Lifetime Extension and Optimal Lifecycle Offshore Wind Turbines

By DNV Energy Systems

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Table of Content

1 Executive Summary

In the Top Consortium Knowledge and Innovation Offshore Wind (TKI Wind op zee) innovation programme, and the first mission-oriented innovation programmes (MMIP1) formulated by the Ministry of Economic Affairs and Climate Policy, bottlenecks were identified which could obstruct the large-scale roll-out of offshore wind energy. Until now, Dutch offshore windfarms are given licenses for 30 years of operation including a maximum of 5 years of construction; this is being considered for an increase to 40 years.

DNV has undertaken a study on lifetime extension and optimal lifecycle for offshore wind turbines, aiming to identify the approach to offshore wind farm design and operation that yields the lowest cost of energy, considering potential changes to the current approach such as extended operational lifetime, increased design life and component replacement strategies. Current industry trends in operating strategy and value optimisation have also been identified to show the direction of travel within the industry.

DNV has undertaken detailed modelling using its Turbine.Architect tool, which enables detailed bottom-up cost modelling of offshore wind farms based on turbine loads and engineering principles. This methodology enables specific elements to be analysed for cost and lifetime, and therefore the economically optimal approach to wind farm design to be identified. The key metric used in these analyses is the Levelized Cost of Energy (LCoE), calculated via a simple discounted cash flow model.

DNV modelled a generic reference turbine broadly similar to those planned for installation in the mid-2020s, combined with site parameters corresponding to the IJmuiden Ver zone in the Dutch North Sea. The hypothetical wind farm was modelled in eight separate scenarios comprising combinations of lifetime extension, extended design life, planned component replacement, and modified O&M strategies, in order to identify the optimal scenario(s). DNV also identified uncertainties within the modelling and opportunities for further research in support of longer-lifetime offshore wind farms.

DNV notes that the offshore wind industry continues to grow and that further cost reduction and technology development is expected; there is, therefore, inherent uncertainty around the practical realisation of some potential scenarios, but DNV considers all modelled scenarios technically feasible and therefore worthy of inclusion in this study.

The primary conclusion of the study is that longer operational lifetimes contribute to reduced cost of energy, which is in line with current industry assumptions with respect to lifetime. It is technically feasible to operate an offshore wind farm for longer than the current industry-standard design life of 25 years, and a reduction in the cost of energy would be expected through either extension of the operating lifetime, full wind farm replacement, or design for longer lifetimes.

The study suggests that lifetime extension of projects with a 25-year design lifetime, by 5-15 years, and full replacement of the wind farm after approximately 30 years, offers the lowest LCoE. However, the advantage in LCoE is relatively small over scenarios in which the design lifetime of turbines and/ or foundations is increased, and there remain uncertainties around factors such as technological development which could affect each strategy differently. As such, no one scenario offers a clear advantage over the others.

2 Introduction

The Netherlands Enterprise Agency (RVO) ("the Customer") has invited DNV Services UK Ltd ("DNV") to submit an offer for a study on "Lifetime extension and optimal lifecycle offshore wind turbines" for the Top Consortium Knowledge and Innovation Offshore Wind (TKI Wind op zee). In the TKI Wind op Zee innovation programme and the first mission-oriented innovation programme (MMIP1) formulated by the Ministry of Economic Affairs and Climate Policy, a number of bottlenecks have been identified which could obstruct the large-scale roll-out of offshore wind energy.
Until now, Dutch offshore windfarms are given licenses for 30 years of operation including a maximum of 5 years of construction; this is being considered for an increase to 40 years. The Customer wishes to gain insight into optimal lifetimes for the WTG and support structure.

The core questions to be addressed in this study are:

1) What are the consequences of building structures which operate for 40 years instead of 25
2) Should all components last the lifetime or should certain major components be replaced
3) How would even longer lifetimes affect the conclusions

These are further split into objectives and subsequent sections below.

1.1 Objectives

The objectives of this study were to:

- Analyse the technical (materials, design etc.) and economic (LCoE) consequences of a longer required lifetime of the main components of wind farms. In doing this, take into consideration the consequences for all switches in the value chain.
- Analyse the most challenging knowledge gaps for the reduction of costs of long-life wind farms.
- Analyse the most promising ways to reduce costs of long-life wind farms, for instance by applying other materials and/ or other designs etc. In doing this, pay attention to the ways to optimize the joint costs of investment and maintenance.
- Conclude with a list of the priorities for Research and Innovation, ranging from low Technology Readiness Levels (TRL), including more fundamental research (e.g. related to materials), to high TRL short term incremental innovations.

3 Approach

This chapter aims to elaborate on the approach of this project. The analysis detailed in this report utilizes Turbine.Architect, which is DNV's in-house engineering and cost-modelling tool for wind energy. This section starts with a general background into the need for the tool, its development and a description of its turbine and wind farm modelling capabilities. This is then followed by a section detailing the Operations & Maintenance analysis tool O2M.

Cost modelling is key to answering the question for a given component or assembly whether it is more cost-efficient to design and manufacture it to last the whole life or whether it is more cost-effective to design and manufacture all or part of it for replacement. It is also useful in considering for example, if designing a turbine for the whole longer life, how it may impact on support structure cost if the turbine mass is higher, the impact on the WTG components for a longer life and the impact on the O&M costs based on the strategy; ultimately Levelized Cost of Energy (LCoE) provides the answer.

3.1 Turbine.Architect

Turbine.Architect is DNV's in-house engineering and cost modelling tool for wind energy that runs on the Renewables.Architect MDAO (Multi-disciplinary analysis and optimization) framework. For this study, a selection of Turbine.Architect engineering and cost modelling tools are used to:

- Size and scale turbine concepts based on estimated loads for varying design life
- Perform turbine and wind farm cost analysis
- Understand the relative attractiveness of design configurations

The strength of Turbine.Architect is that it combines the speed of analysis with accurate results which makes it possible to develop high-level insights into parameter sensitivities and picking out optimum designs and configurations from a set of generated data points. It is a flexible tool with analysis and results customized to customers' needs within reasonable limits.

The main pillars of the Turbine.Architect platform are:

- DNV wind turbine loads database
- Extensive turbine engineering models based on DNV turbine engineering knowledge and skills
- Cost data

For the analysis presented in this report, the primary focus is to derive realistic cost figures for a defined set of scenarios. Therefore, the cost will be the primary metric of interest in line with the wider scope of the project. For the wind turbines, the CAPEX and the cost for installation are obtained from the analysis of Turbine.Architect, while the Operations and Maintenance (O&M) cost is supplied from a more detailed modelling in O2M.

3.1.1 Background

Turbine.Architect performs calculations and outline design, taking account of site conditions and key project cost drivers based on generic design approaches, best estimate unit costs and engineering principles. There is, therefore, uncertainty in the results and these uncertainties could be reduced through the use of more detailed input information, and/or site-specific studies; however, there will remain some uncertainty in the results until detailed engineering design is undertaken.

Even so, DNV has endeavoured to ensure that the predictions for CAPEX components are realistic. For instance, absolute average turbine prices are obtained by scaling the Turbine.Architect predictions to aggregated prices that DNV has observed on recent, comparable European projects.

3.1.2 Structural components modelling

The main support structure components are modelled by Turbine.Architect through separate detailed engineering models for:

- Monopile substructure
- Tower

The following rotor-nacelle assembly (RNA) components are modelled by Turbine.Architect through separate engineering models:

- Nacelle & Hub
  - Yaw system:
    - Yaw bearing
    - Yaw drive: gearboxes, motors
    - Yaw braking system
  - Pitch system:
    - Pitch bearings
    - Motor, gearboxes, inverter, battery, slip ring
  - Main bearing(s) & bearing housing(s)
  - Low-speed shaft
  - Main frame
  - Hub
  - Rear frame
- Blades
- Drivetrain:
  - Generator
  - Gearbox

- Electrical Items:
    - Inverter
    - Transformer
    - Switchgear, cables
- Balance of system:
    - Nacelle cover
    - Hydraulic power unit
    - Controls and communication system

3.1.3 Discussion on impact to components

3.1.3.1 Monopile substructure & tower

The monopile and tower both consist of steel. One of the main impacts of an increased lifetime or life extension is in the form of rust. Different parts of the monopile and tower are protected differently against corrosion. Corrosion forms small pits and material loss in the steel. Corrosion pits are defects in the steel surface from which a fatigue crack can start to propagate through the steel thickness. Management of corrosion reduces the likelihood of corrosion pits and thus a fatigue crack initiation.

