TKI WIND OP ZEE
Topsector Energie

The Netherlands' Long-Term Offshore Wind R&D Agenda

9 October 2019

The Netherlands' Long-Term Offshore Wind R&D Agenda was initiated by the TKI Wind op Zee (Top consortium for Knowledge and Innovation Offshore Wind). The content was delivered by energy transition and offshore wind experts and researchers from the Dutch knowledge infrastructure. The content represents the views of the authors and does not necessarily align with the TKI Wind op Zee view. This R&D agenda provides input for future R&D programming.

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Foreword

Offshore wind energy is set to make a significant contribution to Europe's entire energy system. The Netherlands has ambitious plans and can potentially realize between 35 GW and 75 GW of offshore wind capacity by 2050. This target entails significant challenges. From a research and development perspective, it necessitates significant efforts in several areas. Simply continuing to improve current technology will not be sufficient to achieve these challenges; major breakthroughs are essential.

In order to facilitate a cost effective and secure energy system, wind turbines and wind farms need to be reliable and productive. The power system of today is based on the premise that consumer demand is met by a relatively small number of power stations that can adjust their output as and when required. We are now transitioning to a system with a much larger number of smaller power stations which cannot necessarily be dispatched at will and provide less physical inertia to the electricity network than existing thermal generators. Offshore wind farms, though lacking the dispatch capability of a fossil-fuelled power station, can provide significant amounts of power. The operation of a large number of offshore wind farms in the North Sea will require new thinking in terms of how to manage the variable power flows over large distances and ensure security of supply. There is still much that can be done to make offshore wind farms better able to follow demand and to provide inertia to the grid. This will be done by more advanced control than at present and a better understanding of the wind conditions.

Understanding the wind conditions is also important from the point of view of optimizing the lifetime of the turbines by reducing fatigue loading, again through advanced control. At the same time, the development of new materials and manufacturing methods to make the machines cheaper, lighter, yet more robust will be necessary. Scale-up will require innovations in turbine design while minimizing weight and material requirements. Foundations, for example, are a significant share of the cost of building a wind farm and R&D will be needed particularly in the area of modular design. The management of large fleets of offshore machines presents another challenge in terms of operations and maintenance. Research in this field will need to consider the role of new sensor technology and the analysis of large datasets to provide timely information to a range of stakeholders. Automation and robotics will play an increasing part in the construction, operations and maintenance and indeed the decommissioning of future wind farms. The environmental impact of a large-scale rollout of offshore wind energy in the North Sea also demands significant attention. Research to quantify both positive and negative impacts, manage them and mitigate them where possible during the construction, operation and decommissioning phases will be crucial.

Although much work remains to be done to realize the transition to a net zero-carbon emission energy system, we are fortunate to have world-class research expertise to support the industry in meeting the Dutch government's targets and promote offshore wind power as a key player in the energy transition for the Netherlands. This document sets out in detail the long-term R&D agenda required until 2030 to enable our future transition to a clean and efficient energy system by 2050.

Simon Watson
Director DUWIND, Delft University of Technology

Executive summary

The Netherlands' Long-Term Offshore Wind R&D Agenda sets out the requirements for future knowledge and technology at the lower technology readiness levels (TRLs) that are considered vital for a large rollout of offshore wind power capacity by 2050. The agenda spans the period 2020-2030.

With the recent cost breakthroughs, offshore wind is now established as a crucial pillar of the Dutch energy transition. Developing an affordable, low-carbon energy system in the Netherlands necessitates a large-scale rollout of offshore wind power capacity in the Dutch part of the North Sea – to potentially 35-75 GW by the year 2050. Tough challenges will have to be addressed to successfully roll out such a vast amount of offshore wind power capacity:

- **Costs** – The levelized cost of energy (LCOE) of offshore wind power, and the cost of integrating the generated electricity into the energy system, need to be lowered even more to make offshore wind fully competitive with fossil-fuelled energy technologies, to enable the industrial electrification required, and to keep the energy transition affordable for consumers
- **Rollout** – Achieving a rollout of 2.5 GW per year requires a step change in volumes in a market that is rapidly expanding on a global scale, and requires further industrialization and capacity in the supply chain
- **Supply security** – To provide the lion's share of all of our electricity by 2050, offshore wind has to be a 100% reliable source of energy. This requires further developments in system integrity, availability and balancing capabilities
- **Spatial planning** – Offshore wind farms compete for limited offshore space, and must be optimally planned with, around and between the other users of the North Sea
- **Environment** – To achieve the rollout objectives, the negative environmental impact of offshore wind farms must be mitigated (e.g. bird collisions) and their positive impact enhanced (e.g. oyster beds among wind farms)
- **Public support** – Current public resistance in the Netherlands to onshore wind energy demonstrates that public support for the large capacity rollout of offshore wind power in the North Sea is a "conditio sine qua non"
- **Safety** – A zero-incident target must be in place to maintain and improve personnel safety during the manufacturing, installation, operation and decommissioning of offshore wind farms

The Topconsortium for Knowledge & Innovation Wind op Zee initiated the development of this truly ambitious R&D agenda to meet these challenges. Its contents were delivered by offshore wind experts and researchers from the Dutch knowledge infrastructure and are related to the Integral Knowledge and Innovation Agenda (IKIA) of the Dutch Climate Agreement. The agenda provides input for future R&D programs.

1 Introduction

The recent cost breakthroughs have thoroughly established offshore wind power as a crucial pillar of the Netherlands' energy transition. Developing an affordable, low-carbon energy system in the Netherlands – with a 95% reduction in CO_2 emissions by 2050 in line with the Paris climate agreement – necessitates a large-scale rollout of offshore wind power capacity in the Dutch part of the North Sea, one of the most densely used stretches of sea in the world. Several on and offshore wind energy R&D agendas and programs already exist, but no R&D agenda has yet been developed that specifically caters to large-scale offshore wind capacity expansion. TKI Wind op Zee has taken the initiative on this truly ambitious offshore wind R&D agenda, which spans the period 2020-2030 and proposes the development of the knowledge and technologies indispensable to the large capacity rollout that we need.

The Netherlands' Long-Term Offshore Wind R&D Agenda provides input to the low TRL part of the *Meerjarig Missiegedreven Innovatieprogramma* ("MMIP"), which has been developed as part of the new Dutch Climate Agreement. As such, for its technological content, the agenda focuses on R&D activities in the lower TRL levels (see figure 1).

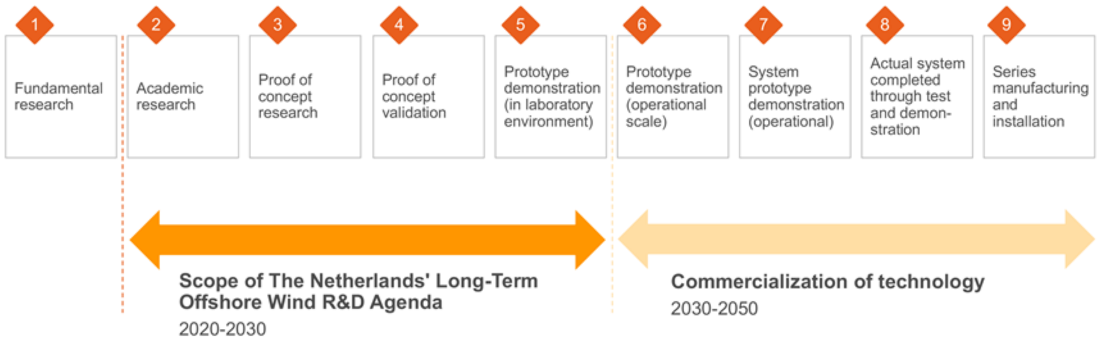

Figure 1 – TRL[1] scope of the technological content of the R&D agenda

1 Technology readiness levels according to the EU Commission

2 Developing the R&D agenda together

The Netherlands' Long-Term Offshore Wind R&D Agenda was developed by energy transition and offshore wind experts, together with a large group of researchers from the Dutch knowledge infrastructure. To develop this R&D agenda, a three-step "backcasting" approach was used (see figure 2):

- **Vision for the year 2050** – We developed a vision for the state of offshore wind in the year 2050, defined as a set of so-called "beacons", and the challenges to achieving this vision
- **Milestones 2030** – We extrapolated scientific and technological achievements, or "milestones", that should be accomplished by 2030 in order to reach one or more of the beacons by 2050. Milestones are particularly challenging to achieve. Each contributes significantly to at least one, though preferably several, of the beacons
- **R&D topics 2020-2030** – Finally, we identified the gaps between the current scientific and technological state-of-the-art and the milestones. R&D topics to close these gaps were proposed. Together, these R&D topics form The Netherlands' Long-Term Offshore Wind R&D Agenda

Figure 2 – "Backcasting" approach to forming the R&D agenda

The vision was developed in September 2018 in a workshop with a group of energy transition, offshore wind and other experts from academia, knowledge institutes, government and industry. We then involved researchers from scientific disciplines directly related to offshore wind who could provide valuable insights into how to address the offshore wind challenges until 2050. Because this process necessitates out-of-the-box thinking, we also involved scientific disciplines that are not already directly related to the wind industry and where Dutch expertise is world class. The goal was also to ensure that the R&D agenda would include technological development necessary for integrating offshore wind into the energy system and the natural environment, e.g. power-to-hydrogen electrolysis for storage and transport, or natural reefs for scour protection. Disciplines beyond science were also involved in the discussions, such as ethics, regulation and economics (see figure 3).

