier, warranty, commissioning costs)
- Support structure (Including tower)
- Floating foundations (including anchors and mooring lines)
- Substation
- Cables
- Installation (this includes foundation, turbine, cable and substation as well as commissioning work for all parts but the turbine.)
- Construction contingency (budget for unforeseeable conditions during the construction phase)

8.1.1.2 OPEX

Operating expenditures (OPEX) such as maintenance, rent and insurance are divided over the lifetime of the plant (Ebenhoch, 2014).

The following components can be included in the OPEX calculation:

- Operations and Maintenance (for separate components such as blades, hub and pitch, gearbox and main shaft, generator, support structure, cables, substation)
- Operating phase insurance
- Transmission charges
- Sea bed rent

8.1.1.3 DECEX

Decommissioning expenditure (DECEX) are the summarized expenses for removal and decommissioning of certain components at the end of a wind turbines design life. According to (Bjerkseter, et al., 2013) it can be seen as “a reversed installation and transportation process”. Infrastructure, substructure, anchors, cables, transition pieces and the substation is removed and sorted for retrieval, abandonment, reuse, refitting, recycling and scrap (Ebenhoch, 2014; Hutton, et al., 2015). Examples for materials that can be sold are the aluminum of the electrical cables or steel of the floating substructures (Castro-Santos, et al., 2013). For the recycled material, the wind farm operator gains revenues, which can be included in the CAPEX (Ebenhoch, 2014) or subtracted from DECEX. The DECEX includes also costs for the planning work, the design of any additional required equipment and further environmental work and monitoring for the decommissioning (Valpy, et al., 2014). Because of the fact that nearly all commercial wind farms are in their infancies, an estimation of the scope of the decommissioning is very difficult. Similar to the relatively inexpensive installation, the decommissioning costs for floating wind turbine concepts are also expected to be lower compared to bottom-fixed concepts according to (Ebenhoch, 2014) and (Bjerkseter, et al., 2013). Available sources provide varying approaches on how to assess decommissioning costs. Sometimes not all parts are expected to be removed from the site (Myhr, et al., 2013). Due to the limited experience with decommissioning work, simplified approaches are often applied, for example by directly linking decommissioning costs to installation costs (Myhr, et al., 2013). Previous work is providing detailed description on the subject, but it can be expected that independent of the technology, DECEX varies between different sites and countries due to varying local regulations.

8.1.1.4 Annual Energy Production (AEP)

According to (Fingersh, et al., 2006) the net AEP is a calculation of the projected energy output of the turbine based on a given annual average wind speed. The gross AEP is adjusted for factors such as rotor coefficient of power, mechanical and electrical conversion losses, blade soiling losses, array losses, and machine availability.

(Fingersh, et al., 2006) provide an AEP spreadsheet which computes the AEP, capacity factor and energy capture ratio for each wind turbine. The individual parameters (for example 50-m wind speed, Weibull K parameter, Rated power, Rotor diameter, Hub height and much more) must be entered before computing.

8.1.1.5 Discount rate/WACC

(SI OCEAN, 2013) describes the discount rate as an “important variable in the LCOE calculation” which translates future expenditures and income back to present values. The WACC can reflect risks just like money market rates and the type of financing source of the project.
(Ebenhoch, 2014) explains that the Weighted Average Cost of Capital (WACC), a specific form of the discount rate, is the average of the costs of equity and debt, and allocates each one the fitting percentage at the financing.

In (Bjerkseter, et al., 2013) the following formula helps to find the matching WACC:

$$WACC = \frac{E}{E+D} \cdot R_E + \frac{D}{E+D} \cdot R_D(1-T) \tag{7}$$

E:	*Market value of equity*
D:	*Market value of debt*
R_E:	*Cost of equity, found from the CAPM (capital asset pricing model) as a function of the risk-free rate, the expected return on the market portfolio and the specific asset' sensitivity to variation in the market portfolio*
R_D:	*Cost of debt found by adding a risk premium to the risk-free interest rate which could be achieved through low-risk value allocations*
T:	*Asset tax rate*

8.1.2 LCOE Calculation Tools

Due to the present development stage of the floating offshore industry there is a lack of LCOE calculation tools because there are only a few full scale floating prototypes installed (Ebenhoch, 2014). Already at early design stages, when simple hydrostatic analyses are performed, the development team tries to calculate the material and manufacturing costs for all imaginable wind turbine designs. Thereby the CAPEX is approximated while the design is optimized (Matha, et al., 2014).

(Härer, 2013), for example, optimizes the costs with the very simple assumption: reducing weight equals reducing costs. In his thesis he applies MATLAB, SIMPACK and GESOP to optimize the design with regards to weight reduction.

A simple LCOE calculation tool is publicly available at the official NREL homepage (NREL, 2015). The "Levelized Cost of Energy Calculator" provides a simple calculation for both utility-scale and distributed generation (DG) renewable energy technologies. The calculator compares capital costs, operations and maintenance (O&M) costs, performance costs and fuel costs.
The calculator is not practicable for a thorough analysis because financing issues, discount issues, future replacement, or degradation costs are not implied, but can be used for a first initial assessment.