- The external surface of the monopile below the level of the lowest astronomical tide (LAT), which is constantly in water, is not always coated. Instead, it has cathodic protection (sacrificial anodes or impressed current) which protects the steel surface of the monopile from corrosion. For an increased life the system can be designed for a longer life, e.g. more sacrificial anodes need to be installed, or further protection could be retrofitted to gain the increase in life. Monitoring the negative potential and material loss of the anodes is a typical O&M activity that will inform the operator of the rate that which material is lost from the anodes, the level of protection and when retrofitting further protection may be needed.

- The internal submerged portion of the monopile below the airtight platform requires paint and/or cathodic protection to protect against corrosion. Re-painting of the submerged internal surface is not considered feasible, but sacrificial anode string could be deployed in later life to control corrosion in this space.

- Above the splash zone, the monopile and tower are coated to prevent corrosion from exposure to water, salt, air and UV light. The coating can last for an additional time as long as required touch-ups are done regularly and over the whole lifetime.

- Comment regarding bolted connections in section 3.1.3.2 applies here too.

In the financial model, corrosion is being controlled during the O&M phase to gain a longer life and the increase in O&M costs have been included depending on the scenario for inspections, repairs and retrofitting of cathodic protection systems. Furthermore, for structures designed for a longer life, DNV has considered an increase in primary steel mass to resist the increase in cyclic loading the structure will experience and increase in sacrificial anode mass due to a longer life for the cathodic protection system. These increases in masses are calculated within Turbine.Architect.

3.1.3.2 Nacelle & hub

The wind turbine rotor hub and nacelle consist primarily of metallic structures as detailed below. Bearings support drivetrain rotation and blade pitching. Components are joined with high strength preloaded bolted connections. Only some components and connections will be primarily fatigue driven.

- Yaw bearing and pitch bearings are highly loaded, high duty mechanical parts. These are slewing bearings rather than rolling bearings and pitch bearings especially, with their angle-limited repetitive travel, are especially difficult to design for long life. There are multiple fatigue and wear related failure mechanisms pitch and yaw bearings are prone to. They are very expensive to replace as significant turbine disassembly is required. To design for longer life, it may be possible in part to achieve this with improved quality: more reliable lubrication systems and higher quality steel with better finishes (hardening, polishing). But it is anticipated that significant upsizing may be needed with consequences for the size of adjacent components. Adjacent reinforcement, typically in the form of stiffening structure may form part of the solution.

- Gearboxes are highly loaded, high duty mechanical parts. There are multiple fatigue and wear related failure mechanisms and have been very expensive to replace as jack-up vessels are required to replace them. To design for longer life, it may be possible in part to achieve this with improved quality, more reliable lubrication systems or higher quality materials with better finishes (hardening, polishing). Increasing the rotor's tip speed reduces the rotor torque which would reduce loads (but increase cycles) on the gearbox. For this study a medium speed planetary gearbox has been assumed for the 15MW WTG, equally a direct drive machine could have been used. A combination of effective condition monitoring (online combined with detailed schedule inspections) of the gearbox and design of the gearbox which allows for up tower replacement of many parts of the gearbox are currently the approach applied by the OEM's to support extended operating time.

- (Spheroidal) cast iron components, such as the hub, main frame and main shaft, are likely to last beyond the design life. Design assumptions are quite conservative owing to high uncertainties about distributions of flaws and residual stresses from the casting process. As a result, typically, the odd casting may fail early in its life but most will survive well beyond design life unless there is a design error or error in the chemistry of the cast iron formulation. Where fatigue strength margins are low, it may be possible to move to a higher casting quality and better post-casting inspections (non-destructive testing) methods. It may be that it pays to introduce small areas of local reinforcement (small changes to the casting mould) at fatigue-driven hotspots. In the case of the main shaft, such upsizing is more likely to be necessary as it is highly fatigue driven. It may be possible to move to higher strength grades of cast iron; however, care must be taken here as sensitivity to correct chemistry is high, making achieving consistent high strength of finished castings difficult.

- Rear frame (also known as the generator frame or auxiliary frame) is typically fabricated from welded plate steel. It is normally reasonably easy to inspect, repair and reinforce. It may be possible to grind welds for improved fatigue life in areas where analysis is pointing to fatigue strength being life-limiting. In some cases the rear frame can be a space frame structure that also supports the nacelle cover and is a combination of cast nodes, cast or steel members and bolted connections.

- Bolted connections can be easily inspected. Typically, the more highly loaded connections, the more prone to fastener failure feature a high number of fasteners. With this comes inherent redundancy – if just one bolt fails in fatigue, structural integrity is maintained. The occasionally broken fastener is picked up during routine inspection and replaced in a timely manner.

The above reasoning is the basis for the cost markup factors chosen and tabulated in Table 3-1.

3.1.3.3 Blades

The structural design of a blade should stay very similar even when designing for a longer life as it is not as primarily driven by fatigue loads (equivalent fatigue loads are only slightly higher for a longer life due to the material of the blade).
Experience with wind turbine blades shows that they do not usually fail structurally, but rather deteriorate starting from the leading edge to the point where aerodynamic properties worsen significantly and the protective layers and coating erode completely. There is ongoing development into improved/disruptive technologies to deal with leading edge erosion e.g.:

- Improved leading-edge materials, additional leading edge protection (like PowerEdge from SGRE) in the form of a polymer attached to the part of the leading edge most prone to deterioration, these can be installed from the beginning, replaced and retrofitted
- Reduced impact by weather (rain, hailstones) and environment (salt particles) through the smart operation of a wind turbine, taking into account real-time environmental measurements and blade load sensor data
- Modularisation of the blade (replaceable leading edge section) would allow for the replacement of most affected blade parts, however, this is not yet available

Overall, it is essential to perform regular blade inspections, maintenance and periodic repairs, as these can increase blade life significantly. If deployed for a longer period of time, it is reasonable to assume a higher number of blades requiring replacement, even if just due to failures because of lightning strikes etc.

3.1.3.4 Electrical systems

The wind turbine electrical systems are specified such that they are able to accommodate the range of scenarios and conditions they shall be exposed to throughout a specified time period, usually 20 or 25 years.

Within the overall wind turbine design process, these scenarios come from a range of load cases as defined within the standard to which the wind turbine is designed to satisfy. This requirement extends to accommodate the expected life of the wind turbine.

In order to confidently achieve a lifetime in excess of the (usual) life, the equipment is specified as such from the outset or managed in operational terms throughout its’ lifetime. The sections which follow provide background as to the conditions which are likely to affect a longer life and the areas within the electrical system which may require management to achieve longer life.

Generator: The generator will be exposed to varying degrees of heat and centrifugal forces which in turn incur mechanical stresses within the rotor and stator windings and support structures. The primary issue is expected to be the materials used to insulate the rotor and stator windings. This issue primarily is discussed below although the cursory discussion on other areas also follows.

As the wind turbine operates throughout the power curve in accordance with wind conditions, the generator rotor and stator windings will carry varying levels of current. For operating conditions around and beyond nominal wind turbine output, the current flows will bring about higher but expected operating temperatures. The insulation design and materials utilised therein are specified to accommodate the operating scenarios the machine will be exposed to and the duration the machine will be required to accommodate them.

If life extension is to be considered, then the operation of the machine would need to be managed, such that operation at or above nominal output, for example, is to be minimised or avoided. As heat is a significant factor in the life of the insulating material and is directly related to current flows, the operation of the machine particularly at high outputs would need to be regulated, potentially below nominal output. This means that peaks in energy production are to be avoided to facilitate longer-term energy yield. This will ensure rotor and stator winding currents and crucially, temperatures are maintained to within suitable levels and thus insulation life is to some degree, managed.

Where a life in excess of the usual 20- or 25-years period is to be considered from the outset, then the lifetime expectations should be specified and passed on to the equipment supplier so that the insulating materials used within the rotor and stator structures are suitably designed.

With respect to the mechanical forces brought about during extended life, these would need to be managed through regulation of the machine operations, specifically at and above nominal output. The bearings may require enhanced maintenance or replacement. For a design-life of beyond the usual 20- or 25-year period, these would need to be designed accordingly. The bearings may need replacement regardless.
For other supporting systems, for example, cooling systems inclusive of pumps and fans etc., and dust extraction in the case of machines with slip rings and carbon brushes, these will require replacement throughout wind turbine life regardless of intentions for extended life or designed long-life.