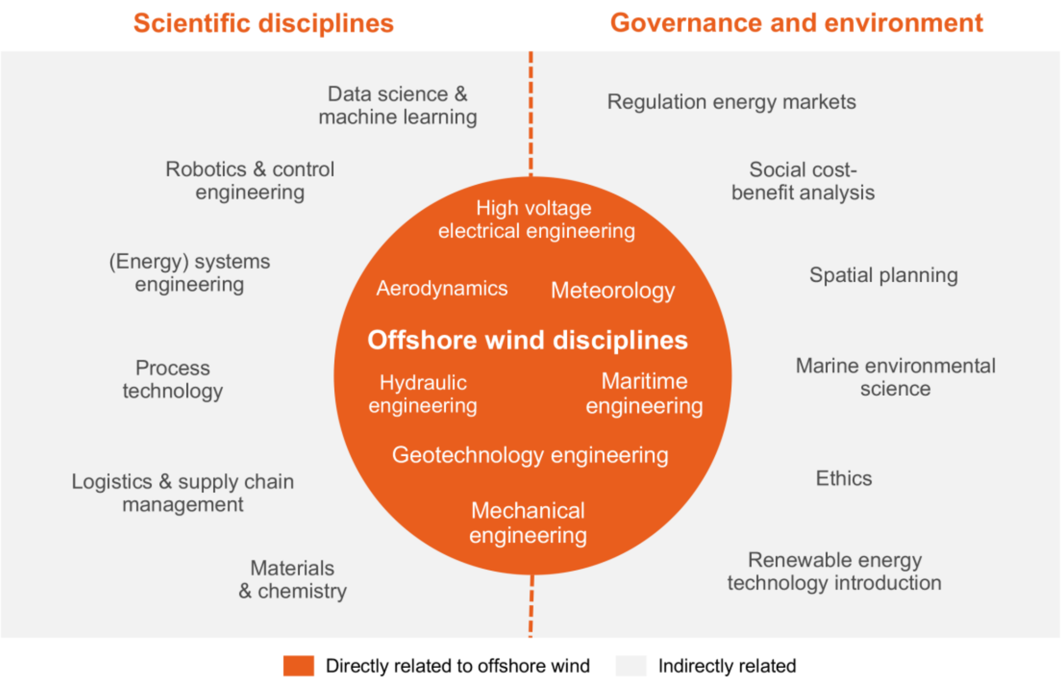

Figure 3 – Scientific and other disciplines involved in the vision development

Three workshops were organized with researchers in April and May of 2019 to develop the milestones and the R&D topics. Figure 4 lists the workshop participants, who thereafter wrote the milestones. Authors are specified per milestone in chapter 5.

Author	Discipline	Organization
Henk Akkermans	Supply chain management	Tilburg University
Peter Alderliesten	Process Engineering	TKI Energie & Industrie
René Alderliesten	Aerospace structures & materials	Delft University of Technology
Sukanta Basu	Atmospheric turbulence	Delft University of Technology
Pavol Bauer	Electrical engineering & networks	Delft University of Technology
Wouter Beelaerts van Blokland	Operations and production management	Delft University of Technology
Roeland de Breuker	Aerospace structures & materials	Delft University of Technology
Jianning Dong	Electrical engineering & networks	Delft University of Technology
Clemens Dransfeld	Aerospace structures & materials	Delft University of Technology
Santiago J. Garcia	Novel aerospace materials	Delft University of Technology
Roger Groves	Inspection & monitoring systems	Delft University of Technology
Annelies Huygen	Energy market regulation	TNO
Harm Jeeninga	Energy innovation	TNO
Roland van de Kerkhof	Supply chain management	HAME/ NIOZ/ WUR-AEW
Han Lindeboom	Marine environmental science	Tilburg University

Author	Discipline	Organization
Andrei Metrikine	Offshore & structural engineering	Delft University of Technology
Mohamad Ghaffarian Niasar	Electrical engineering & networks	Delft University of Technology
GerJan Piet	Marine environmental science	Wageningen Marine Research
Han La Poultré	Smart energy systems	Centrum Wiskunde & Informatica
Pavel Purgat	Electrical engineering & networks	Delft University of Technology
Zian Qin	Electrical engineering & networks	Delft University of Technology
Tim Raaijmakers	Offshore & hydraulic engineering	Deltares/ Delft University of Technology
Laura Ramirez Elizondo	Electrical engineering & networks	Delft University of Technology
Erik-Jan de Ridder	Maritime & hydrodynamic engineering	MARIN
Armando Rodrigo Mor	Electrical engineering & networks	Delft University of Technology
Stephan Rutten	Robotics	Delft University of Technology
Novita Saraswati	Offshore wind farm installation and O&M	TNO
Thiago Bastista Soeiro	Electrical engineering & networks	Delft University of Technology
Richard Stevens	Nummerical simulations of turbulence	University of Twente
Behnam Taebi	Energy ethics	Delft University of Technology
Julie Teuwen	Windturbine blade structures & materials	Delft University of Technology
Jose Rueda Torres	Electrical engineering & networks	Delft University of Technology
Ton Veldkamp	Windturbine technology	TNO
Olaf Waals	Maritime/ hydraulic engineering	MARIN
Jan Willem Wagenaar	Wind energy measurements	TNO
Simon Watson	Wind energy systems	Delft University of Technology
Edwin Wiggelinkhuizen	Wind energy technology	TNO
Jan Willem van Wingerden	Wind turbine control	Delft University of Technology

Figure 4 – Milestone authors and participants in April/May 2019 workshops

3 Offshore wind in the year 2050

In July 2016, the average winning strike price of the Borssele I and II wind farms tender was announced at EUR 73/MWh – which surprised almost everyone in the industry. The grid connection costs were published at EUR 14/MWh, leading to a total cost of EUR 87/MWh. Since then, even lower strike prices have been announced, with recent records of EUR 44/MWh (excluding grid connection) for the Dunkirk wind farm, and EUR 45-47/MWh (2012 prices, including grid connection) for the UK Round 3. Subsidy-free wind farms have been awarded in tenders in the Netherlands and Germany. Figure 5 presents the strike price development at the year of final investment decision (FID).

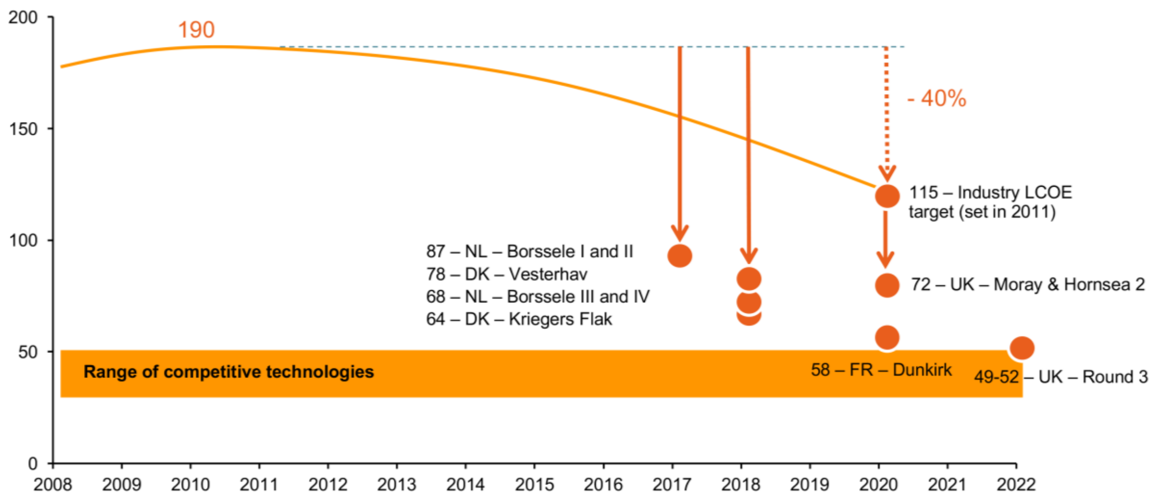

Figure 5 – Strike prices and LCOE[2] target [EUR/MWh, 2018 prices, FID, incl. grid connection]

After the first strike prices at these low levels were published, questions arose as to whether these price levels were sustainable. After all, they could have been the result of cyclical developments in the economy, like interest rates and prices for oil and steel. To understand what really lies behind the very low strike price of the Borssele tender, the main cost drivers were analysed, their impact on the LCOE, and how they have changed over time. To illustrate the impact of these cost drivers, figure 6 compares them at the time of the Borssele tender in 2016 with the circumstances at the non-competitive first round of contracts for difference in the UK in 2014, which awarded subsidies to five different wind farms. This comparison reveals that most of the changes in the main cost drivers were structural. It can thus be concluded that the current price levels are sustainable, even though prices may go up somewhat if the interest rate and prices for oil and steel rise in the future.

2 The industry LCOE target was set by the Crown Estate in 2011: 100 GBP/MWh for final investment decision (FID) in 2020. FID is typically 2 years before full operation. An estimated average of 14 EUR/MWh is added for the grid connection. UK strike have been indexed to the year 2018. The zero-subsidy wind farms in the Netherlands and Germany are not included in the figure. Source: Crown Estate, RVO, press clippings; Roland Berger analysis

		UK – 2014 First round CfD	NL – 2016 Borsele I and II	Indicative impact on LCOE
	Strike prices [EUR/MWh, incl. grid]	**170-188**	**87**	
STRUCTURAL	Track record [TWh]	104	180	↘↘↘
STRUCTURAL	Technical/operational innovation	Ongoing	Ongoing	↘↘
STRUCTURAL	Bankable turbine suppliers [#]	1	3	↘↘
STRUCTURAL	Turbine capacity [MW]	3-4	7-8	↘↘
STRUCTURAL	Competitive bidding for subsidy	No	Yes	↘↘
STRUCTURAL	Pipeline and support certainty	No	Yes	↘↘
STRUCTURAL	Grid connection certainty	No	Yes	↘
STRUCTURAL	Wind farm capacity	90-400	700	↘
CYCLICAL	Interest base rate [German bond 10 years]	~2%	~0%	↘↘↘
CYCLICAL	Steel price [EUR/t]	410-450	320-340	↘
CYCLICAL	Oil price [Brent, USD/bbl]	57-107	36-50	↘

Figure 6 – Comparison of main cost drivers between 2014 and 2016[3]

Due to this sustainable cost breakthrough, offshore wind is now established as a crucial pillar of the Netherlands' energy transition. The European Commission has calculated that 240-450 GW of offshore wind energy is needed to decarbonize the European energy sector by 2050. In the Esbjerg declaration of June 20, 2019, energy ministers of the North Sea countries declared their ambition to accelerate the deployment of offshore wind. According to a PBL-ECN scenario[4], a successful transition to a low-carbon energy system in the Netherlands (a 95% reduction in CO_2 emissions in line with the Paris climate agreement) will see 61% of electricity generation coming from offshore wind, necessitating the installation of between 35 and 75 GW of offshore wind by 2050. In the Dutch Climate Agreement, a capacity rollout of 1 GW/year has been agreed. The pace will have to be increased to 2.5 GW/year in the 2030-2050 period. Depending on the actual scale, by 2050, offshore wind may cover 17-26% of the Dutch Exclusive Economic Zone (EEZ) in the North Sea (figure 7).