A more complex LCOE calculation tool was provided by (Ebenhoch, 2014) in Microsoft Excel. The LCOE calculation tool takes different costs for an offshore wind turbine into account. The tool calculates the LCOE for bottom-fixed solutions and typical floating structures (i.e. spar buoy, tension leg, semi-submersible). The specific methodology to calculate the LCOE with the calculation tool is based on equation (2).

In LIFES50+ an advanced LCOE tool is developed and will be published in deliverable D2.3.

8.2 Life cycle assessment (LCA) of a floating offshore wind turbine

As an addition to the calculation of the LCOE, life cycle assessment of electricity generation systems provides the footprint on (and hence the cost to) the environment. The general approach is the determination of the separate operations performed during the lifetime of the considered system and to collect information on the associated environmental impacts of these operations (Arvesen, et al., 2012). While many studies have dealt with onshore and fixed bottom offshore wind energy, very limited information on floating wind energy is available (Arvesen, et al., 2012), (Davidsson, et al., 2012).

(Weinzettel, et al., 2009) have investigated LCA focusing on the Sway concept hosting a 5MW wind turbine by application of the LCA assessment tool SimaPro. They defined operations for both wind power plant and auxiliary system (Figure 30) and found that their floating concept had a comparable environmental impact to fixed bottom offshore systems.

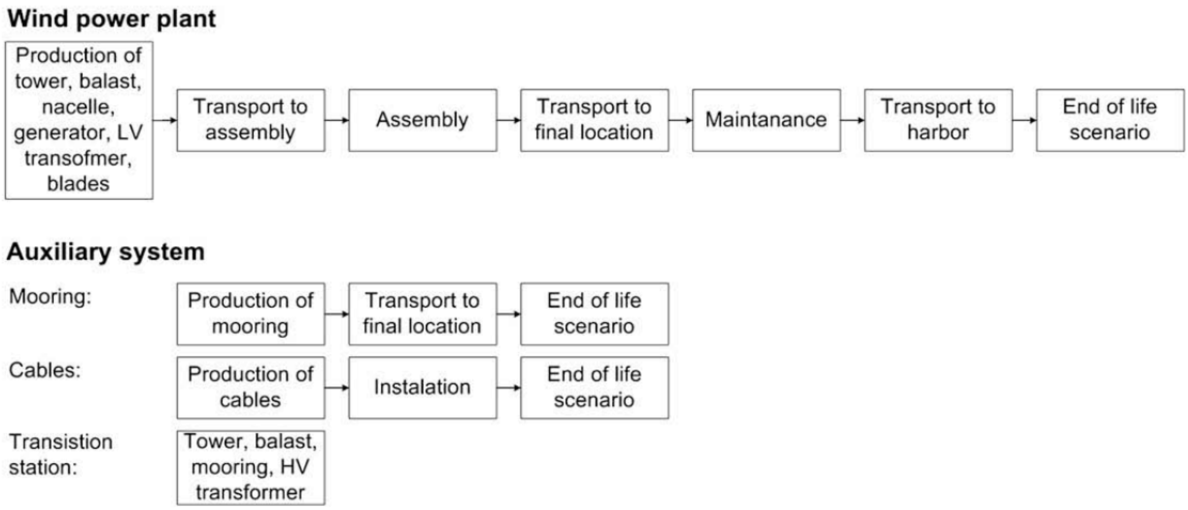


Figure 30: Lifetime process flow chart of a floating offshore wind turbine system (Weinzettel, et al., 2009)

8.3 Risk Management and Assessment

The main source of information of this section is the LIFES50+ Deliverable D6.1 (Hutton, et al., 2015) due to its extensive information about risk management and assessment. On a certification level, (DNV-GL, 2001) can be used as reference for floating offshore wind turbine systems (regarded as new technology). There, the verification of a new technology is based on risk assessment of the regarded system (Figure 31). To complete this report other information sources are added and identified, where appropriate.

According to (ISO Guide 73, 2009), risk is the “effect of uncertainty on objectives”. Effect, i.e. consequence, has to be understood as deviation from the expected scenario, it can be positive and/or negative. Risk is often expressed by potential events, their related likelihood of occurrence and consequences.

Risk assessment can be described as the overall process of risk identification, risk analysis and risk evaluation (ISO Guide 73, 2009). As shown in Figure 32, risk assessment itself is a crucial part of the global risk management process.

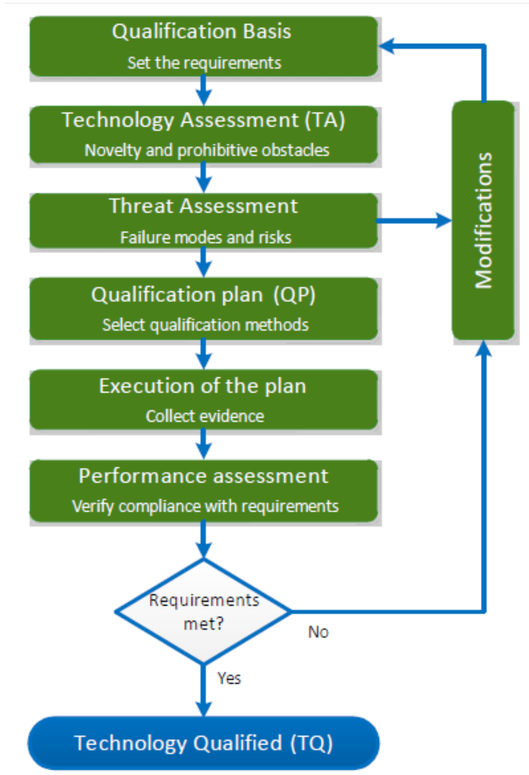


Figure 31: Procedure for qualification of new technologies (DNV-GL, 2001)