Power converter: The power converter will require routing maintenance as part of normal wind turbine operations and maintenance activity. This will include replacement of converter modules. They are expected to require replacement as they are not expected to achieve 20 or 25 year life. Therefore extended life or designed long-life is considered achievable through normal routine operations and maintenance.

Supporting systems inclusive of control gear, heaters and cooling systems are expected to require servicing and replacement within the 20 or 25 year life and so again extended life or designed long-life is considered achievable without a significant step change in operations and maintenance activity or ongoing cost projections.

Power transformers: As with the generator, the primary issue affecting the life of the transformer is expected to be the longevity of the insulating materials. When the wind turbine operates throughout the power curve in accordance with wind conditions, the primary and secondary transformer windings will carry varying levels of current. For operating conditions around and above nominal wind turbine output, the current flows will bring about higher operating temperatures. The insulation design and materials utilised therein are specified to accommodate the operating scenarios the transformer will be exposed to and the duration expected to accommodate them.

If life extension is to be considered, then the operation of the machine would need to be managed, such that operation at or above nominal output, for example, shall be minimised or avoided. As heat is a significant factor in the life of the insulating material and is directly related to current flows, the operation of the wind turbine at high outputs would need to be regulated, potentially below nominal output. This means that peaks in energy production are to be avoided to facilitate longer-term energy yield. This will ensure the transformer winding currents and thus temperatures are maintained to within suitable levels.

Where a life in excess of the usual 20 or 25 years period is to be considered from the outset, the lifetime expectations should be specified to the transformer supplier such that the insulating materials can be designed accordingly.

Tower cables: Two main issues are expected to have an impact on tower cable life; the specification of the insulating material and, where there are any dynamic sections, the physical fatigue life/integrity.
The insulating material issue is similar to the case with the generator and the transformer. If the operating temperature of the cable throughout its' life is well within its design specification, extended life or designed long-life can be expected. Where life extension is considered partway through usual life, curtailed operation of the wind turbine may be required to extend insulating material life.
Where dynamic flexible cables are used to accommodate the yawing of the nacelle, there is a potential fatigue life issue. The fatigue life for these sections of cable could, in the usual case, be less than the usual 20 or 25-year life of the turbine and so replacement may be required regardless.

Switchgear: Assuming the switchgear is not excessively operated throughout usual wind farm life, extended life is expected. Supporting systems such as protection, control gear and battery chargers are expected to require replacement, even within usual life. Switchgear components would also require routine servicing and replacement.

Electrical infrastructure - Infield cables: The insulating material issue for the infield cables is similar to the wind turbine tower cables. If the operating temperature of the infield cabling throughout its' life is well within its design specification, extended life or designed long-life can be expected.

Where life extension is considered part way though usual life and cables have been exposed to relatively high temperatures, curtailed operation of the wind turbines may be required. Some sectors within the wind farm will be exposed to higher levels of current and thus temperature than others. Therefore, if life extension is considered part-way through life, then the cables should be assessed on a case-by-case basis.

General considerations: Extended life or designed long-life can be achieved through a combination of the following:

- Suitable up-front design work to account for long-life
- Wind turbine output power regulation, to avoid or minimise nominal and above-nominal output.
- Routine and enhanced Operations and Maintenance (O&M) activity

3.1.4 Assumptions

The inputs to the Turbine.Architect models were determined based on discussions with the Customer. Additional parameters were based on DNV's experience in turbine modelling, particularly in the European market and the North Sea. The basic assumptions are:

- 15 MW turbine, DNV suggestion to use the IEA Wind 15-Megawatt Offshore Reference Wind Turbine /1/ as a basis. This leads to the following turbine headline parameters
    - 150 m hub height
    - 240 m rotor diameter
    - IEC Class type 1B, assuming 10 m/s annual mean wind speed and 0.14 turbulence intensity
    - Geared drivetrain with permanent magnet generator (PMG)
    - Design tip speed ratio 9, maximum tip speed 95 m/s
    - Carbon blades with individual pitch control (IPC)
- Monopile substructure
- Offshore site assumptions are based on the IJmuiden Ver site off the Dutch coast:
    - Wind conditions: 10.0 m/s annual mean wind speed at 120 m height ***/2/***
    - 30 m average water depth
    - 46 nautical miles distance to IJmuiden Port
    - Metocean conditions: 1.44 m long term mean significant wave height, otherwise typical sea conditions as for similar sites
    - Typical North Sea soil conditions
- Farm assumptions

    - 1 GW wind farm, resulting in 67 turbines with 15 MW rating
    - Substation and export cables provided externally and excluded from calculations

- Discount rate 6%
- Lifetime will be varied between 25 and 60 years, depending on the scenario and component

The assumptions for the turbine size and power represent realistic estimates for the timeline of the project. The extended design life is a trend in the market and is based on reasonable assumptions. However, turbines and substructures with this design life are not yet commercially available in the market and all costs and design are generated by Turbine.Architect are based on existing smaller turbines with shorter design life as well as predicted trends based on industry experience.

Lifetime Increase

In order to model all increased design life scenarios, it is necessary to derive a cost for wind turbine components that are designed for more than the standard 25 years. As explained in 0, Turbine.Architect draws on a loads database, extensive engineering knowledge and skills and costs data to derive a reasonable design and cost for each component. Fatigue loads can be automatically adjusted to a higher lifetime, resulting in a stronger design of fatigue driven components. However, a turbine is comprised of many components which are not directly driven by fatigue loads. To capture the necessary adjustments and added cost of designing such components, various domain experts within DNV are consulted. The following table outlines the estimated cost increase of wind turbine components for changing from 25 years to 40 years of design life, in which the designated "markup factor" was applied to component costs derived by Turbine.Architect to account for the increased lifetime.

Table 3-1 Component Cost Assumptions

	Component	Markup factor	Comment
Nacelle	Bedplate mainframe	1.05	Move to higher casting quality and better post-casting inspections methods; potential local reinforcements where fatigue driven
	Generator frame	1.1	Assuming fabrication; reinforcement; grinding of welds
	Yaw	1.15	High duty mechanical, multiple fatigue/wear related failure mechanisms and very expensive to replace; significant upsizing, quality improvements (lube, steel, etc) and adjacent reinforcement
	Gearbox	1.15	Assuming medium speed planetary designed for life
	Low-speed shaft	1.1	Move to higher casting quality and better post-casting inspections methods; potential slight upsize as highly fatigue driven
	Inverter	1.02	Cyclic load driven elements

	Transformer	1.02	Cyclic load driven elements
	Generator	1.1	Estimate relating to cyclically loaded elements including bearings
	Main bearing	1.05	Assuming separated taper roller bearings
	Main bearing housing	1.05	As for main frame
	Balance of system	1.1	
	Contingencies	1.1	Benefit of investing in higher quality extras
Rotor	Blades	1.1	
	Hub	1.07	Move to higher casting quality and better post-casting inspections methods; potential reinforcements where fatigue driven
	Pitch bearing	1.2	High duty mechanical, multiple fatigue/wear related failure mechanisms and very expensive to replace; significant upsizing, quality improvements (lube, steel, etc) and adjacent reinforcement
	Pitch system	1.1	Cost increase associated with pitch bearing upsizing and parallel quality improvements
Electrical Infrastructure	Infield cables	1.1	Designed for life as costly to replace, additional cost for insulation

The design of the turbine tower and monopile is highly fatigue load driven. Required stronger design for an increased design life is captured by the models and in line with in-house experts' assumptions.

3.2 Operations modelling (O2M)

DNV has been developing the O2M model since 2005. O2M is a time-domain model, based on Monte Carlo simulation with turbine failures occurring on a stochastic basis and the impact of weather simulated using long-term time series data for the area of interest. This approach enables the simulation of O&M requirements, availability and accessibility constraints relating to weather and asset utilisation, and seasonal effects to be captured. Analyses take into account the wind farm configuration, such as the number of turbines, vessel travel times, failure rates etc., and account for lost production as well as direct operating costs.

O2M modelling has been used to inform O&M strategy, costs, availability and resourcing for more than 50 commercial projects around the world with customers including major utilities, turbine suppliers and project owners. In this study, DNV used its O2M software to assess implications of increased maintenance – if, for example, life extension was used to extend a life towards 40 or more years versus designing for that lifetime in the first place and consequently incurring less O&M during the operating lifetime.