3 Source: Roland Berger analysis
4 Source: PBL-ECN: The future of the North Sea, Scenario IV "Sustainable Together" estimates 17-26% surface coverage of the Dutch EEZ by 2050

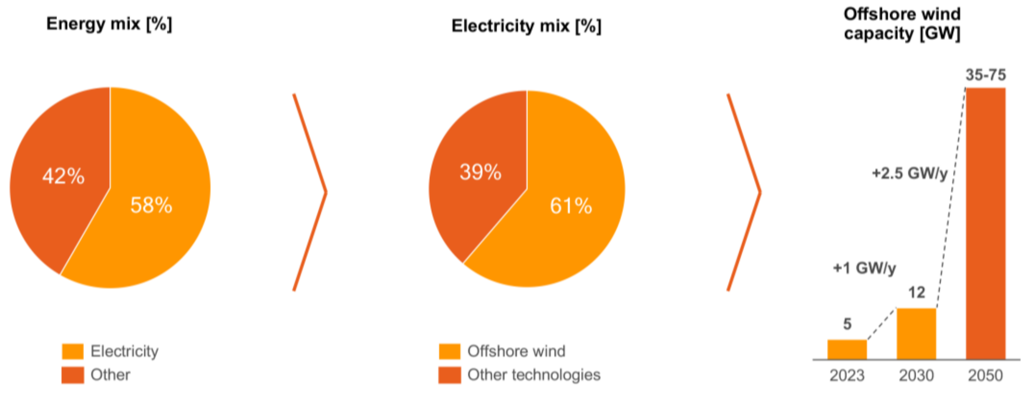

Figure 7 – Offshore wind capacity in the Dutch EEZ, 2023-2050[5]

Tough challenges will have to be addressed to successfully roll out this vast amount of offshore wind power capacity (see figure 8):

- **Costs** – The levelized cost of energy (LCOE) of offshore wind power, and the cost of integrating the generated electricity into the energy system, need to be lowered even more to make offshore wind fully competitive with fossil-fuelled energy technologies, to enable the industrial electrification required, and to keep the energy transition affordable for consumers
- **Rollout** – Achieving a rollout of 2.5 GW per year requires a step change in volumes in a market that is rapidly expanding on a global scale, and requires further industrialization and capacity in the supply chain
- **Supply security** – To provide the lion's share of all of our electricity by 2050, offshore wind has to be a 100% reliable source of energy. This requires further developments in system integrity, availability and balancing capabilities
- **Spatial planning** – Offshore wind farms compete for limited offshore space, and must be optimally planned with, around and between the other users of the North Sea
- **Environment** – To achieve the rollout objectives, the negative environmental impact of offshore wind farms must be mitigated (e.g. bird collisions) and their positive impact enhanced (e.g. oyster beds among wind farms)
- **Public support** – Current public resistance in the Netherlands to onshore wind energy demonstrates that public support for the large capacity rollout of offshore wind power in the North Sea is a "conditio sine qua non"
- **Safety** – A zero-incident target must be in place to maintain and improve personnel safety during the manufacturing, installation, operation and decommissioning of offshore wind farms

5 Source: PBL-ECN: The future of the North Sea, Scenario IV "Sustainable Together" estimates 17-26% surface coverage of the Dutch EEZ by 2050

Challenges	Description
Costs	> Further reduce costs for full competitiveness with fossil energy technologies
Rollout	> Achieve timely rollout of necessary capacity
Supply security	> Safeguard 100% supply security
Spatial planning	> Use acceptable amount of space in the North Sea, and plan optimally
Environment	> Achieve net positive impact on the environment
Public support	> Achieve strong public support for the capacity rollout
Safety	> Achieve 100% safety during manufacturing, installation, operation and decommissioning

Figure 8 – Challenges to the 35-75 GW offshore wind capacity rollout by 2050

In the vision for offshore wind in 2050, all of these challenges will have been overcome. To describe this target in concrete terms, several "beacons" were defined:

- **Low cost from larger turbine size** – By 2050, turbines will have reached their maximum size. Increasing the rated power of turbines has been the most important way to reduce costs to date. Experts agree that the laws of physics and economics will eventually put an ultimate limit on the size of turbines – but experts do not agree on what that limit is, given current turbine design. Some expect that a turbine size of 25 MW will be possible by the year 2050. Others are even working on a concept for a 50 MW turbine[6]. Radically alternative turbine designs may facilitate the development of even larger ones
- **Low cost from standardized turbine platform** – In an analogy to large commercial aircraft, the industry may freeze the move to larger turbines by way of a standardized turbine platform, avoiding the risks and expenses of the development of even larger sizes, and reap significant benefits from modularity and standardization in the supply chain. Floating foundations can facilitate such standardization, as they do not require a bespoke design for different water depths and seabed conditions. Experts in the September 2018 workshop suggested that such a standardized platform could be achieved at a 15 MW turbine size by the year 2030. They also suggested that turbines be designed for a 25-year lifetime, while support structures last 50 years. Thus, wind farms can be repowered without having to invest in new support structures at each end-of-lifetime cycle
- **Optimal wind farm design** – Optimization of wind farm design will significantly increase energy output and reduce the amount of space required. It will also reduce the LCOE of the wind farm
- **Optimal integration into energy system** – Offshore wind energy forms an important and integral part of the entire energy system
- **Full international interconnectivity** – All countries around the North Sea will have fully integrated their energy markets by 2050. This will be facilitated though a network of submarine interconnectors that are integrated with the wind farm grid connections
- **Supply chain efficiency** – By the year 2050, the wind farm supply chain will resemble the automotive supply chain. Manufacturing, installation, operation, maintenance and

6 https://www.colorado.edu/ecee/2016/02/17/paos-morphing-wind-turbine-inspired-nature

decommissioning of wind farms will be highly efficient. This will require standardized design of components, automation of manufacturing processes and seamless logistics

- **Zero breakdown** – All wind farms will achieve 100% uptime by 2050, e.g. export cables will no longer be disrupted by fish trawler nets. Today, while their turbines achieve well above 95% uptime, offshore wind farms and their grid connections are still far from achieving zero breakdown
- **Strong support from stakeholders** – Through effective consultation and alignment processes, all stakeholders will strongly support the capacity rollout: the offshore energy sector, shipping, fisheries, defence, tourism, NGOs, etc.
- **Net positive impact on the environment** – The positive effects of wind farms on the environment (e.g. reformation of the original North Sea fauna and habitat among wind farms) will outweigh their negative effects (e.g. bird collisions)
- **Adequate availability of human capital** – By 2050, the industry will have sufficient human capital available thanks to education and training efforts. The availability of human capital, in particular in the technical disciplines, is indispensable to a successful rollout

Figure 9 charts how the beacons address the challenges of the capacity rollout.

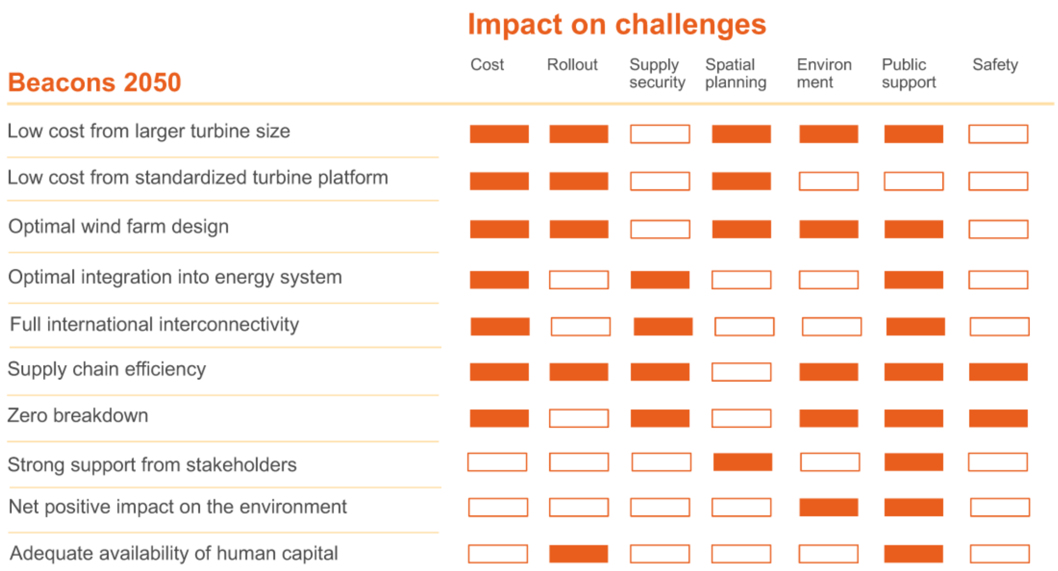

Figure 9 – Impact of the beacons on the challenges

4 The Netherlands' Long-Term Offshore Wind R&D Agenda

The R&D agenda is shaped by a collection of milestones that have to be reached by the year 2030 in order to realize the beacons by the year 2050. The gaps between the current scientific and technological state-of-the-art and the milestones have been defined, and R&D topics to close these gaps are proposed. Together, these R&D topics form The Netherlands' Long-Term Offshore Wind R&D Agenda[7].

Inspired by the 2050 vision for offshore wind, the authors developed milestones for 2030 in each of their fields of expertise. Below, the milestones and corresponding R&D topics are categorized into nine main topics: turbines; wind farms; electrical systems and grid connection; materials; integration into energy system; inspection, monitoring and diagnostics; supply chain; environment; and governance.

4.1 Turbines

Due to scale economies, the size of offshore wind turbines has increased rapidly in recent years. Today, the largest turbine model being developed has a rated power of 12 MW. While this trend is expected to continue over the coming years for the currently dominant turbine design, it is not clear how turbines will develop over the longer term. Radically alternative designs may disrupt this development path. In an analogy to large commercial aircraft, the industry may, for example, freeze growth by standardizing the turbine platform, avoiding the risks and R&D expense of even larger sizes, and reaping significant benefits from modularity and standardization in the supply chain. The milestones in this section propose R&D into several of these potential long-term technology developments. The components of a typical offshore wind turbine are presented in figure 10.