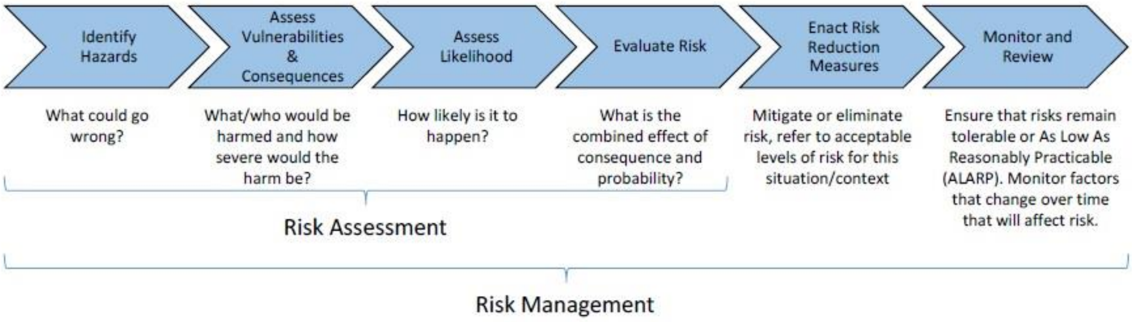


Figure 32: Risk Management Process (Hutton, et al., 2015)

In the context of offshore deep water floating wind turbine substructures, LIFES50+ deliverable D6.1 defines four different areas of risks: Technology Risk, Health, Safety and Environment Risk, Manufacturing Risk and Commercialisation Risk. However, this section focuses mainly on technology risk and the associated risk management process due to its large influence on the LCOE (Karlynn Cory, 2009).

In order to give a short overview about the risk management process (Figure 32) its framework is detailed below:

- Risk Identification: All potential sources of hazards are systematically identified by means of HAZOP/HAZID (*Hazard and Operability Study/ Hazards Identification*).

- Risk Analysis: Procedure to identify significant failure modes, to discern the reason of risk and to determine the severity and likelihood of it.

- Risk Evaluation: Risks are evaluated considering their severity and likelihood and the decision of further risk reduction is made.

- Risk Reduction: Risk reduction is necessary if the severity of the risk is high, it can be done by mitigating the severity and/or the probability of the hazard.

- Risk Monitoring and Review: Review the risk assessments periodically to ensure that the risk of the system is not fluctuating.

8.3.1 Technology Risk Identification

The objective of risk identification is to identify sources of risks, areas of impact, events, their causes and their potential consequences (2009). The result of this phase is an extensive list of technology risks. The guidance of the identification process according to LIFES50+ deliverable D6.1 is represented in Figure 33.

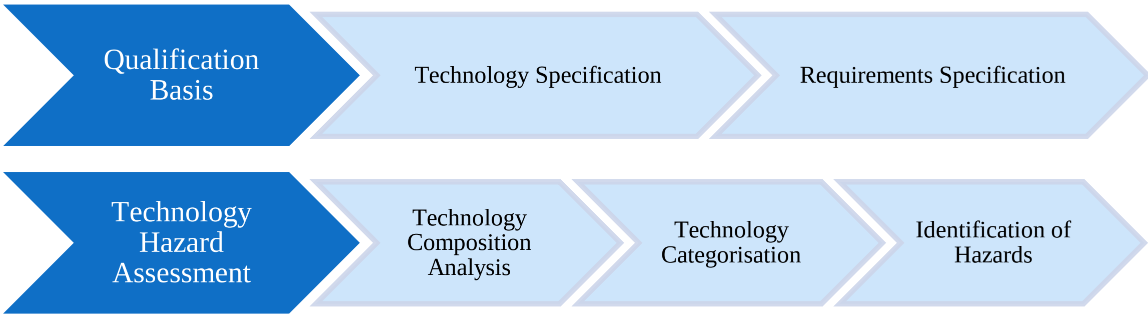


Figure 33: Technology Risk Identification Process (Hutton, et al., 2015)

The process begins with the qualification basis. For this, criteria are determined against which the technologies should be assessed such as, the specification of the technology, its required functions, the environment, acceptance criteria and performance expectation.

The next step is the technology hazard assessment, which determines the involved new or novel technology within the overall floating substructure concept and their associated hazards. As a technology can be integrated in another technology, for better understanding of the new elements within the concept, a technology composition analysis has to be applied. For this, the system must be decomposed into its elements and functions. In order not to forget any risk, it is recommend to identify the functional elements across the entire life cycle. A representative hierarchy for a floating wind substructure concept is shown in Figure 34.