4 Modelling

4.1 Scenarios

Longer life for offshore wind turbines can be obtained in a number of different ways. One way would be to design components for a longer design life, increasing their resistance to loading, deterioration and other causes of failure. Alternatively, another option would be to replace components after a certain time. This replacement can either happen after a certain defined lifetime, or whenever required due to component failure.

In order to assess the impact on project availability and operational expenditure, DNV has considered the following generic assumptions:

- Project consists of 67 x 15MW project (1,005 MW total capacity) (average failure rate of 5.7 failures per WTG per year in 25 year lifetime)
- Port of Operations: IJmuiden (~46 nautical miles average distance to IJmuiden I, II, III, IV, V and Ver).
- Site is operated independently and an average electricity revenue price of 50€/MWh has been assumed.
- Optimal strategy is the deployment of 2 x Hybrid Surface Effect Ship (SES) vessels with an average transit speed of 35 knots and a safe transfer limit of 2m Hs.
- Base case lifetime of 25 years to then apply the different expected costs for lifetime extension works and overhauls for different scenarios as well as availability implications when repairs and overhauls are performed.

Further to these generic assumptions, the Customer and DNV agreed on a set of seven scenarios to analyse, one base case and six different strategies for extended turbine life, detailed in Table 4-1.

Table 4-1 Scenario Definition

#	Scenario	Sub-structure design life	Turbine design life	Wind farm life	O&M	Notes
1	Base case	25 yrs.	25 yrs.	25 yrs.	Normal	Status quo
2	Lifetime Extension (LTE) overhaul	25 yrs. (O&M)	25 yrs. (O&M)	40 yrs.	Normal	Overhaul components
3	LTE sweat	25 yrs. (O&M)	25 yrs. (O&M)	40 yrs.	Sweat	The sweat case assumes reliability of WTGs reduces and some units are left offline as repairs are not cost-effective.
4	40 yrs. design life	40 yrs.	40 yrs.	40 yrs.	Normal	Design turbine and substructure for a longer life
5	60 yrs., swap rotor	60 yrs.	25 yrs. for rotor, 40 yrs. for nacelle & tower (O&M)	60 yrs.	Normal	Rotor considered replaceable, other parts designed for longer life and extended life through additional maintenance and overhauls
6	60 yrs. swap rotor & nacelle	60 yrs.	25 yrs. for rotor & nacelle, 40 yrs. for tower (O&M)	60 yrs.	Normal	Rotor & nacelle considered replaceable, tower designed for longer life
7	60 yrs. WTG repowering	60 yrs.	25 yrs. (O&M)	60 yrs.	Normal	Complete replacement of turbine including tower after 30 years
8	60 yrs. windfarm replacement	25 yrs.	25 yrs. (O&M)	30 yrs.	Normal	Complete replacement of turbine, tower, substructure, foundation and cables after 30 years.

A more detailed description of all scenarios is provided in the table below:

Table 4-2: O&M assumptions per scenario

Scenario 1 - Base Case	
WTG Availability (energy-based)	Typical profile with ramp up for first 4 years, 15 years mature operations and then degrading availability of 0.125% per year due to age.
Jack up vessel costs	Assumption of 8 days per repair campaign including mob and demob and weather delay and assuming 120kEUR per day.
Lifetime extension works	Normal lifetime of 25 years. Therefore, no lifetime extension works costs included. However, note that OPEX includes fatigue assessment on year 3 and on year 20 as well as thorough walk-downs on year 20 in all locations to assess safety and structural integrity. Also included in the service base costs of this scenario is cost of structural condition monitoring system allowance of ~60kEUR per year as standard even without lifetime

	extension expected in order to assess the lifetime of structures in case they don't reach the design lifetime.
Scenario 2 - LTE Overhauls (40 years lifetime extension)	
WTG Availability (energy-based)	Availability improvements due to overhauls. Reduction from standard 0.125% to 0.1% as the reduction in availability is mainly driven only by the main components which keep increasing in failures. Reduction in availability on years 6, 11, 16, 21, 26, 31 and 36 in which overhauls are performed with 24 hours downtime per overhaul.
Balance of Plant (BoP) availability excl: OFTO and Grid (energy-based)	Assumption that array cables can last for 60 years, so no additional Opex or availability impact is assumed.
Jack up vessel costs	Assumption of 8 days per repair campaign including mob and demob and weather delay and assuming 120kEUR per day. Main component replacements even on last year of operations.
Parts and consumables	Costs as modelled with O2M assuming fixed failure rates after overhauls start as the overhauls replace all minor components reaching end of lifetime before they fail.
Overhauls	Assumption of 2.3mEUR per overhaul. Estimated by comparing cost difference when fixing the failure rates from mature operations onwards against assumption when normal failures increase. Allowing a 50% additional cost as all fleet components are to be replaced and not only the ones that are failing.
Lifetime extension	Lifetime extension works costs includes fatigue assessment on year 3, 20 and 35 with 175kEUR per assessment. Thorough walk-downs on year 20 and 35 in all locations to assess safety and structural integrity. Retrofit of all corrosion protection systems on year 25 to last for another 15 years at 120kEUR per location. Also not included in this cost item but included in the service base costs, is structural condition monitoring system allowance of ~60kEUR per year as standard even without lifetime extension expected in order to assess the lifetime of structures in case they don't reach the design lifetime.
Scenario 3 - LTE sweat (40 years)	
WTG Availability (energy-based)	Standard reduction of 0.125% in availability per year from year 19 onwards after 15 years of mature operations. Significant reduction in availability in year 40 as 10 turbines are left offline as costs of replacing a main component are expected as higher than annual revenue from the turbines.
BoP availability excl: OFTO and Grid (energy-based)	Assumption that array cables can last for 60 years, so no additional Opex or availability impact is assumed.
Jack up vessel costs	Assumption of 8 days per repair campaign including mob and demob and weather delay and assuming 120kEUR per day. No main component replacements on last year 40.
Parts and consumables	Costs as modelled using O2M and last year no main component replacements.
Overhauls	No overhauls
Lifetime extension	Lifetime extension works costs includes fatigue assessment on year 3, 20 and 35 with 175kEUR per assessment. Thorough walk-downs on year 20 and 35 in all locations to assess safety and structural integrity. Retrofit of all corrosion protection systems on year 20 to last for another 20 years at 120kEUR per location. Also not included in this cost item but included in the service base costs, is structural condition monitoring system allowance of 50k per year as standard even without lifetime extension expected in order to assess the lifetime of structures in case they don't reach the design lifetime.

Scenario 4 - 40 years design life	
WTG Availability (energy-based)	Extending the mature operations by 5 years as turbine is designed for longer lifetime so assuming lifetime of components are slightly better. Standard reduction of 0.125% in availability per year from year 23 onwards. In year 40 is when 10 turbines are left offline as costs of replacing a major component are expected as higher than revenue from the turbines from the year.
BoP availability excl: OFTO and Grid (energy-based)	Assumption that array cables can last for 60 years, so no additional Opex or availability impact is assumed.
Jack up vessel costs	Assumption of 8 days per repair campaign including mob and demob and weather delay and assuming 120kEUR per day. No main component replacements on last year 40.
Parts and consumables	Costs as modelled and last year no main component replacements.
Overhauls	No overhauls as design lifetime is 40 years.
Lifetime extension	Lifetime extension works costs includes fatigue assessment on year 3, 20 and 35 with 175kEUR per assessment. Thorough walk-downs on year 20 and 35 in all locations to assess safety and structural integrity. Retrofit of all corrosion protection systems is not required as they are designed for lifetime of 40 years. Also not included in this cost item but included in the service base costs, is structural condition monitoring system allowance of ~60kEUR per year as standard even without lifetime extension expected in order to assess the lifetime of structures in case they don't reach the design lifetime.
Scenario 5 - 60 years design of foundations, 25 years design of rotor, 40 years design of nacelle & tower	
WTG Availability (energy-based)	Extending the mature operations by 5 years as turbine is designed for longer lifetime so assuming lifetime of components are slightly better. Reduction in availability on year 30 when rotor swap is performed at 3 days per turbine downtime with all addressed in one year. Standard reduction of 0.125% in availability is improved to 0.1% per year from year 31 onwards as we have new rotors and we perform overhauls. During overhauls, we have a reduction of 24 hours per turbine for the overhauls of small components. In year 60 is when 6 turbines are left offline as costs of replacing an MC are expected as higher than revenue from the turbines from the year.
BoP availability excl: OFTO and Grid (energy-based)	Assumption that array cables can last for 60 years, so no additional Opex or availability impact is assumed.
Failure rates	Failure rate of main components is reduced by 25% after rotor swap on year 30 and stays the same for remaining lifetime as components are replaced with new and this balances the failure rates in the lifetime.
Jack-up	Rotor swap of 3 days per rotor in year 30 as well as the other 10 replacements required on year 30 and assuming 120kEUR per day. No main component replacements on last year 60.
Parts and consumables	Costs as modelled with O2M and last year no main component replacements. After rotor swap failure rates remain constant so we modelled with constant failure rates and still increase on failure rates of the other components in a small gradient.
Overhauls	Swap of all rotors on year 30 at 6.1mEUR per rotor assumption and 2.3m EUR overhauls every 5 years to keep the lifetime of the other components.
Lifetime extension	Lifetime extension works costs includes fatigue assessment on year 3, 20, 35 and 50 with 175kEUR per assessment. Thorough walk-downs on year 20, 35 and 50 in all locations to assess safety and structural integrity. Retrofit of all corrosion protection systems is not required as they are