7 The R&D agenda is related to the Integral Knowledge and Innovation Agenda (IKIA). Its contents represent the views of the authors themselves, and provide input for future R&D programming

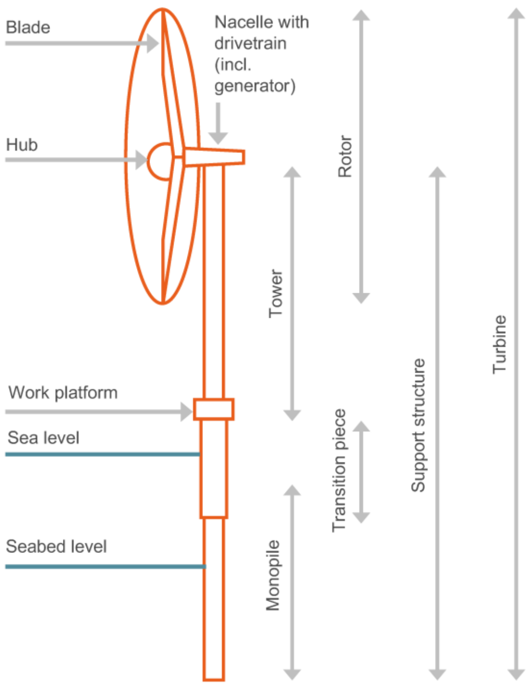

Figure 10 – Offshore wind turbine components[8]

Milestone 1 – Optimal turbine size
In order to determine the optimal size for offshore wind turbines, research is proposed in the following fields: aerodynamics, hydrodynamics, structural design, logistics, O&M and cost modelling throughout the supply chain.

Milestone 2 – Alternative drivetrain designs
Innovative drivetrain concepts, such as a hydraulic, permanent magnet-free and modular generator system, can reduce costs, enhance reliability and provide fault tolerance for the wind turbine drivetrain. Research into alternative generation technology, as well as into the technology and tools to design and model such alternatives, is proposed.

Milestone 3 – Alternative designs for turbine topology
Turbine topology design can cover the generator as well as the support structure. Novel designs for the generator can lower costs: airborne wind energy systems, multi-rotor designs, secondary rotor designs, two-bladed downwind designs and vertical axis designs, to name a few examples. Alternative support structures have the potential to reduce the volume of materials required and to ease deployment. It may also be beneficial to move to floating structures even in relatively shallow water depths, due to standardization and lower installation costs.

Milestone 4 – Modular approach for turbine design
Most modern offshore wind turbines are single model designs, with few components applied across models. Significant cost reductions from a more industrialized supply chain can be achieved if turbines are designed with standardized components. Furthermore, as turbines get larger, the logistical challenge in terms of their offshore installation becomes greater, requiring

8 Illustration source: "Analysis and design of monopile foundations for offshore wind-turbine structures", Marine Georesources and Geotechnology, January 2015

larger vessels and cranes for transportation and lifting. Designing turbines in smaller, standardized modules can reduce transport and installation costs. Milestone 35 in chapter 4.7 proposes specific research into joining methods for modular blades.

Milestone 5 – Optimal dynamic equilibrium for support structures
Milestone 6 – Active control devices for support structures

Wind turbines are currently designed such that the optimal energy yield and the longest service life are achieved when the support structure and the blades of the turbine are fatigued as little as possible (i.e. when vibration is minimized). The current state-of-the-art for reducing fatigue loads includes dynamic blade pitching to mitigate the loading of the support structure or the use of passive dampers in the tower. For the design of even larger turbines, it may be advantageous to have all turbine components function optimally when in certain dynamic (oscillating) equilibrium (milestone 5). The next step would be active control devices to suppress the most damaging vibration patterns in the support structure (milestone 6).

Milestone 7 – Scalability of floating structures for wind and solar

Offshore floating support structures will grant access to deeper waters and to more steady and higher wind speed regions in the ocean. However, limited experience in floating wind turbine structures makes it a very costly solution. Research should focus on novel high-fidelity design models which can accurately model the complete systems. Furthermore, it should be possible to model the integration of floating solar panels into offshore wind farms.

Milestone 8 – Critical failure state design of support structures

The suboptimal design of wind turbine support structures leaves a lot of room for further reductions in materials and thus costs. In current design practice, the individual safety factors used for loads and strengths have a chain effect on the material volumes used in the support structure, from rotor and nacelle to the base. Current load cases, for example, consider worst case scenarios that have a very low probability of occurrence. Milestone 8 aims to optimize the support structure design and achieve minimal material use by exploring the critical failure limits through a commercial-scale pilot. Such a pilot could also be used to demonstrate other technical innovations; in fact, the rarity of such an opportunity to demonstrate innovations in a full-scale offshore pilot is often the reason why valuable innovations never reach the market. Figure 11 depicts the milestones in turbines as they relate to the beacons.

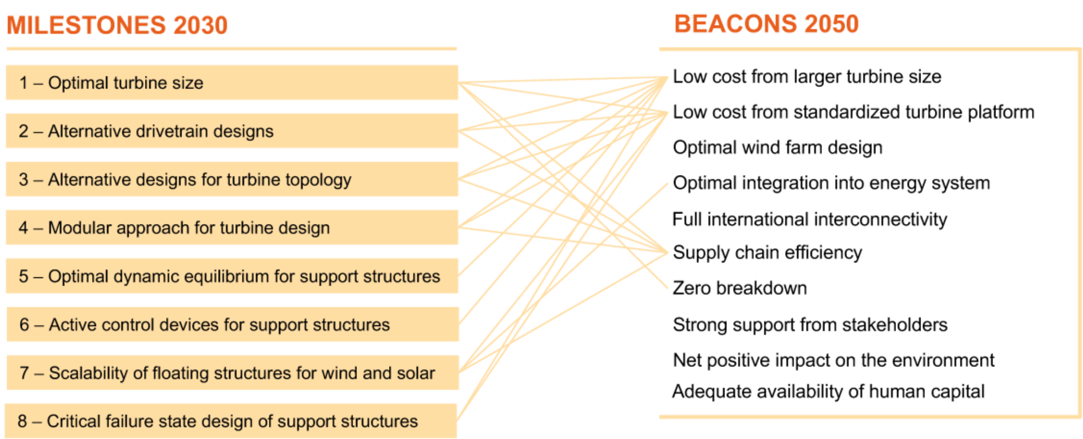

Figure 11 – Turbine milestones as they relate to the beacons

4.2 Wind farms

The ambitious plans for offshore wind power will require a significant slice of the Dutch part of the North Sea. Offshore wind developments need to share space with other sea users, like fisheries, oil and gas exploration and exploitation, shipping, the military, and those who use the sea for recreational purposes. Wind farms should use the available space and wind inflow as efficiently as possible. First, a meticulous characterization of the wind inflow and its interaction with the wind farm has to be made. This will inform the optimal design, layout and control of individual turbines within that wind farm. An integrated approach may lead to variations in design, hub height and rated power of the turbines across the wind farm. Finally, the optimal spatial planning of the wind farms in the North Sea can be made.

Milestone 9 – Characterization of wind inflow fields
A comprehensive turbulent inflow repository for the North Sea region needs to be developed. Advanced numerical modelling frameworks should be developed to accurately simulate wave-atmosphere-wake and farm-farm interactions. Substantial research effort should be dedicated to the validation of numerically generated inflow fields, and intensive field experiments involving next-generation sensors (e.g. 3D wind scanner, spinner lidar) should be conducted at various offshore locations.

Milestone 10 – Optimal turbine design, layout and control within wind farm
Novel techniques from computational science, statistics and optimization should be developed in order to incorporate the character of atmospheric conditions in the design, layout and control of wind turbines within wind farms. The increasing amount of measurement data, such as lidar measurements, should be efficiently assimilated to improve and calibrate model predictions. The effect on damage, wear, and operations and maintenance should also be incorporated, as well as impact on the marine environment and marine activities.

Milestone 11 – Wind farm and turbine integrated design
New approaches should be explored to achieve an optimal integrated design of wind farms and their individual turbines. For example, would it be possible to design more densely packed wind farms in order to reduce sea surface use? Or to reduce the cost of connections by designing rotors and controls adapted to wake conditions? Alternatively, should components like the drivetrain or tower be adjusted to account for the wake conditions?

Milestone 12 – Optimal wind farm spatial planning
Spatial planning of wind farms needs to be done carefully as aerodynamic interactions within and between large wind farms need to be considered. An appropriate geographical distribution, i.e. building wind farms at different locations, can improve the availability of wind power as the correlation between wind speeds reduces with increasing distance.
Figure 12 depicts the milestones in wind farms as they relate to the beacons.

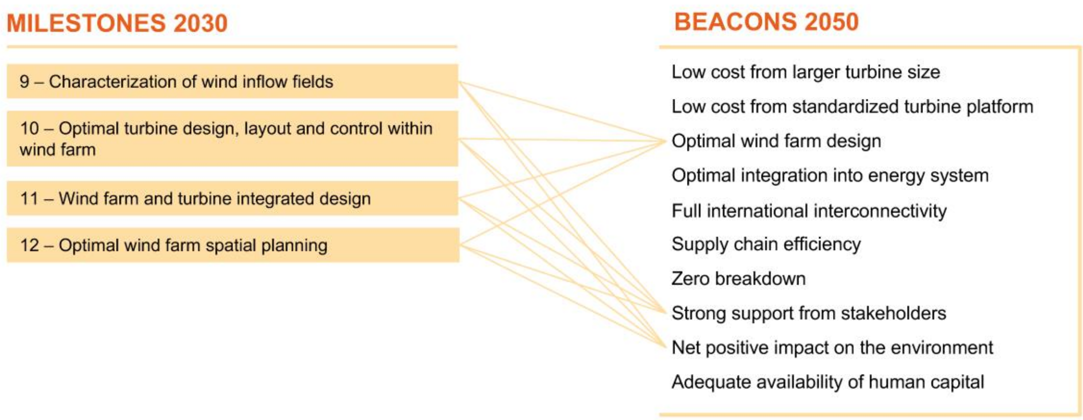

Figure 12 – Wind farm milestones as they relate to the beacons

4.3 Electrical systems and grid connection

Due to the harsh conditions offshore, the electrical systems and grid connection for offshore wind farms require a very robust design. Nevertheless, zero breakdown has not yet been achieved; the electrical systems are not yet fully stable, and the cables still fail due to extreme loading during or after installation. Significant cost reductions are also still possible through capacity design and component modularity.

Milestone 13 – Optimal design of grid connection
An important aspect of offshore wind farm design is optimizing the farm's capacity with respect to the capacity of inter-array and export electrical infrastructure. An accurate level of overplanting and capacity optimization requires the development of advanced models and tools that take into account the limitations imposed by different components of offshore grid electrical infrastructures.

Milestone 14 – Grid redundancy through modularity
Offshore wind generation is known for high maintenance costs and for the harsh conditions in which the hardware must operate. Research has therefore focused on predictive maintenance and on designing robust power electronics systems that enable operation under harsh conditions and allow for planned maintenance. Modules and platforms need to be defined with interfaces that maximize grid redundancy, minimize maintenance costs, and enable further technology innovation of modules.