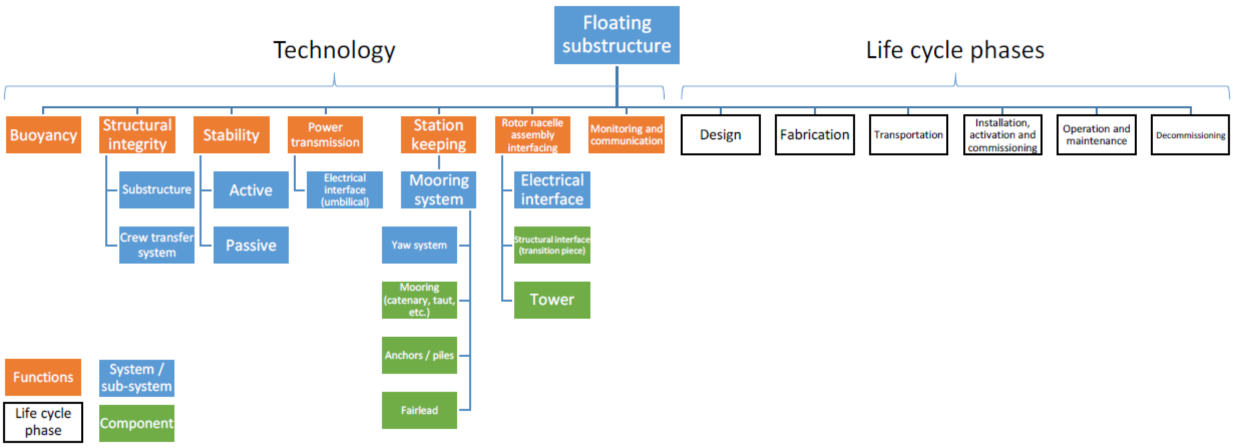


Figure 34: Hierarchy of Floating Wind Substructure Concept (Hutton, et al., 2015)

After identifying the technologies, the process can be continued with the categorisation considering the degree of its novelty and the area of application. (DNV-GL, 2001) implies four categories: no new technical uncertainties, new technical uncertainties, new technical challenges and demanding new technical challenges.

The last step of technology hazard assessment is the identification of hazards related with each of the technology elements. The recognition of hazards in the early design phase will encourage the identification of the parts which need further development prior to the start of technology risk analysis.

The identification of hazards is done by means of HAZOP/HAZID (*Hazard and Operability Study/ Hazards Identification*). HAZOP belongs to the qualitative hazards identification methods and is generally a system approach (Kacprzak, 2013).

An example of a risk register considering different hazards is shown in Table 10. (Kacprzak, 2013) compares the different hazard identification methods and explains their relation which are shown in Figure 35.

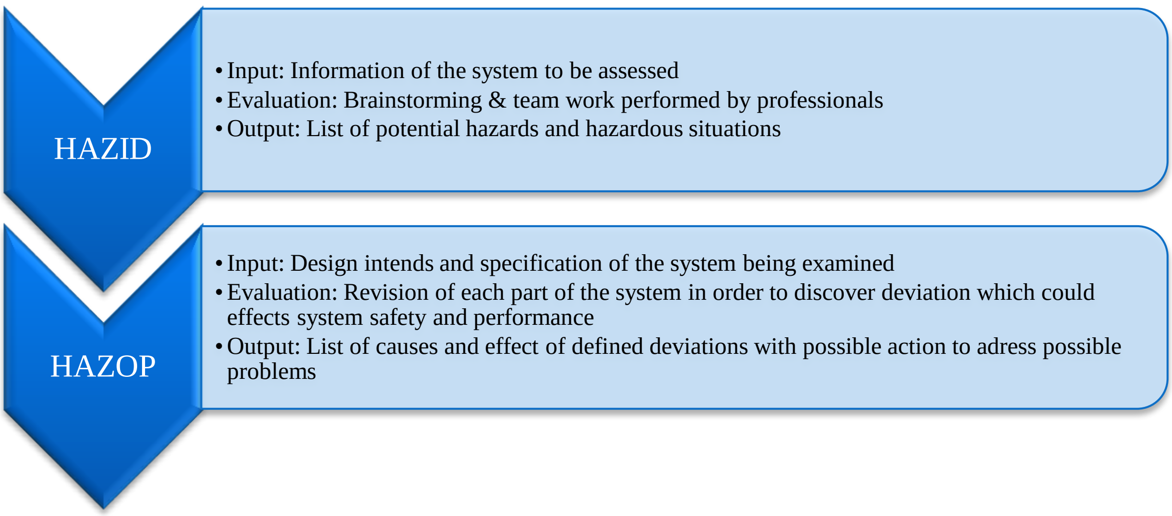


Figure 35: Relation between HAZID and HAZOP (Kacprzak, 2013)

8.3.2 Technology Risk Analysis

The risk analysis process identifies significant failure modes of the recognized elements of technology and evaluate their related risks. The outcome of this phase is a list of failure modes with severity and likelihood ratings for the novel technology elements identified in the risk identification process. The entire process of technology risk analysis is exemplified in Figure 36.