	designed for lifetime of 60 years. Also not included in this cost item but included in the service base costs, is structural condition monitoring system allowance of ~60kEUR per year as standard even without lifetime extension expected in order to assess the lifetime of structures in case they don't reach the design lifetime.
Scenario 6 - 60 years design of foundations, 25 years for rotor & nacelle, 40 years for tower (O&M)	
WTG Availability (energy-based)	Mature operations standard of 15 years as turbine is designed for 25 years lifetime. Reduction in availability on year 30 when rotor and nacelle swap is performed at 4 days per turbine downtime with all addressed in one year. Standard reduction of 0.125% per year in availability is of 0.1% per year as we are doing standard minor overhauls and is eliminated from year 31 onwards for another 15 years of additional mature operations as we have new rotors and nacelles and we perform overhauls. During overhauls, we have a reduction of 24 hours per turbine for the overhauls of small components. In year 60 is when 6 turbines are left offline as costs of replacing a major component are expected as higher than revenue from the turbines from the year.
BoP availability excl: OFTO and Grid (energy-based)	Assumption that array cables can last for 60 years, so no additional Opex or availability impact is assumed.
Failure rates	Failure rate of MCs reset to new equipment values after nacelle and rotor swap on year 30 and standard failure profile keeps going until end of lifetime of 60 years.
Jack-up	Rotor swap and nacelle of 4 days per rotor in year 30 and no other replacement required on year 30 and assuming 120kEUR per day. No main component replacements on year 60.
Parts and consumables	Costs as modelled and last year no main component replacements. After rotor and nacelle swap, failure rates go back to original values.
Overhauls	Swap of all rotors on year 30 at 14.6mEUR per rotor and nacelle assumption and 2.3m EUR overhauls every 5 years to keep the lifetime of the other components.
Lifetime extension	Lifetime extension works costs includes fatigue assessment on year 3, 20, 35 and 50 with 175kEUR per assessment. Thorough walk-downs on year 20, 35 and 50 in all locations to assess safety and structural integrity. Retrofit of all corrosion protection systems is not required as they are designed for lifetime of 60 years. Also not included in this cost item but included in the service base costs, is structural condition monitoring system allowance of ~60kEUR per year as standard even without lifetime extension expected in order to assess the lifetime of structures in case they don't reach the design lifetime.
Scenario 7 - 60 years design of foundations, 25 years for rotor & nacelle and tower (WTG Repowering)	
WTG Availability (energy-based)	Mature operations standard of 15 years as turbine is designed for 25 years lifetime. Reduction in availability on year 30 when rotor and nacelle swap is performed at 5 days per turbine downtime with all addressed in one year. Standard reduction of 0.125% per year in availability is of 0.1% per year as we are doing standard minor overhauls and is eliminated from year 31 onwards for another 15 years of additional mature operations as we have new rotors and nacelles and we perform overhauls. During overhauls, we have a reduction of 24 hours per turbine for the overhauls of small components. In year 60 is when 6 turbines are left offline as costs of replacing an MC are expected as higher than revenue from the turbines from the year.
BoP availability excl: OFTO and Grid (energy-based)	Assumption that array cables can last for 60 years, so no additional Opex or availability impact is assumed.

Failure rates	Failure rate of MCs reset to new equipment values after nacelle and rotor swap on year 30 and standard failure profile keeps going until end of lifetime of 60 years.
Jack-up	Rotor swap, nacelle and tower of 5 days per rotor in year 30 and no other replacement required on year 30 and assuming 120kEUR per day. No main component replacements last year 60.
Parts and consumables	Costs as modelled and last year no main component replacements. After rotor, nacelle and tower swap, failure rates go back to original values.
Overhauls	Swap of all turbine including tower on year 30 at 17mEUR per turbine assumption and 2.3m EUR overhauls every 5 years to keep the lifetime of the other components.
Lifetime extension	Lifetime extension works costs includes fatigue assessment on year 3, 20, 35 and 50 with 175k EUR per assessment. Thorough walk-downs on year 20 and 50 in all locations to assess safety and structural integrity. Retrofit of all corrosion protection systems is not required as they are designed for lifetime of 60 years. Also not included in this cost item but included in the service base costs, is structural condition monitoring system allowance of 60kEUR per year as standard even without lifetime extension expected in order to assess the lifetime of structures in case, they don't reach the design lifetime.
Scenario 8 - 25 years design of foundations, 25 years for rotor & nacelle and tower (Windfarm replacement after 30 years)	
WTG Availability (energy-based)	Same and Scenario 1 for first 30 years. Second 30 years considered future offshore wind turbine technology which is estimated to have a cost reduction factor of 0.6 based on /3/.
Jack up vessel costs	Same and Scenario 1 for first 30 years. Second 30 years a cost reduction factor of 0.6 was applied based on /3/.
Lifetime extension works	Same and Scenario 1 for first 30 years. Second 30 years a cost reduction factor of 0.6 was applied based on /3/.

Ultimately, each of these scenarios will lead to varying costs in design & manufacturing, O&M and installation & decommissioning. The overarching analysis approach using Turbine.Architect, O2M and some financial modelling will provide a LCoE, which is a sensible metric to identify the most cost-effective strategy.

4.2 Financial Model

In order to effectively compare the different scenarios, a financial model is built. It contains adjusted inputs for each of the seven scenarios and calculates the overall LCoE, which serves as an important metric to compare the different options. The following inputs feed into the financial modelling.

- CapEx:
    - Project start, year 0: Development, supply & installation of WTG & foundation, electrical infrastructure
    - For scenarios 5, 6 & 7 only, year 29: supply & installation of replacement rotor, nacelle and/or tower

  - For scenario 8, year 30; entire decommissioning of the first wind farm, supply & installation of replacement of wind turbines, substructure and foundations and BoP.
  - Decommissioning, year 25, 40 or 60: decommissioning & disposal of WTG, foundation & cables
- O&M cost: yearly expenditure obtained from O2M with the added cost of campaigns to ensure longer life
- Availability: matched availability for O&M and longer life assumptions
- Energy yield: expected energy production obtained from Turbine.Architect modelling, considering the projected availability and losses (electrical and wake losses from Turbine.Architect models, standard assumptions for turbine interaction & performance)
- Discount factor: feeds into calculation of discounted cost and discounted GWh and consequently LCoE

5 Results

Turbine.Architect is run with several different modifications to represent all scenarios outlined in section 4.1. The table below represents some intermediate results to outline how the CAPEX of the wind turbine changes due to an increase in design life.

Table 5-1 Resulting increased cost of wind turbine components

Wind Turbine Component	Cost increase going from 25 to 40 years design life	Consisting of components
Rotor	11.7 %	Blade, hub, pitch system & bearing
Nacelle	9.7 %	Mainframe, rear frame, yaw, gearbox, low-speed shaft, main bearing, inverter, transformer, generator
Tower	6.6 %	
TOTAL WTG	**10.0 %**	**Rotor, nacelle, tower**
Monopile	9.3 %	

The following tables show the projected cost of capital, O&M, and availability for each of the seven cases. The colouring of the table highlights the less favourable (red) through to more favourable (green) values on each item to enable quick comparison.