Milestone 15 – 100% stable DC connection
For a wind farm located more than 50 to 100 km offshore and larger than 200 MW, an HVDC system has lower losses than an HVAC system. Furthermore, a DC link can limit fault propagation from the wind farm to the main grid, and from the main grid to the wind farm. Nevertheless, many challenges have to be tackled in order to achieve a 100% stable connection: for example, more flexible coordinated control, stable transition between connection and disconnection of offshore farms, and suitable converter design to reduce the losses further and allow more flexibility in the network.

Milestone 16 – Grid harmonics mitigation and resonance damping
Most new wind farm connections will entail significant cable lengths, which may amplify already present harmonics. In addition, the replacement of thermal generation with converter-based technologies may result in the increased generation of harmonics. The combination of these factors will have a negative effect on power quality. Research should focus on interconnected system analysis to gain deeper insight into the summation of various harmonic contributions from the onshore grid and from the wind turbines. Consequently, advanced control strategies should be developed for harmonics mitigation and resonance damping.

Milestone 17 – Mitigating physical failure of cables
Failure of inter-array or export cables can result in significant loss of revenue, particularly when it comes to power cables in highly dynamic power generation environments which include offshore wind. The offshore wind industry requires innovations that make power cables less susceptible to failures, fatigue, and wear and tear during both cable installation and operation. Further research is proposed that will focus on cable load alleviation and monitoring during installation, operation and maintenance.
Figure 13 depicts the milestones in electrical systems and grid connection as they relate to the beacons.

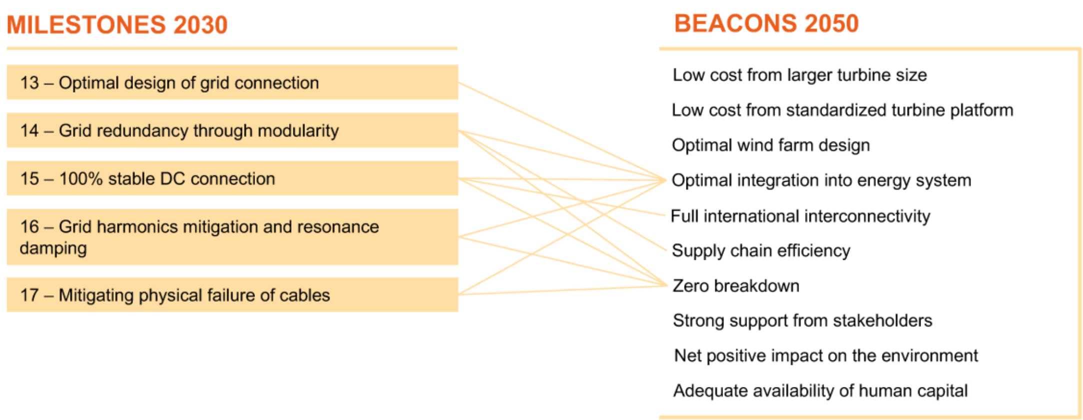

Figure 13 – Electrical systems and grid connection milestones as they relate to the beacons

4.4 Materials

As offshore wind turbines become larger and wind farms more numerous, material requirements will grow in terms of quantity, properties (such as strength), and their impact on the environment throughout their life cycle. Turbines are getting heavier, too, which presents a growing logistical challenge when installing offshore. Topics like the scaling of blades, for example, are to some extent limited by the strength and durability of the materials used.

Different parts of the turbine and balance of plant are made from different materials. Blades are large composite structures of glass fiber-reinforced plastics (GFRP), carbon fiber-reinforced plastics (CFRP), wood, adhesives and other core materials. Large volumes of steel are used,

mainly in the support structure, the drivetrain (including the main shaft, bearings, generator and gearbox) and the nacelle (drivetrain support and yaw bearing). Rare earth metals are required for permanent magnet generators. Foundations incorporate steel and concrete.
Research into new materials, durability and damage tolerance, circularity and availability will enable larger, cheaper and more reliable turbines, a more efficient supply chain, and a lower impact on the environment.

Milestone 18 – Strong, lightweight, durable composites for blades
Milestone 19 – Self-healing and healable materials
Research into novel materials will benefit all components of the wind turbine:

- **Blades** – Innovations which are easier to manufacture (e.g. which lend themselves to automation, more consistent quality, etc.) should be investigated. Also, composites should be developed that are easier to disassemble between different materials. The materials need to be durable, fatigue-resistant, light, and suitable for modular construction (milestone 18)
- **Foundations** – Alternative materials should be investigated which can produce lighter and more environmentally-friendly foundations (e.g. reduced volumes of concrete) and which are easy to deploy, are corrosion-resistant, conducive to aquatic life and easier to decommission
- **Towers** – Research is required to reduce the use of steel, for example to find composite materials that make towers lighter and easier to install but which have the structural properties, like stiffness, that are required
- **Functional components and structures for wind farms –** Self-healing and healable materials could make functional components and structures more durable (milestone 19)

Milestone 20 – Direct measurement of fatigue life in support structures
Milestone 21 – Characterization of composites resistance
Large-scale and direct measurement of the loading of the inner structure will allow for a better understanding of the fatigue life of metals. Such research will facilitate a lighter design of metal foundations (milestone 20). For composites, durability and damage tolerance should be researched (milestone 21). Instead of stress-life, a more intuitive physics-based methodology should be developed to describe the durability of composite material, including energy dissipation mechanisms to characterize the intrinsic resistance to damage growth.

Milestone 22 – Life-cycle assessment of composite blades
Milestone 23 – Recycling methods for fiber-reinforced polymers
Carbon and glass fiber-reinforced polymers offer high strength and stiffness at low weight and are therefore key materials in the realization of very large wind turbine blades. With increasing size and manufacturing volumes, the end-of-life scenarios of such parts become important. Life-cycle assessment of novel thermoset and thermoplastics manufacturing processes for large-scale fiber-reinforced polymer composites and their joining methods should be conducted for comparison with alternative materials and technologies (milestone 22). Circular design and recycling methods for these materials should also be developed (milestone 23).

Milestone 24 – Availability of materials
The large-scale deployment of offshore wind power capacity and the need for smart grid connections have raised concerns about the sufficient availability of materials, in particular of rare earth materials. The future availability and costs of materials for offshore wind turbines and grid connections need to be assessed in view of critical short to medium-term economic,

political and geographical factors. Figure 14 depicts the milestones in materials as they relate to the beacons.

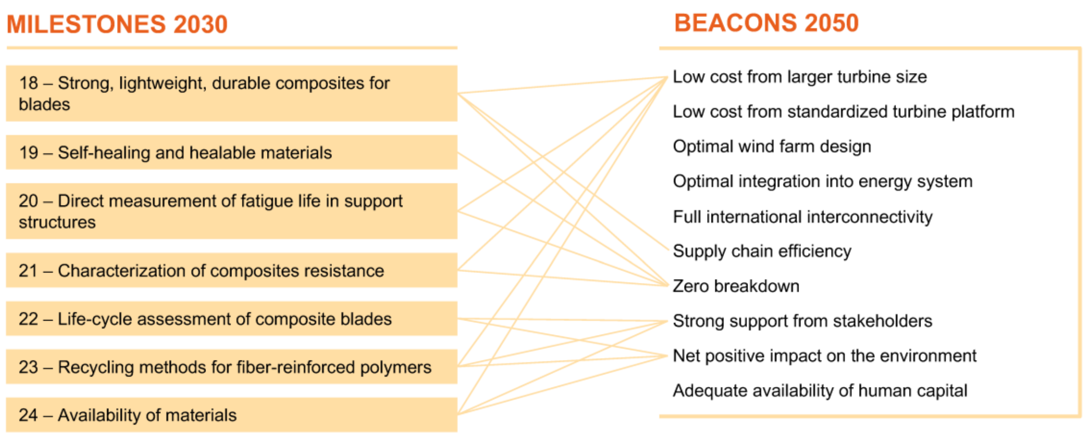

Figure 14 – Materials milestones as they relate to the beacons

4.5 Integration into energy system

In the energy system of 2050, most electricity will be generated from renewable sources. Electricity demand will have grown significantly, as energy use in industry, transport and buildings will be almost fully decarbonized. As offshore wind farms will provide a large part of all electricity in the Netherlands, their seamless integration into the overall energy system will be essential. A growth path for offshore wind that is balanced by a transition path for electrification and/or the uptake of renewable hydrogen in industry is required to maintain market stability and as a result a suitable investment climate.

Electricity-to-gas, and in particular, electricity-to-hydrogen, will play a pivotal role in decarbonizing the entire energy system. Hydrogen will be used as an energy carrier for the generation, storage and transport of energy. Hydrogen will also be used for transportation, renewable feedstock, industrial heat and residential heat. As renewable feedstock for industry, it will often be used in combination with carbon capture and utilization (CCU). Lowering the capital costs of electrolysers will be key to bringing down the costs for renewable hydrogen. Once capital costs play only a marginal role in the hydrogen production costs, the full-load operating hours of electrolysers will no longer be the determining factor in the business case. This will allow for their use as flexible conversion units and shift the emphasis to average electricity costs and electrolyser efficiency.

Once electrolysis technology is mature, a large share of the renewable hydrogen[9] will probably be produced offshore because the transportation of hydrogen through submarine pipelines in large volumes is more cost-efficient than electricity through power cables. For this purpose, electrolysis plants will be installed on dedicated platforms or (floating) islands. Hydrogen will be a medium to store energy offshore, in tanks placed on the islands or in depleted gas fields. In

9 Offshore transportation and storage of gas may well be developed in other forms than hydrogen, e.g. by converting hydrogen into ammonia, methanol, dimethyl ether or formic acid

the longer term, it is conceivable that floating wind farms will be installed in the middle of the ocean to benefit from even higher wind speeds and capacity factors. They will deliver their electricity to floating production, storage and offloading (FPSO) vessels, where it will be transformed into hydrogen, and supertankers will transport the hydrogen to shore.

As an alternative to hydrogen, offshore wind energy can be used for synthetic hydrocarbons production, fresh-water generation and hydraulic pressure generation for industrial processes. By further diversifying wind power uses and conversion steps to other powering modalities, the scope of the enormous offshore wind capacity can be broadened, harnessed and fed into the energy system.