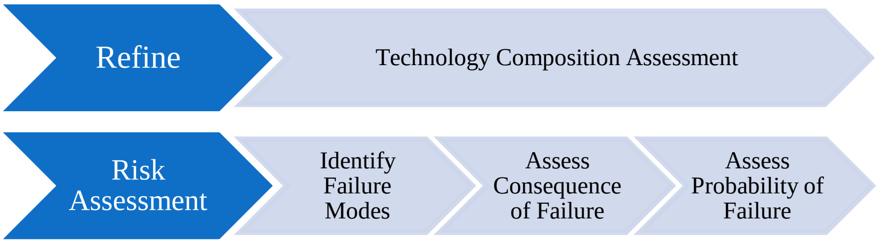


Figure 36: Technology Risk Analysis Process (Hutton, et al., 2015), (DNV-GL, 2001)

8.3.2.1 Technology Composition Assessment

LIFES50+ project emphasises the importance of a review of the technology composition for the floating substructure. Therefore, the partition shown in Figure 34 shall be divided into more elements and interfaces. This will aid in identification an isolation of the novel elements and consequently result in early potential failure modes detection.

8.3.2.2 Identification of failure modes

The next step of the technology risk analysis process is the identification of possible failure modes and related failure mechanisms. The identified hazards by means of HAZOP can be used as approach for the identification of failure modes. To perform technology risk analysis, Failure Mode and Effect Analysis (FMEA) is applied.

The FMEA is a design tool that identifies risk within a design in order to limit or avoid it. Hence, the FMEA drives towards higher reliability, higher quality and improved safety. It is a formalized but subjective analysis for methodical identification of possible root causes, failure modes and the assessment of their relative risks as it is normally carried out by a team of experts. The causes of failure are the root causes which lead a component to fail. However, the root causes do not describe the mechanism by which the component has failed and as consequence failure modes are the diverse ways in which a component may fail. The main disadvantage of FMEA is that no combined failure modes are possible be examined (Arabian-Hoseynabadi, et al., 2010).

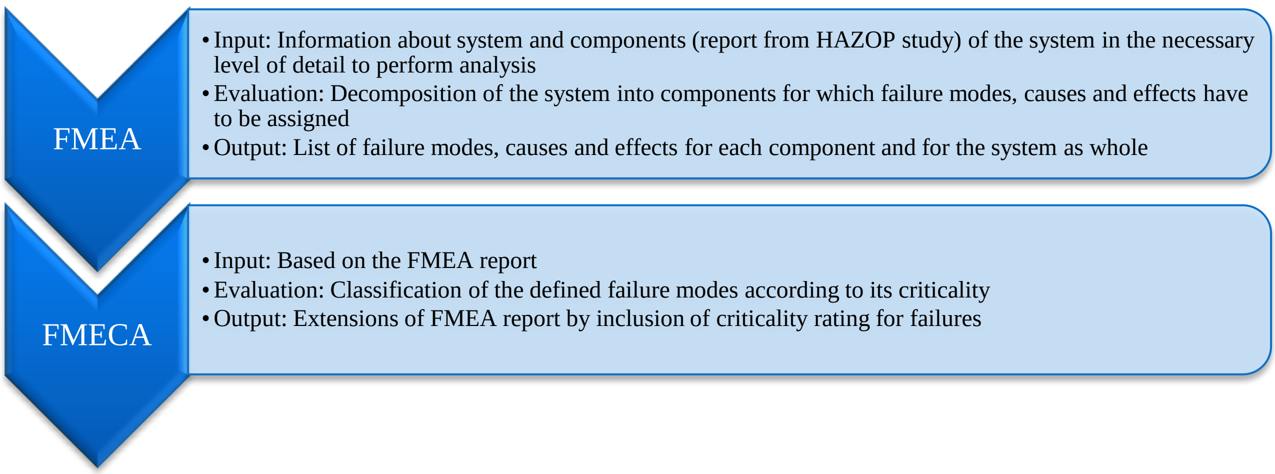


Figure 37: Relation FMEA and FMECA (Kacprzak, 2013)

The extension of FMEA is FMECA (Failure Mode, Effect and Criticality Analysis) which includes criticality analysis which defines the importance of each failure mode.

8.3.2.3 Assessment of consequence of failure

In the context of technology risk within floating wind substructures, the consequence of failure can be categorised into two system: the local and the global system. The local system is considered as the element of technology being assessed (e.g. the anchor chain), whereas the global system is the floating substructure (Table 10: Example Technology Risk Register with Risk Ranking Table 10).

For example, the consequence for new technology, in terms of the local system can be: insignificant, reduced part of main function, loss of parts of main function, loss of main function or loss of main function and damage to interfacing and surrounding systems.

8.3.2.4 Assessment of probability of failure

Expert judgment and knowledge are essential when assessing the likelihood of failure. Furthermore, if quantitative measures exist they should be used to aid the assessment.

The probability of failure is associated with safety classes, this means failures which imply low risk for personal injuries or less economic loss are categorised into a low safety class. However, failures which imply large possibilities for personal injuries, fatalities or very large economic loss are categorised into a high safety class (DNV-GL, 2011).

8.3.2.5 Risk assessment

As soon as the identification of failure modes and the assessment of consequence and probability of failure are completed, the technology risk rating can be evaluated. A risk matrix is used for the assessment of the overall risk of the failure mode based on severity and likelihood.