Table 5-2 Capital, O&M cost, and availability for scenario 1 - 25 years base case

	Years 0 to 4	Years 5 to 9	Years 10 to 14	Years 15 to 19	Years 20 to 24	Year 25
Capital (m€)	1,887	0	0	0	0	67
O&M (m€ / year)	29.8	31.0	33.6	38.2	43.9	0
Availability	96.6	97.5	97.5	97.4	96.8	0

Table 5-3 Capital, O&M cost and availability for scenario 2 – 40-year lifetime extension overhaul

	Years 0 to 4	Years 5 to 9	Years 10 to 14	Years 14 to 19	Years 20 to 24	Years 25 to 29	Years 30 to 34	Years 35 to 39	Year 40
Capital (m€)	1,887	0	0	0	0	0	0	0	67
O&M (m€ / year)	29.8	31.6	34.2	38.8	46.0	50.1	52.1	51.7	0
Availability	96.6	97.4	97.4	97.4	97.0	96.6	96.2	95.8	0

Table 5-4 Capital, O&M cost and availability for scenario 3 – 40-year lifetime extension sweat

	Years 0 to 4	Years 5 to 9	Years 10 to 14	Years 14 to 19	Years 20 to 24	Years 25 to 29	Years 30 to 34	Years 35 to 39	Year 40
Capital (m€)	1,887	0	0	0	0	0	0	0	67
O&M (m€ / year)	29.8	31.1	33.7	38.3	45.7	50.1	52.4	47.4	0
Availability	96.6	97.5	97.5	97.4	96.8	96.2	95.6	92.0	0

Table 5-5 Capital, O&M cost and availability for scenario 4 – 40-year design life

	Years 0 to 4	Years 5 to 9	Years 10 to 14	Years 14 to 19	Years 20 to 24	Years 25 to 29	Years 30 to 34	Years 35 to 39	Year 40
Capital (m€)	2,051	0	0	0	0	0	0	0	67
O&M (m€ / year)	29.8	31.1	33.7	38.3	44.1	50.1	52.4	47.4	0
Availability	96.6	97.5	97.5	97.5	97.4	96.8	96.2	92.6	0

Table 5-6 Capital, O&M cost and availability for scenario 5 – 60-year swap rotor

	0 to 4	5 to 9	10 to 14	14 to 19	20 to 24	25 to 29	30 to 34	35 to 39	40 to 44	45 to 49	50 to 54	55 to 59	60
Capital (m€)	2,034	0	0	0	0	0	0	0	0	0	0	0	67
O&M (m€ / year)	29.8	31.6	34.2	38.8	44.6	140.5	46.4	46.4	46.7	47.2	47.3	44.0	0
Availability	96.4	97.4	97.4	97.4	97.3	96.6	96.1	95.7	95.3	94.9	94.5	91.7	0

Table 5-7 Capital, O&M cost and availability for scenario 6 – 60-year swap rotor & nacelle

	0 to 4	5 to 9	10 to 14	14 to 19	20 to 24	25 to 29	30 to 34	35 to 39	40 to 44	45 to 49	50 to 54	55 to 59	60
Capital (m€)	1,979	0	0	0	0	0	0	0	0	0	0	0	67
O&M (m€ / year)	29.8	31.6	34.2	38.8	44.6	258.6	29.8	31.6	34.2	38.8	44.6	45.8	0
Availability	96.4	97.4	97.4	97.4	96.9	96.2	97.2	97.4	97.4	97.2	96.8	93.5	0

Table 5-8 Capital, O&M cost and availability for scenario 7 – 60-year repowering

	0 to 4	5 to 9	10 to 14	14 to 19	20 to 24	25 to 29	30 to 34	35 to 39	40 to 44	45 to 49	50 to 54	55 to 59	60
Capital (m€)	1,968	0	0	0	0	0	0	0	0	0	0	0	67
O&M (m€ / year)	29.8	31.6	34.2	38.8	44.6	292.4	29.7	31.6	34.2	38.8	44.6	45.8	0
Availability	96.4	97.4	97.4	97.4	96.9	96.2	97.2	97.4	97.4	97.2	96.8	93.5	0

Table 5-9 Capital, O&M cost and availability for scenario 8 – 2 x 30-year full farm replacement

	0 to 4	**5 to 9**	**10 to 14**	**14 to 19**	**20 to 24**	**25 to 29**	**30 to 34**	**35 to 39**	**40 to 44**	**45 to 49**	**50 to 54**	**55 to 59**	**60**
Capital (m€)	1,887	0	0	0	0	0	1,199	0	0	0	0	0	40
O&M (m€ / year)	29.8	31.1	33.7	38.3	45.7	50.1	14.1	18.4	19.8	22.3	25.7	30.5	0
Availability	96.6	97.5	97.5	97.4	96.8	96.2	77.1	97.5	97.5	97.4	97.0	96.3	0

Table 5-10 Summary of LCoE

#	Scenario	Substructure design life	Turbine design life	Wind farm life	O&M	LCoE (EUR/MWh)	Lifetime average annual production [GWh]
1	base case	25 yrs.	25 yrs.	25 yrs.	Normal	37.3	4659
2	LTE overhaul	25 yrs. (O&M)	25 yrs. (O&M)	40 yrs.	Normal	33.4	4642
3	LTE sweat	25 yrs. (O&M)	25 yrs. (O&M)	40 yrs.	Sweat	33.4	4613
4	40 yrs. design life	40 yrs.	40 yrs.	40 yrs.	Normal	35.5	4628
5	60 yrs. swap rotor	60 yrs.	25 yrs. for rotor, 40 yrs. for nacelle & tower (O&M)	60 yrs.	Normal	34.6	4598
6	60 yrs. swap rotor & nacelle	60 yrs.	25 yrs. for rotor & nacelle, 40 yrs. for tower (O&M)	60 yrs.	Normal	34.8	4641
7	60 yrs. WTG repowering	60 yrs.	25 yrs. (O&M)	60 yrs.	Normal	35.0	4641
8	2 x 30 yrs. full farm replacement	25 yrs.	25 yrs. (O&M)	30 yrs.	Normal	33.6	4575

Figure 5-1 below shows the annual energy production range for each scenario. Scenarios 1 and 2 have O&M strategies which guarantee maximum availability and best turbine performance; however, this comes at a slight additional LCoE. The 40-year design life scenario and the 60-year replacement scenarios are run with O&M sweat strategies as this is more economically feasible. Changing any of these to an overhaul strategy would increase the lifetime minimum annual energy production and slightly increase the LCoE. The 60 years rebuild scenario has a period of zero production when the wind farm is decommissioned and a new wind farm is constructed.

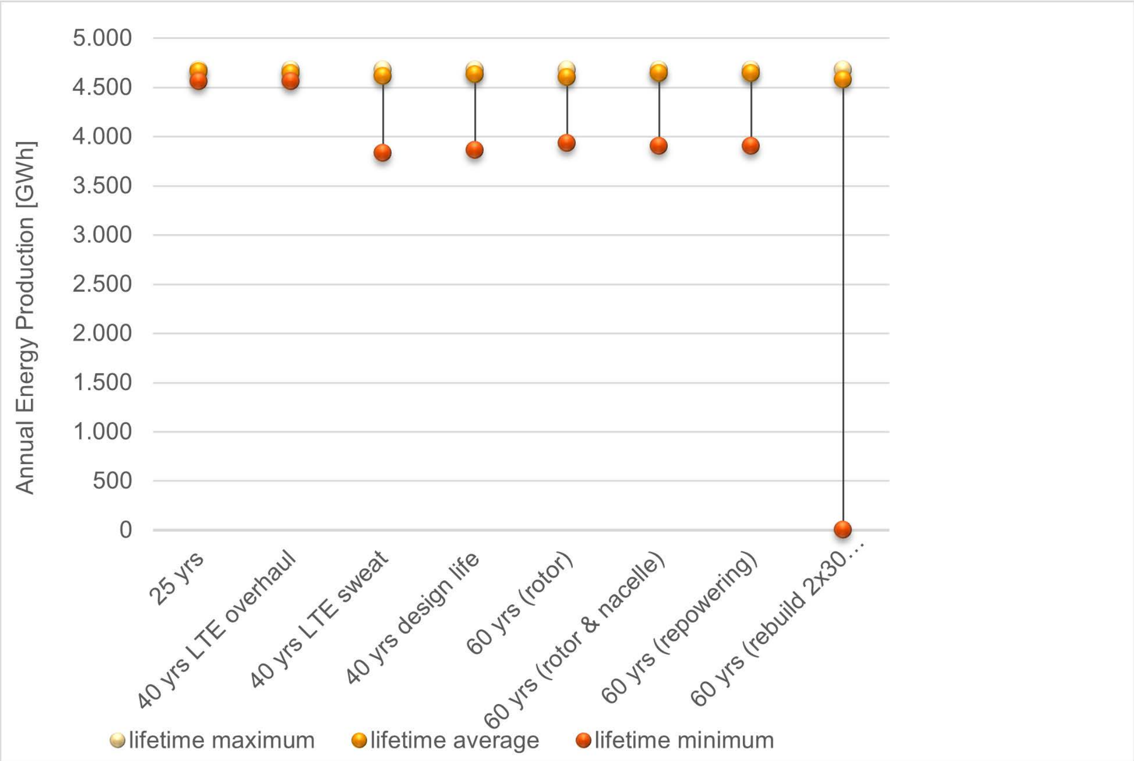

Figure 5-1 Annual Energy Production for different scenarios

5.1 Sensitivities

5.1.1 Impact of increasing discount rate

Based on a sensitivity analysis of the LCoE modelling, DNV has identified that the results are sensitive to the assumed discount rate. For the LCoE modelling, DNV has considered a discount rate of 6% which is considered as the base case. Due to the risks of the scenarios not being current standard, DNV recommends considering the impact of an increased discount rate of 8% on the LCoE modelling. Please see the table below summarising the impact of the increased discount rate on the results.