Eventually, all countries around the North Sea will have to be optimally interconnected, and their energy markets will be fully merged. Wind farms in the Dutch EEZ will thus also provide electricity to other North Sea countries. Developing a North Sea-wide electricity grid requires further R&D in terms of grid and offshore wind farm planning, multi-terminal HVDC design and operation, and regulatory schemes.

As a first step, offshore wind farms will be made more flexible to cater for the demands of the energy system. Eventually, full integration of wind farms will be achieved through cost-effective offshore storage of the energy produced and more sophisticated design, operation and maintenance.

Milestone 25 – Flexible offshore wind farms

Current offshore wind farms are optimized for maximum annual production at minimum levelized costs. However, their production will need to become more predictable and flexible to adapt to fluctuating market demands. Also, offshore wind farms face increasing requirements to prevent grid congestion and maintain stability and voltage quality due to the steep rise of the share of renewables and the phasing out of fossil-fuelled generation. Therefore, offshore wind farms will supply to various emerging short-term markets and offer a broad range of ancillary services. Research should be conducted into how to achieve such flexible offshore wind farms.

Milestone 26 – Innovative offshore energy storage

Scenarios exists where hydrogen serves as a medium for offshore energy storage. There are multiple potential purposes of such storage, including ramp rate limitation, black start, daily storage and seasonal storage. Other potential options exist, like batteries and subsurface water column storage. R&D into such innovative offshore energy storage options is proposed.

Milestone 27 – (Re)design and maintenance of energy system infrastructures surrounding wind farms

Milestone 28 – Control and operations of energy system surrounding wind farms

Offshore wind farms, their related offshore and local onshore networks (e.g. infrastructures for electricity transportation), conversion and storage facilities, and other assets, as well as their various industry players and stakeholders, form a complex energy system. Such energy systems need to be designed, extended, redesigned and maintained with a focus on good overall system performance, e.g. in terms of energy supply, congestion and storage management, and of control of the wind turbines themselves (milestone 27). Novel techniques and knowledge should be developed to deal with the automatic control and operations of such complex systems (milestone 28).

Milestone 29 – Combining wind energy generation with electrolysis to gas
Milestone 30 – Meshed hybrid (AC-DC-H_2) offshore transmission system
More specifically, milestone 29 proposes an intelligent power flow control system for the variable wind power generation, the required system dispatch of energy, the necessary provision of ancillary services, and the management of hydrogen storage/usage. Milestone 30 targets the research necessary to achieve a meshed hybrid offshore transmission system for the efficient transport of both electricity and hydrogen to the shore and between countries.

Figure 15 depicts the milestones in energy system integration as they relate to the beacons.

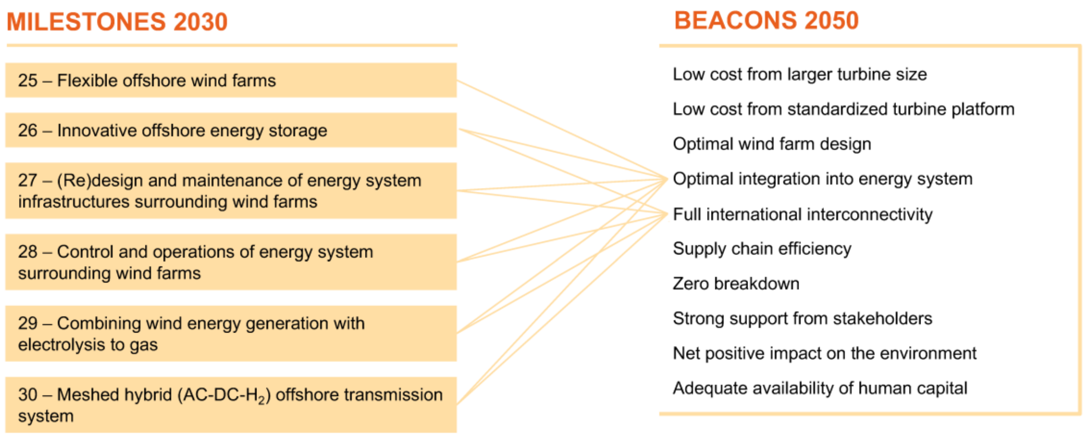

Figure 15 – Integration into energy system milestones as they relate to the beacons

4.6 Inspection, monitoring and diagnostics

Effective maintenance leads to lower downtime rates and higher output at offshore wind farms, and thus to lower the overall LCOE. However, offshore maintenance is costly due to difficult access and operating conditions for personnel and scheduling uncertainty around the weather. Maintenance therefore represents a significant portion – 10-15% – of the lifetime costs of wind farms. More efficient and effective maintenance through automated inspection, monitoring and diagnostics will have an important impact on the LCOE.

Milestone 31 – Continuous, swarm-based autonomous subsea asset monitoring
Though many key components can have dedicated sensors for monitoring, there will always be the need for mobile inspection, visual or otherwise. Automating such inspections requires the development of autonomous airborne and underwater drone technology, therefore R&D is proposed to develop continuous, swarm-based autonomous subsea asset monitoring.

Milestone 32 – Remote structural health and condition monitoring and diagnostics for turbines
Thanks to considerable efforts to optimize maintenance in recent years, the uptime of new offshore turbines can now be well above 95%. Current industry practice uses a combination of inspection by personnel and data-driven or damage model approaches based on available sensor and operating data. There is substantial potential to further reduce costs and downtime by developing more advanced sensors and prognostic algorithms, e.g. to determine the

consumption of fatigue life, crack growth, and probability of failure. Since wind turbine systems are often monitored differently from machine to machine, this also requires setting up a cross-industry working group to develop measurement standards for monitoring and data collection.

Milestone 33 – Condition monitoring and diagnostics of HVDC electrical offshore assets
For electrical systems and cables, the goal is to achieve a fully automated system that works without the physical presence of people in the offshore facility. That goal can only be achieved by means of remote monitoring and diagnostics systems to ensure a continuous flow of electrical energy.
Figure 16 depicts the milestones in energy system integration as they relate to the beacons.

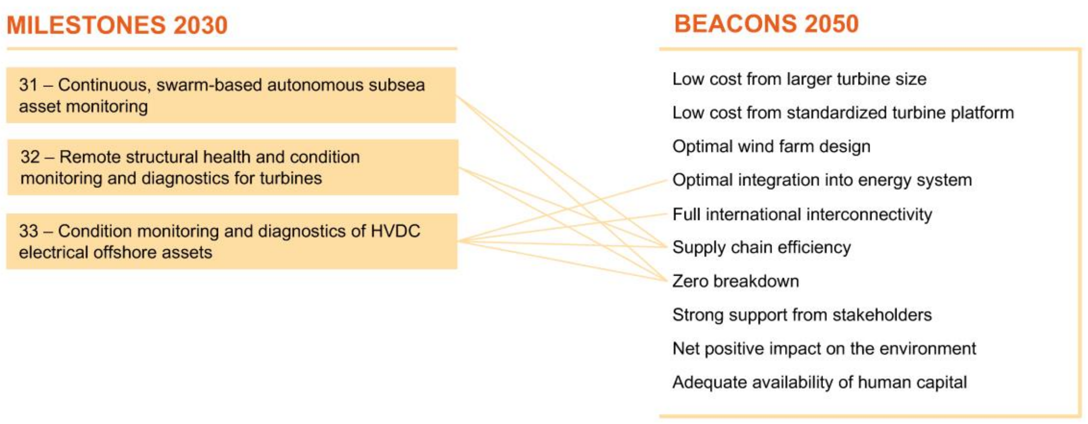

Figure 16 – Inspection, monitoring and diagnostics milestones as they relate to the beacons

4.7 Supply chain

The offshore wind farm supply chain, as it is understood in this R&D agenda, inherently entails a European dimension; most parties in the supply chain operate internationally. To achieve Europe's target of 240-450 GW of offshore wind energy by 2050, considerable developments must be seen in the supply chain, not only in terms of output capacity but also in terms of efficiency and effectiveness. With its geographical position, its open, deep ports and its skilled workforce, the Netherlands is ideally positioned to attract an important part of the future offshore wind supply chain.
The offshore wind supply chains consists of multiple and interacting steps, which are dominated by the life cycle of turbines. In offshore wind, the supply chain life cycle consists of the following stages:

- Design
- Procurement
- Manufacturing
- Installation
- Operation & maintenance
- Decommissioning

These six stages form the core of the integrated supply chain model shown in figure 17. The figure also indicates where the milestones in this topic will impact the efficiency of the supply chain. In each of their life-cycle stages, wind farm assets generate huge amounts of data. Supply chain control uses this data to manage the supply chain. Over time, knowledge of how to best control the supply chain needs to be further developed.

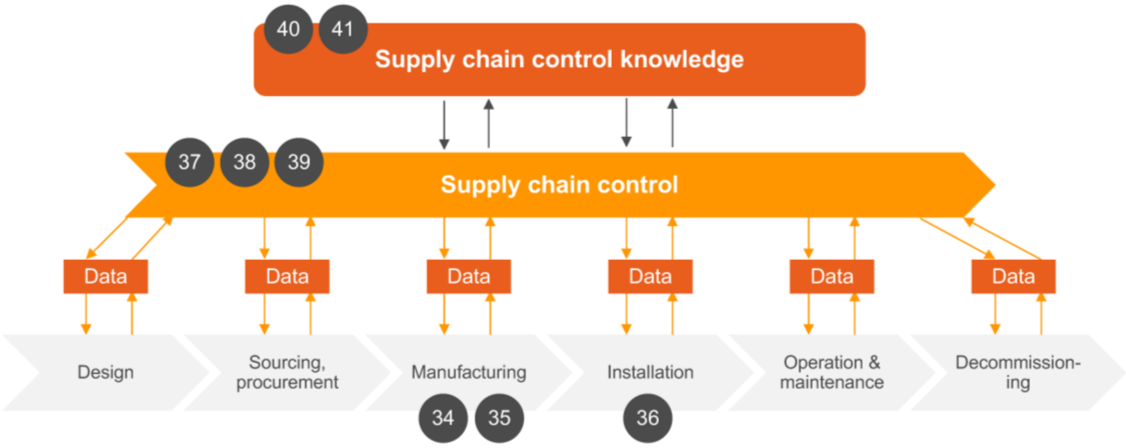

Figure 17 – Integrated supply chain model in offshore wind and the impact of the milestones[10]

Milestone 34 – Automation in blade manufacturing
Manufacturers of generators, electrical equipment, cables and monopiles are already relatively industrialized with automated manufacturing processes. However, the manufacturing of blades and jacket foundations is barely automated and is very labour intensive. R&D is proposed in the area of automating blade manufacturing to address this concern.