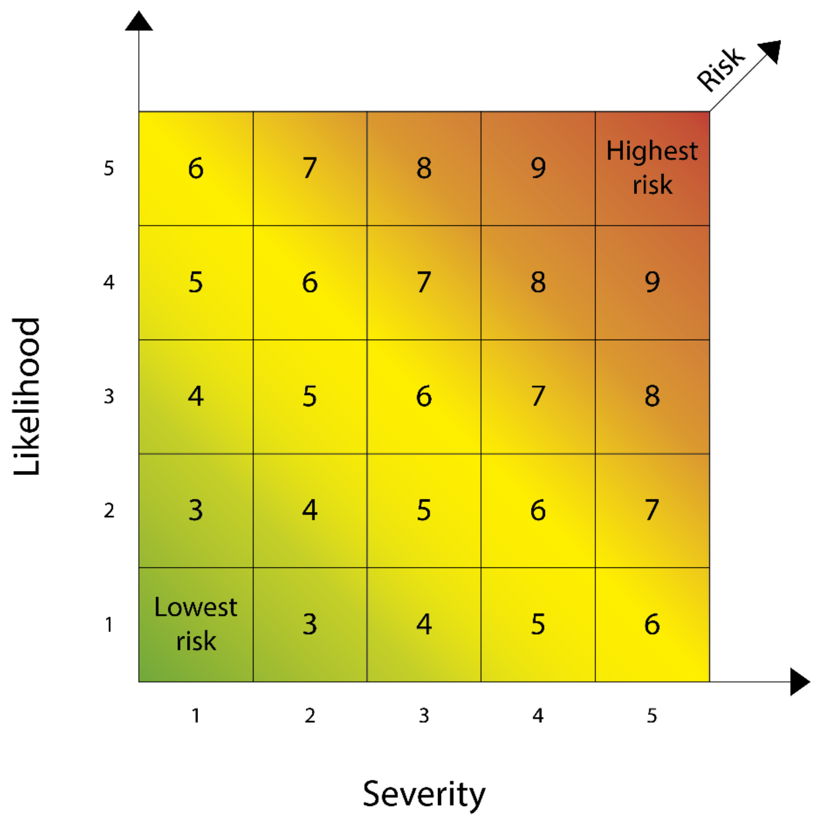


Figure 38: Example of Risk matrix (Hutton, et al., 2015)

The risk matrix illustrates the order of the risks from the lowest risk (low likelihood, low severity) to the highest risk (high likelihood, high severity). Furthermore, this matrix allows to determine the risk level by means of summation of the likelihood score and the severity score being the lowest risk level from 2-3, the medium level from 5-7 and the highest level from 8-10.

As part of LIFES50+ deliverable 6.1 an example of the overall risk analysis process including the associated risk levels was developed and is shown in Table 10.

Table 10: Example Technology Risk Register with Risk Ranking (Hutton, et al., 2015)

Function	Sub-function	Element	Hazard	Failure Mode	Life cycle phase	TRL	Novelty	Probability	Consequence			Risk		
									Local system	Global system	Economic	Local system	Global Sys-tem	Economic
Station keeping	Mooring	Mooring chain	No tension	Chain link fractured	O&M	8	2	3	4	3	3	M	M	M
				Interface pin fractured	O&M	8	2	4	4	3	3	H	M	M
				Increased length	O&M	8	2	1	2	1	2	L	L	L
		Gravity anchor	Moving when loaded	Friction low	O&M	8	2	3	3	2	3	M	M	M

8.3.3 Technology Risk Evaluation

The objective of the technology risk evaluation is to contrast the results of the technology risk analysis with the technology risk criteria and to determine if the risks are acceptable, tolerable or unacceptable including the decision of the necessity of further risk reduction. The outcome of this process is a list of risks that require treatment and the priority for treatment implementation.

For more information about how risk evaluation can be further extended sources (Hutton, et al., 2015) and (DNV-GL, 2001) can be consulted.

8.3.4 Technology Risk Reduction

Critical risks that must be submitted to risk reduction measures which includes risk reduction, control arrangements and continuous monitoring of the risks. The ISO standard (ISO, 2010) points out that risk reduction can be performed with the elimination of hazards, or by reducing their consequence or probability of occurrence, or both. Furthermore, the designer shall verify whether the new protective measures applied do not add new hazards.

A comprehensive overview on risk reduction is given in the following sources of information (ISO, 2009), (ISO, 2010).

8.3.5 Technology Risk Monitoring and Review

As risk management is a continuous process, it is important to review the risk assessments periodically to secure that variable factors are not having an undue effect on the risk of the system.

8.4 Influence of Risk on LCOE

The levelized cost of energy (LCOE) is used to compare the prices of electricity productions costs of different sources of energies during lifetime. During the research for this report many information sources found (as explained in Section 8.1) calculate the LCOE of offshore wind power with given parameters not considering variables.

The LCOE of offshore wind power can vary depending on materials used, manufacturing methods, capacity factor, capital costs, operation and maintenance costs, downtime, etc.

According to (James, et al., 2015) the currently dominant material used for FOWT substructures is steel, which is the case for fixed bottom structures as well and where therefore considerable experience already exists. However some substructure designers are using concrete in their concepts, which is on one side heavier than steel, but on the other side can be 10 times cheaper than steel (James, et al., 2015). In the context of industrialization concrete brings benefits in terms of increased local content, which lowers the transportation costs and allows to be more flexible in manufacturing. Furthermore concrete is less prone to corrosion and therefore seems to be more robust than steel structures. However one of the drawbacks of concrete is less experience in large scale fabrication compared to steel, which has been widely used by the oil & gas industry.