Table 5-11 Discount Rate Sensitivity

#	Scenario	Base case LCoE (EUR/MWh)	Increase discount rate LCoE (EUR/MWh)
1	Base case	37.3	42.4
2	LTE overhaul	33.4	39.2
3	LTE sweat	33.4	39.1
4	40 yrs. design life	35.5	41.8
5	60 yrs. swap rotor	34.6	41.1
6	60 yrs. swap rotor & nacelle	34.8	41.0
7	60 yrs. WTG repowering	35.0	41.1
8	2 x 30 yrs. full farm replacement	33.6	39.5

5.1.2 Impact of CapEx variation

The sensitivity of all scenarios to a 15% CapEx variation is shown in Figure 5-2. Varying the CapEx of any scenario by 15% changes the LCoE by 10.6% to 12.0%, which highlights how windfarms largely consist of an upfront investment and any variation in such directly affects the overall viability. However, DNV's experience shows that a 15% variation in CapEx is easily possible through variations in procurement prices, technological advancements, or complications in project execution. Considering these bands instead of singular values ultimately shows that the differences between the scenarios assessed are small in comparison to other potential variations.

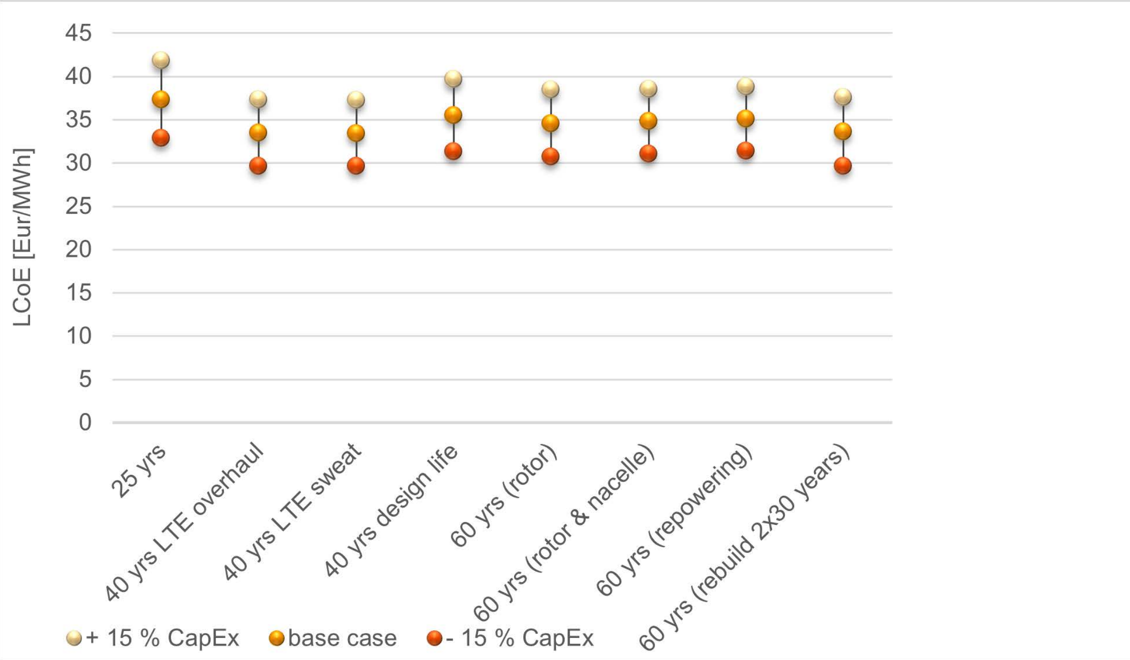

Figure 5-2 Sensitivity of LCoE to CapEx variation for all scenarios

6 Current Industry Trends

The world's first offshore wind farm was commissioned in Denmark in 1991, the 5 MW Vindeby offshore wind farm was successfully operated for 25 years and was decommissioned in 2017. The Vindeby project was designed for a 20-year life and was operated for an additional 5 years before decommissioning. Over the period from 2001-2003 the following offshore wind farms were commissioned in Denmark and the UK, Middelgrunden, Horns Rev 1, Rødsand I and North Hoyle. These wind farms are now reaching the end of their 20-year design life and a combination of either full wind farm repowering or life extension are being considered.

If the wind farm owner is able to maintain the lease, access to the grid and obtain consent, repowering of the site with the latest technology would enable the economic benefit of installing new larger offshore wind turbines on the site. Due to the increase in wind turbine size, repowering would require the full replacement of the old wind farm (wind turbines, foundations, and electrical balance of plant) and the potential reuse of some of the grid connection assets. Life extension of the wind farm would enable additional revenue from the existing project, with the potential requirement to vary the lease, grid connection and consent.

With the introduction of the 6-8 MW offshore wind turbines in 2015, the design life of offshore wind turbines was increased to 25 years and all current offshore wind farms are designed for a 25-year life. Based on lessons learnt from operating onshore wind farms beyond their design life, offshore wind farm operators and developers of existing and new projects are planning 5-15 years of life extension beyond the 25-year design life. The offshore wind industry considers that life extension of an offshore wind farm beyond the design life is technically feasible and standards have been developed to support the operation of offshore wind farms beyond their design life.

The offshore wind industry considers life extension in the operation and maintenance strategy for new projects under development to enabled projects to be more competitive in acquiring site leases through the increase in asset value. To date, DNV is not aware of wind farm developers considering increasing their design life beyond 25 years, as part of the life extension strategy.

Offshore wind turbines are currently designed and certified for a design life of 25 years and DNV is not aware of an offshore wind turbine manufacturer planning to deliver wind turbines with a design life above the current industry standard. Increasing the offshore wind turbine and project design life above 25 years is expected to increase project DEVEX and CAPEX. Additionally, based on discussions with financial advisors, increasing the asset design life beyond 25 years may have tax implications in some markets.

Based on current market trends Scenarios 2 & 3 (lifetime extension) are the current industry standard approach. DNV expects that this reflects the age and maturity of the industry, in that these approaches can be deployed with existing technology and assets, whereas alternative strategies involving variation at the design stage were not previously required and therefore have not yet been used. Now that the offshore wind industry has matured and is established as a viable long-term prospect, such strategies may come into play in continuing cost reduction efforts.

As detailed above for the ageing Danish and UK offshore wind farms, the duration of lifetime extension will depend on the risk and economics of repowering the site with new wind turbine technology. The following commercial and regulations items may impact when an operator would choose to repower a site:

- The ability to extend the site lease and project consent for life extension;
- The ability to maintain/vary the site lease and consent for repowering;
- The availability and lifetime of grid connection;
- Energy market; and
- Site lease fees.

Repowering will enable the site to benefit from the latest wind turbine technology to increase the value of the site. The advancements in wind turbine technology are expected to result in the requirement of new wind turbine foundations and wind farm electrical balance of plant. As it is not possible to instal a 20 MW wind turbine on a foundation and electrical balance of plant infrastructure designed for 15 MW wind turbine. Therefore, Scenario 7 – Repowering is currently not considered by the industry due to the rate of advancement in wind turbine technology. This Scenario could be considered in the future when the rate of advancement in wind turbine technology significantly reduces.