Milestone 35 – Joining methods for modular blade designs
As turbines become larger, the logistical challenge in terms of manufacturing, assembly and installation becomes greater. Larger components such as blades, towers and generators require larger vessels. This can increase the costs of installation as such larger vessels are (and will be) scarce. For instance, to ensure the deployment of large wind turbine sizes and reduce their logistical challenge significantly, it will be crucial to develop blades which can be manufactured in several sections that can be assembled at the installation site or a marshalling yard nearby. Milestone 35 aims to develop high stiffness, strength and fatigue-resistant joining methods for modular blade designs to accommodate the logistics of ultra-long blades; this milestone is a corollary to milestone 4 (see chapter 4.1), which proposes further research into the modularity of all turbine components.

Milestones 36 – Optimal integrated installation method for tower, nacelle and rotor assembly
The current practice of a bottom-mounted wind turbine installation is based on the sequential approach. First, the foundation is installed. Thereafter, sometimes after a significant time window, the tower is installed. The nacelle and rotor (hub and blades) are then mounted on top of the tower. The objective of milestone 36 is to develop semi-active and active control devices that will be integrated in the tower, nacelle and rotor assembly of offshore wind turbines to enable their optimal and integrated installation.

Milestone 37 – Supply chain efficiency through digitalization
In each of their life-cycle stages, wind farm assets generate huge amounts of data. This is also shown in figure 17. This data layer needs to be managed and, more importantly, used to control the entire network, especially the operational logistics control driven by condition-based maintenance assessments (see previous section). Research is proposed to achieve an

10 Source: Henk Akkermans, Tilburg University

integrated digital end-to-end supply chain to enable seamless logistics in installation and O&M, both land and marine-based.

Milestone 38 – Optimization of standardization throughout supply chain in ramp-up phase
Planning the supply chain is especially problematic during the first years, i.e. the ramp-up years, since so many aspects are in flux. There is the temptation (and business need) to simplify matters through standardization of design. The risk of this is premature termination of innovation, which conflicts with another business need to remain open to new design choices. How to manage this paradox during the ramp-up stage is the subject of milestone 38.

Milestone 39 – Sufficient turbine manufacturing, transportation and installation capacity
The coming years face a considerable challenge to develop sufficient manufacturing, transportation, installation, maintenance and decommissioning capacity. By making information available supply chain-wide through enterprise resource planning (ERP) systems, (which are used in most manufacturing supply chains), it will be possible to plan strategically for sufficient production, transportation and installation capacity.

Milestone 40 – Design guidelines to increase learning capability throughout ramp-up
The offshore wind industry needs to learn how best to manage its supply chain. What will drive this learning curve, and how it can be made as steep as possible, depends on the speed of growth in knowledge. Optimizing that growth is the topic of milestone 40.

Milestone 41 – Assessment of system risk (unk-unks) and how to manage it
By and large, this R&D agenda focuses on the problems that occur often and that can be foreseen. However, the largest risks are often those that are most unlikely and totally unanticipated. These low-likelihood but high-impact events, also known as supply chain tsunamis, are often the result of the inevitable "unknown-unknowns". How to deal with these is the subject of milestone 41.
Figure 18 depicts the supply chain milestones as they relate to the beacons.

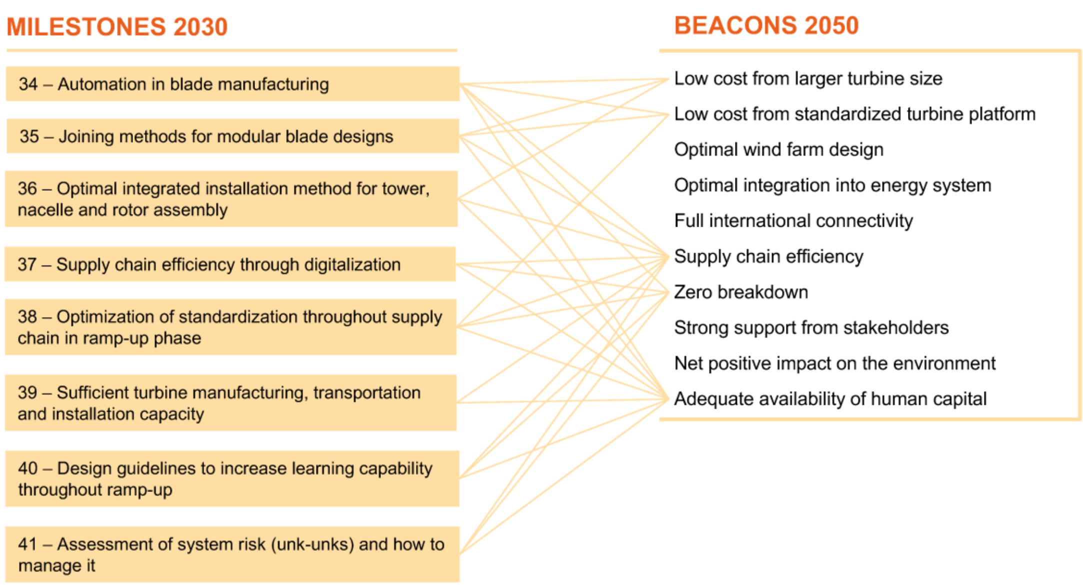

Figure 18 – Supply chain milestones as they relate to the beacons

Obviously, all of the supply chain milestones improve the efficiency of the supply chain and thus contribute to the adequate availability of human capital. Technically oriented milestones are not the only ones to contribute to the availability of human capital for offshore wind. Education and lifelong training will guarantee a pool of qualified staff for the development, construction and maintenance of offshore wind farms, as well as the manufacturing of components. Such efforts, however, fall outside the scope of this primarily academic research-oriented agenda, but are addressed by the Topsector Energy, TKIs and MMIPs.

4.8 Environment

A large-scale capacity rollout of offshore wind, potentially covering 17-26% of the Dutch EEZ by the year 2050, needs to be executed in an environmentally responsible way. Installation, operation, maintenance and decommissioning of wind farms can potentially impact, both directly and indirectly, the flora and fauna above and below sea level. Offshore wind farms can also impact winds, currents, waves, stratification and turbidity. The positive effects of wind farms on the environment (e.g. the reforming of the original North Sea fauna and habitat among wind farms) must significantly outweigh their negative effects (e.g. bird collisions).

Milestone 42 – Ecological effects of large-scale offshore wind capacity rollout
Many wind farms have been installed in the North Sea over the last decade, and their short-term environmental effects have been extensively investigated. However, the potential effects of a large-scale capacity rollout are still largely unknown. Milestone 42 proposes research to fully understand the potential positive and negative effects of large-scale rollout, specifically on the ecology of the North Sea. Further research is proposed to optimize and predict the effects of mitigation, compensation and development of new habitat types and ecosystems, as well as offsetting.

Milestone 43 – Changing impact on coastal erosion
Milestone 44 – Mitigating negative environmental impact of offshore installation and operation
There is already some experience in mitigating the negative effects of individual offshore wind farms. Examples include bubble curtains that mitigate underwater noise from piling and radar detection of the approach of flocks of birds so that wind turbines can temporarily be shut down. Milestone 43 will seek to better understand and predict potential coastal impact and effects on flood risk of a large-scale rollout. Optimal spatial planning of wind farms will be developed to minimize coastal impact, or effective mitigation measures will be developed. Milestone 44 proposes further research into even more effective measures to mitigate the negative impacts of the installation and operation of offshore wind farms on the environment.

Figure 19 depicts the environmental milestones as they relate to the beacons.

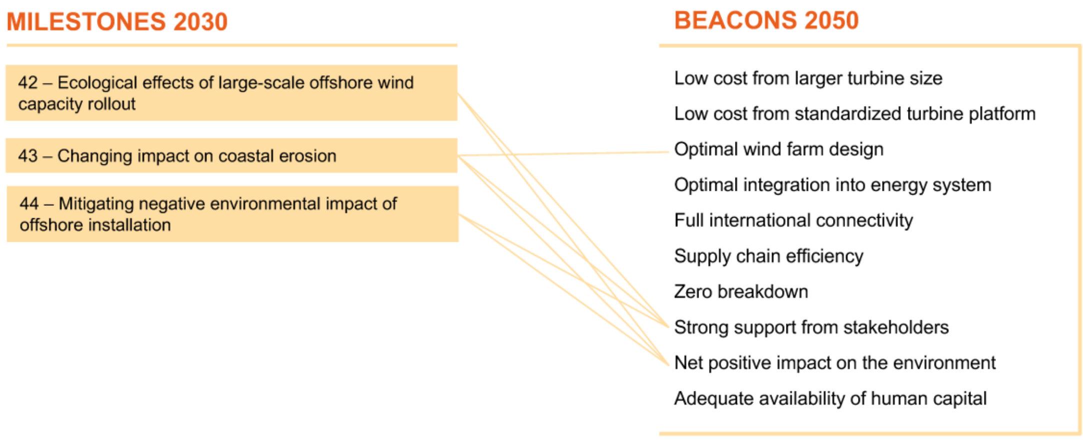

Figure 19 – Environmental milestones as they relate to the beacons

4.9 Governance

The potential installation of 35-75 GW of offshore wind power capacity in the Dutch part of the North Sea is a truly complex endeavour from the point of view of governance. For this endeavour to be realized, international, national, regional and local governments will have to work closely together. They will have to develop policies, regulations and agreements in close cooperation with the stakeholders involved: the offshore energy sector, shipping, fisheries, defence, tourism, NGOs, etc.

Milestone 45 – Ethical issues of large-scale implementation of offshore wind
A better understanding of which stakeholders play a role, which values they uphold and how those could change for a large-scale rollout of offshore wind, and whether such rollout would give rise to new stakeholders (e.g. new exploitation purposes for fisheries) or perhaps new values (such as non-anthropocentric environmental benevolence), must be developed. Offshore wind farms should also comply with the basic principles of the tripartite model of energy justice: recognition, participation and distribution of burdens and benefits.

Milestone 46 – Optimal regulation for infrastructure and market design
The envisioned large-scale capacity rollout of offshore wind power capacity can lead to inefficient solutions and public resistance: costs can actually be or can just be perceived to be too high, both in terms of actual economic costs as well as costs to the environment and society. The challenge for the authorities is to design regulations that will lead to the optimal infrastructure for energy generation in the North Sea, and an optimal market model to achieve the highest added value at fair prices, a seamless integration into the energy system, and a net positive impact on the environment.