In the end both materials steel and concrete are expected to be able to exceed the minimum lifetime of 20 years and the choice which material with its related cost benefits is to be used is again depending on the substructure design and must be made after a deeper analysis.

However, other sources of information like (Luengo, et al., 2015) describe that the LCOE of wind power depends mostly on capacity factor, capital expenditure, weighted average cost of capital (WACC) and operation and maintenance costs. Including the interaction of variables as for example wind turbine design, operational availability, potential power curtailment and the quality of the wind resource. Furthermore, Tavern also includes the mean time between failures (MTBF), the mean time to repair (MTTR) and the reliability of the different components.

At the present time wind turbines are designed for 25 years of lifetime with the possibility of extension of their operation time. Through extending their operation and increasing the electricity production, the return on investment (ROI) will increase and the LCOE decrease. In order to reach this, (Luengo, et al., 2015) point out the necessity of failure mode identification throughout the lifespan of offshore wind turbines and the consideration of end of life (EOL) scenarios, e.g. life extension, repowering and decommissioning.

The National Renewable Energy Laboratory (NREL) conducted a representative study about the relative impacts of various financial, technological and wind resource variables on the LCOE of a wind project (Karlynn Cory, 2009).

The considered technical variables are capacity factor, total installation cost, operation and maintenance and levelized replacement cost, whereas the considered financial variables are Target IRR (internal rate of return), return on debt and loan duration. Each impact of a variable is reviewed by a range of high-cost, base-case and low-cost values for six financing structures, these are Corporate (Corp), Strategic Investor Flip (SIF), Institutional Investor Flip (IIF), Back Leveraged (BL), Cash Leveraged (Cash Lev) and Cash and Production Tax Credit Leveraged (Cash and PTC LEV).

The study compares which of the variables have individually the greatest impact on the LCOE. For this, one variable is tested while the others are held fixed to the base-case assumption. All ranges in which the input variables are varied, are based on realistic project characteristics. The output (Figure 39) is that capacity factor and installation cost have the largest impact on the LCOE while O&M costs have a moderate impact. The lowest impact has the levelized replacement cost.

The target IRR also shows a large impact on the LCOE due to the characteristics of the financing structure institutional investor flip. Generally, if the financing structure uses 100% equity the impact of target IRR is higher.

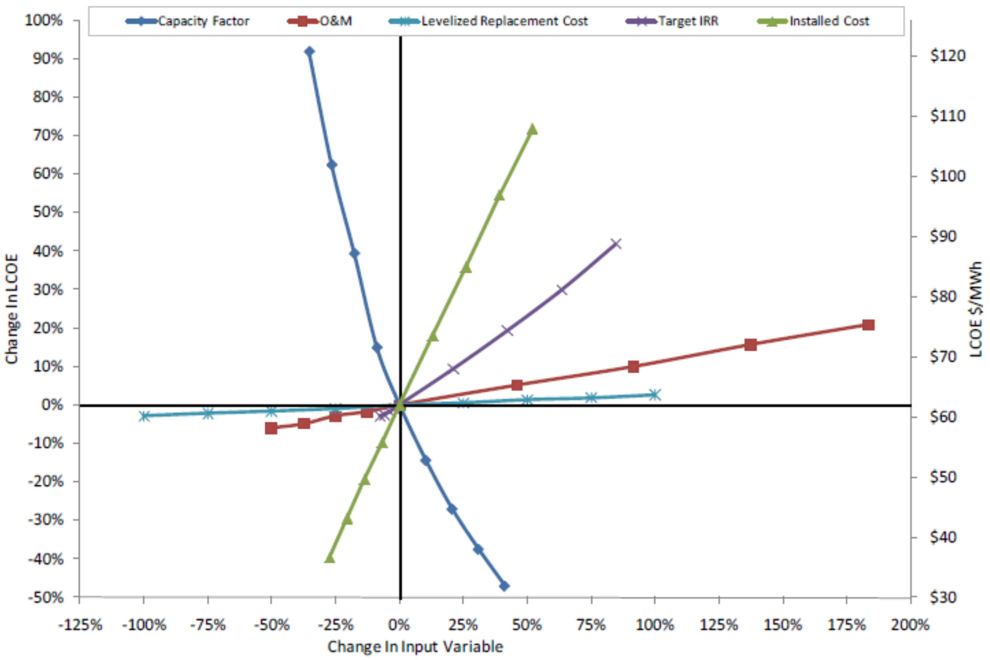


Figure 39: Institutional Investor Flip of LCOE sensitivities by input variable (Karlynn Cory, 2009)

Furthermore, the study analysis a multivariable scenario where technical and financial variables influence simultaneously on the LCOE. Therefore, the input ranges for the variables need to be adjusted due to the unlikelihood that the project would have all favourable impacts (i.e., low-cost) or least favourable (i.e., high-cost) values together. The result is illustrated in Figure 40. Depending on the financial structure the base-case multivariable scenario varies between an LCOE of $54-$74/MWh for onshore wind power which is comparable with the power prices in the Unites States in 2008.