Due to future commercial and regulations conditions, highlighted above, it may not be economic to repower a project. Therefore, the operator may consider the replacement of wind turbine rotors or nacelles with the same size wind turbine to achieve a 40-60 year operational life, as detailed in Scenarios 5 and 6. This approach is generally not considered by the industry to the rate of advancement and cost reduction in offshore wind. This Scenario could be considered in the future when the rate of advancement in wind turbine technology significantly reduces.

7 Conclusions and recommendations

DNV has undertaken technical LCoE modelling of Scenarios 1-8 for RVO, considering the impact of increasing the operational life of an offshore wind farm from 25 years up to 60 years. The modelling considered the technical aspects of each scenario based on the assumptions detailed in Section 3. DNV has not considered commercial, regulatory or legal aspects in the LCoE analysis. The main conclusions are summarised below:

1. It is technically feasible to operate an offshore wind farm beyond the current industry standard design life of 25 years;
2. The results of the analysis show all scenarios of a longer operational life result in a similar reduction in LCoE over the base case for a 25-year offshore wind farm, as shown in Section 5;
3. The results are based on a number of technical assumptions as detailed in Section 3 and are subject to uncertainty. Based on the level of uncertainty in the results DNV considers there is no clear optimum scenario between life extension (Scenarios 2 & 3), increased design life (Scenarios 4-7) and full wind farm replacement (Scenarios 8);
4. The sensitivity analysis detailed in Section 5 shows the results are highly sensitive to discount rate;
5. The current industry trend is life extension, extending the operational life of offshore wind farms by 5-15 years beyond the certified design life (Scenarios 2 & 3), as discussed in Section Current Industry Trends6. When designing wind turbines and foundations, a certified design lifetime of 25 years is typically assumed. Extension of the operational lifetime can be justified from both a technical and an economic point of view. However, it should be noted that there is uncertainty in the duration of life extension, OPEX and availability of offshore wind farms operating beyond their certified design life;
6. There are technical and commercial risks associated with Scenarios 4-7 due to the rate of development of new wind turbine technology and the commercial availability of offshore wind turbines with a design life longer than the industry standard of 25 years. DNV notes that significant European market coordination and standardisation may be required to enable the market to move to offshore wind turbines with a design life longer than 25 years;
7. The full wind farm repowering after 30 years would allow the site to benefit from future wind turbine technology (Scenario 8). Additional work would be required to confirm the optimum lease duration for two wind farms, due to the time taken to decommission and construct the second wind farm. There is additional uncertainty in the optimum lifetime of each single wind farm, as life extension has shown to reduce LCoE.
    - It is noted that this scenario assumes that a developer is awarded exclusive rights for the 60-year duration of the lease, which enables the optimal lifetime of two wind farms to be aligned. If the development rights were to be

re-opened prior to the construction of the second project, it would be expected that the first project would initiate lifetime extension efforts to maximise value from both the wind farm and the lease period.

8. The commercial and regulations framework will need to support the selected future site lease scenario to reduce the development risks; and
9. DNV recommend RVO continue with industry stakeholders to discuss changes to site leases.

Overall, each scenario shows benefit, but there are enough uncertainties that mean there is no clear single optimum and that DNV considers continued stakeholder engagement to be a possible next step.

7.1 Model uncertainties

Based on the study DNV has identified the following gaps in knowledge in the LCOE analysis and uncertainty in the modelling:

1. Interface between site lease, grid connection and lifetime of the wind farm.
2. Environmental, Social and Governance impact of each scenario.
3. Offshore wind is projected to reduce in cost by approximately 40% by 2050, hence more research is required into the level and impact of cost reduction and optimum lease duration to enable full wind farm repowering.
4. The duration of life extension, and OPEX and availability during life extension, are considered as a knowledge gap;
5. The commercial availability of offshore wind turbines with a design life longer than 25 years;
6. Foundation inspection, maintenance and overhauls for a 40-60 year operational life;
7. Reliability of 66kV array cables beyond design life of 25 years; and
8. Reliability of the export system for a 40-60 year operational life.

7.2 Priorities for future research and innovation

Based on the study DNV has identified the following future research and innovation priorities for the identified gaps in knowledge. For each area DNV has assessed the Technology Readiness Levels (TRL), as summarised below;

1. The duration of life extension which can be achieved on an offshore wind farm [TRL 7/8];
2. The reliability of offshore wind farms in later life and during life extension [TRL 7/8];

3. Technical and commercial requirement to increase the design life of offshore wind turbines [TRL 7/8];
4. Foundation inspection, maintenance and overhauls for a 40-60 year operational life [TRL 7/8];
5. Reliability of 66kV array cables beyond design life of 25 years [TRL 7/8];
6. Lifetime of the offshore grid connection for 60 year wind farm life [TRL 7/8];
7. What is the optimum offshore grid connection solution for full wind farm repowering [TRL 7/8]; and
8. Reliability of the grid connection asset for a 40-60 year operational life [TRL 7/8].

Technology Readiness Levels (TRLs) are a measure of a technology's qualification development state. The technology readiness level can be defined both for a system and for components. The scale varies from rough ideas to field proven technology, and the level is normally determined by the amount or scale of performed tests. TRLs can be used to map out the phases of a technology qualification programme, providing that they include sufficient detail, including the acceptance criteria for each level.

Technology readiness levels have been defined for different innovative industries such as automotive, aviation or oil and gas industries. The defined levels provide a general indication of the development stages and comparability of novel technologies. The rating of technology readiness levels of floating wind turbines applied in this service specification refers to the definition of the European Union in Horizon 2020 - Work Programme 2014-2015 General Annexes, Extract from Part 19 - Commission Decision C(2014)4995. Certification services support the achievement of specific TRLs and are directly linked to the defined technology development stages, see Figure 1-4.

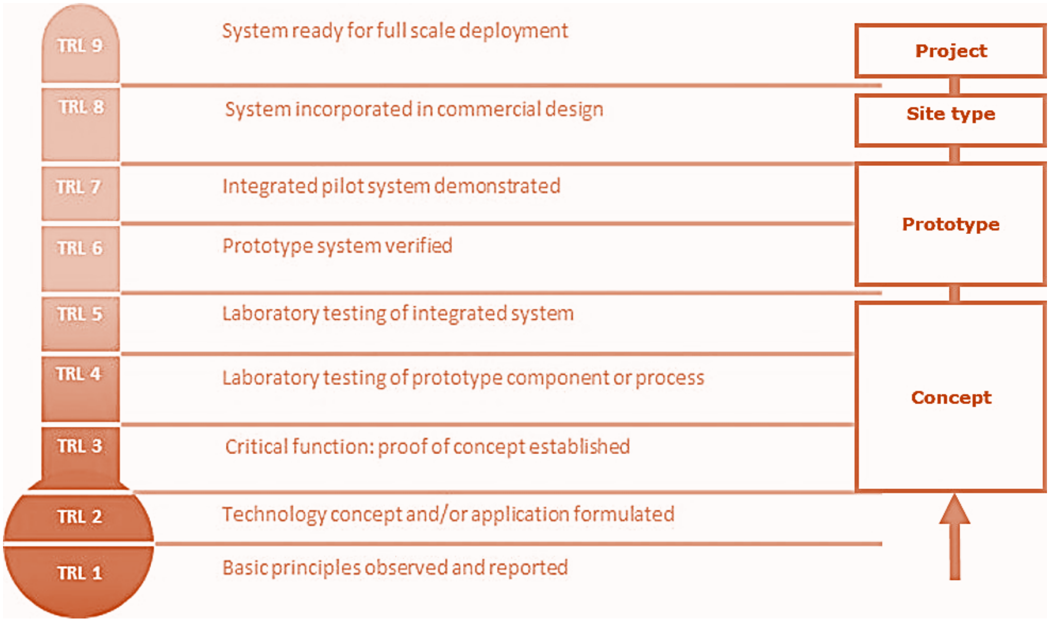

Figure 7-1 Technology readiness levels according to EU definition and corresponding certification levels

8 References

/1/ Gaertner, Evan, et al. *IEA wind TCP task 37: definition of the IEA 15-megawatt offshore reference wind turbine*. No. NREL/TP-5000-75698. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2020.

/2/ DHI for Rijksdienst voor Ondernemend Nederland (RvO.nl), *Metocean desk study and database for Dutch Wind Farm Zones*, March 2019 https://offshorewind.rvo.nl/file/download/55039978, 29/10/2021

/3/ https://eto.dnv.com/2021

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