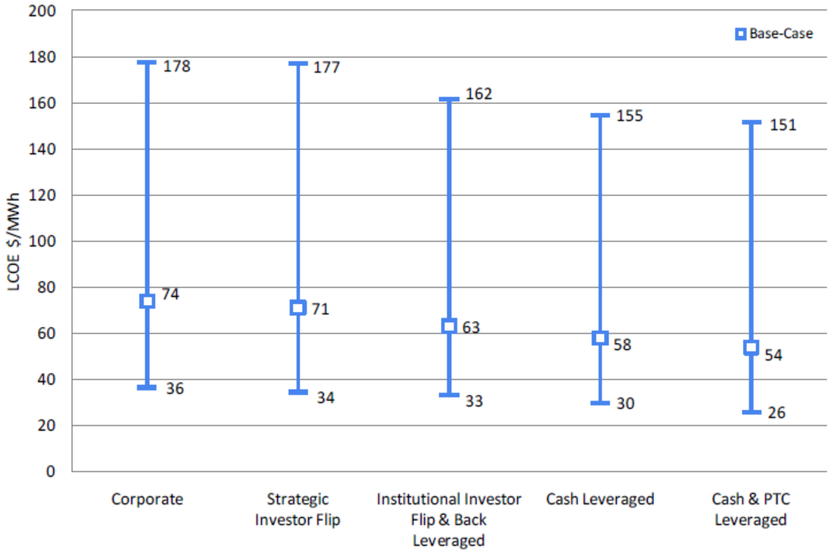


Figure 40: Multivariable scenarios of LCOE ranges (Karlynn Cory, 2009)

NREL compares also the impacts of the technical variables and the financing variables in the multivariable scenario. The LCOE was valued with the financing variables set to the high-cost and then low-cost multivariable scenario values while the technical variables were held constant to their base-case values and then vice versa. In Figure 41, the range of estimated LCOE that results from varying the financing variables is shown in the darker colour, while the range of LOCE from varying the technical variables is displayed in the lighter colour. To conclude, the technical variables have a larger impact on the estimated LCOE than the financial variables.

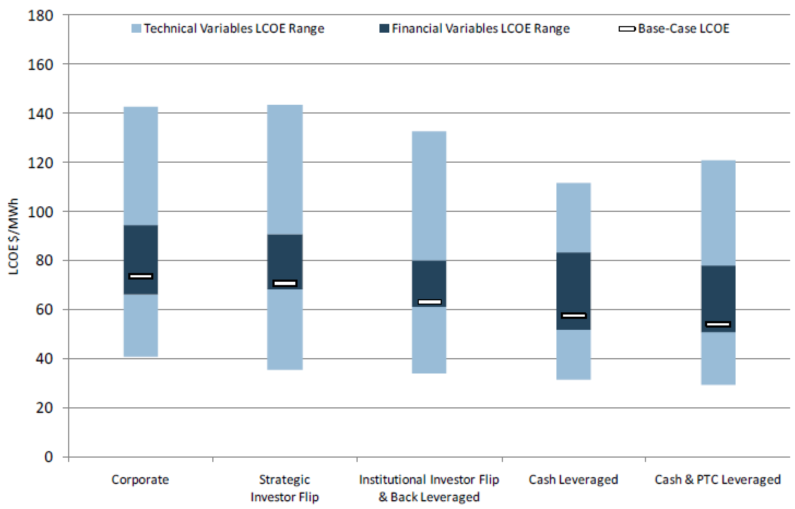


Figure 41: Variable LCOE Ranges (Karlynn Cory, 2009)

The ranges shown in Figure 41 can be understood as uncertainty, (Hutton, et al., 2015) points out the incomplete knowledge of the likely values of the resulting LCOE considering this uncertainty as inevitable for new technologies. In the mentioned report, the uncertainty in LCOE is used as an indicator of commercial risk.

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Appendix A: Questionnaire for state-of-the-art controller design for floating offshore wind turbines

Closed-loop control:

1. Was the design of the closed-loop controller for the floating wind turbine different from the onshore version?
2. Which control inputs did you use (only collective pitch and generator torque or additional individual pitch or even more)?
3. Which sensor did you use (rotor speed, tower acceleration, platform inclination, blade root bending, or others)?
4. Did you adopt a method from the literature for the collective pitch controller (Hansen et al. 2005, Larsen and Hanson 2007)?
5. Did you had constant generator torque above rated wind speed?
6. How would you rather classify your controller (combination of SISO-loops or MIMO, designed by loop-shaping or by tuning of weights)?
7. In which simulation environment did you test the controller (bottom fixed with wind input or coupled FOWT with wind and wave input)?

Supervisory Control:

1. Was the design of the supervisory control for the floating wind turbine different from the onshore version?
2. Did you introduce more operation modes compared to onshore case?
3. What are the important design driving conditions/ environmental considerations?

Safety System:

1. Was the design of the safety system for the floating wind turbine different from the onshore version?
2. Did you introduce special emergency procedures?
3. What are the important design driving conditions/ environmental considerations?

Additional questions:

1. What questions would you like to have answered from an R&D perspective with respect to controller design for floating wind turbines?