Milestone 47 – Design of dedicated market model mechanisms
Novel market mechanisms should be investigated and developed to achieve optimal coordination between players and stakeholders in the energy system around offshore wind

farms. Such market mechanisms should be automatic, in other words, performed and operated by ICT. In addition, such market mechanisms should satisfy societal and economic objectives with respect to business as well as end-users. Different boundary conditions or objectives can demand different market mechanisms. This requires R&D in the areas of e.g. computer science, economics, game theory, artificial intelligence (AI), electrical engineering and physical sciences.

Milestone 48 – Methodology to assess and accelerate technological innovation
The successful installation of 35-75 GW of offshore wind power capacity will require both breakthroughs and incremental technological innovation in many domains. At present, there are a lot of new ideas and concepts for harvesting offshore wind energy. A reliable screening and selection process needs to be developed to assess the potential value of new concepts and ideas at an early stage. By developing an indicator for the potential success of a concept, it will be easier to select those ideas to focus on.
Figure 20 depicts the governance milestones as they relate to the beacons.

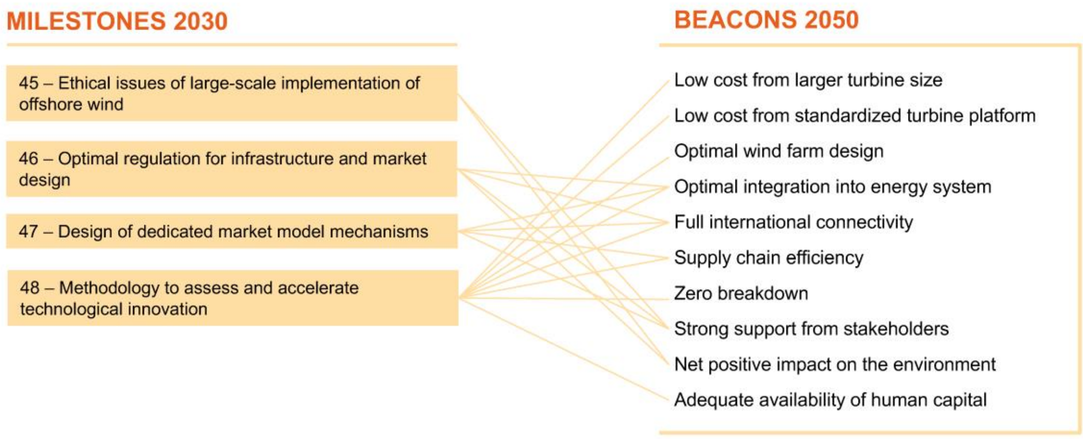

Figure 20 – Governance milestones as they relate to the beacons

5 Milestones for the year 2030

This chapter presents the 48 milestones for the year 2030 in detail. A summary at the beginning of each section specifies the milestone's author(s), its objective for the year 2030, and its contribution to the 2050 beacon(s). Each section then expounds on the background behind proposing the R&D, the current state-of-the-art, and the proposed R&D topics for the 2020-2030 period. Table 1 lists the 48 milestones and their authors.

	Milestone title	Authors
Turbines		
1	Optimal turbine size	Jan Willem Wagenaar, Roeland de Breuker
2	Alternative drivetrain designs	Jianning Dong, Pavol Bauer, Simon Watson
3	Alternative designs for turbine topology	Simon Watson
4	Modular approach for turbine design	Simon Watson
5	Optimal dynamic equilibrium for support structures	Andrei Metrikine
6	Active control devices for support structures	Andrei Metrikine
7	Scalability of floating structures for wind and solar	Olaf Waals, Erik-Jan de Ridder
8	Critical failure state design of support structures	Tim Raaijmakers, Maxim Segeren
Wind farms		
9	Characterization of wind inflow fields	Sukanta Basu
10	Optimal turbine design, layout and control within wind farm	Han la Poutré
11	Wind farm and turbine integrated design	Richard Stevens
12	Optimal wind farm spatial planning	Richard Stevens
Electrical systems and grid connection		
13	Optimal design of grid connection	Mohamad Ghaffarian Niasar, Pavol Bauer
14	Grid redundancy through modularity	Pavol Bauer, Pavel Purgat
15	100% stable DC connection	Pavol Bauer, Laura Ramirez Elizondo
16	Grid harmonics mitigation and resonance damping	Zian Qin, Pavol Bauer
17	Mitigating physical failure of cables	Olaf Waals, Erik-Jan de Ridder
Materials		
18	Strong, lightweight, durable composites for blades	Clemens Dransfeld, Julie Teuwen
19	Self-healing and healable materials	Santiago J. Garcia
20	Direct measurement of fatigue life in support structures	Andrei Metrikine
21	Characterization of composites resistance	Rene Alderliesten
22	Life-cycle assessment of composite blades	Clemens Dransfeld, Julie Teuwen
23	Recycling methods for fiber-reinforced polymers	Clemens Dransfeld, Julie Teuwen
24	Availability of materials	Ton Veltkamp, Novita Saraswati, Edwin Wiggelinkhuizen

	Milestone title	Authors
Integration into energy system		
25	Flexible offshore wind farms	Richard Stevens, Simon Watson, Edwin Wiggelinkhuizen
26	Innovative offshore energy storage	Andrei Metrikine
27	(Re)design and maintenance of energy system infrastructures surrounding wind farms	Han la Poutré
28	Control and operations of energy system surrounding wind farms	Han la Poutré
29	Combining wind energy generation with electrolysis to gas	Thiago Batista Soeiro, Pavol Bauer
30	Meshed hybrid (AC-DC-H2) offshore transmission system	Jose Rueda Torres, Pavol Bauer
Inspection, monitoring and diagnostics		
31	Continuous, swarm-based autonomous subsea asset monitoring	Stephan Rutten
32	Remote structural health and condition monitoring and diagnostics for turbines	Roger Groves, Simon Watson
33	Condition monitoring and diagnostics of HVDC electrical offshore assets	Armando Rodrigo Mor, Pavol Bauer
Supply chain		
34	Automation in blade manufacturing	Julie Teuwen
35	Joining methods for modular blade designs	Julie Teuwen
36	Optimal integrated installation method for tower, nacelle and rotor assembly	Andrei Metrikine
37	Supply chain efficiency through digitalization	Wouter Beelaerts van Blokland
38	Optimization of standardization throughout supply chain in ramp-up phase	Henk Akkermans, Roland van de Kerkhof
39	Sufficient turbine manufacturing, transportation and installation capacity	Henk Akkermans, Roland van de Kerkhof
40	Design guidelines to increase learning capability throughout ramp-up	Henk Akkermans, Roland van de Kerkhof
41	Assessment of system risk (unk-unks) and how to manage it	Henk Akkermans, Roland van de Kerkhof
Environment		
42	Ecological effects of large-scale offshore wind capacity roll-out	Han Lindeboom, GerJan Piet
43	Changing impact on coastal erosion	Tim Raaijmakers, Sukanta Basu
44	Mitigating negative environmental impact of offshore installation and operation	Andrei Metrikine
Governance		
45	Ethical issues of large-scale implementation of offshore wind	Behnam Taebi
46	Optimal regulation for infrastructure and market design	Annelies Huygen, Edwin Wiggelinkhuizen
47	Design of dedicated market model mechanisms	Han la Poutré
48	Methodology to assess and accelerate technological innovation	Olaf Waals, Bob Meijer

Table 1 – List of milestones and authors

1 – Optimal turbine size

Authors
Jan Willem Wagenaar, Roeland de Breuker

Objective
Design the optimal size of an offshore wind turbine

Beacons
- Low cost from larger turbine size
- Low cost from standardized turbine platform
- Supply chain efficiency
- Zero breakdown

Background
Nowadays, the trend for offshore wind turbines is upscaling in all aspects one could think of; rated power, hub height, rotor diameter, etc. The main reason for this upscaling is to lower the cost of offshore wind energy. Here, in simple terms, the logic is that for one large wind turbine only one substructure is necessary and that the number of components that need operation and maintenance during their lifetime is smaller compared to an offshore wind turbine fleet with lower-capacity turbines.

The first offshore wind farm in the Netherlands, the Windpark Egmond aan Zee, or OWEZ, has wind turbines with a rated power of 3 MW. Nowadays, the tendered offshore wind farms are developed using to-be realized 10+ MW wind turbines. It is clear that this trend will continue for a while.

Current state-of-the-art
It is foreseen that by 2030, the optimal turbine size has been reached. It is also foreseen that the costs for further increasing the turbine size no longer outweigh the costs to produce, install and operate it. Design optimization studies to upscale wind turbines have been carried out in the past. Typical sizes that are investigated are up to 20 MW. One easy way is to use the wind turbine scaling laws, though many researchers have proven that these laws are no longer valid when using novel structural technologies. Design optimization studies typically investigate the scaling up of a fixed wind turbine layout.

Proposed R&D topics
In order to design the optimal size of an offshore wind turbine, R&D is at least needed in the following fields: aerodynamics, structural design, logistics and operation and maintenance, cost modelling and standardization. Below, we provide some details on where the R&D should focus on:
- **Aerodynamic yield and loading** – From the incoming wind field and Reynolds numbers (see milestone 9) knowledge is needed on the flow around the airfoils and through the rotor to enable making yield estimates. After all, this is the "engine" of the machine. Furthermore, from the aerodynamic modelling, insights are gained on the aerodynamic forces on the turbine. As these will increase, knowledge is needed on what these forces will be and what structures are needed to bear them, all the way from the rotor to the substructure. With the driving wind forces, what will be the interaction with the sea(bed) and what is necessary to withstand that?

- **Multidisciplinary design** – When designing a 15-25 MW wind turbine for a lifetime of 25 years with zero breakdowns, multiple closely interconnected disciplines need to be taken into account. Concurrent optimization of wind turbine layout (horizontal axis wind turbine (HAWT), vertical axis wind turbine (VAWT), floating or fixed, other), blade shape, drivetrain and the support structure, together with in-situ condition monitoring of the entire system, is essential to design the optimal size wind turbine. Furthermore, the wind turbine, which is designed in a multidisciplinary fashion, needs to be embedded into a wind farm to maximize the wind farm capacity factor
- **Logistics and operation and maintenance** – With a first sketch of the optimal wind turbine size, knowledge is needed on what the supply chain, logistics and operations and maintenance look like. Where will the components come from, where will they be assembled and how is the turbine installed? In addition to that, what infrastructure – artificial islands, harbors, vessels, etc. – is necessary to achieve this? The same applies to the operation and maintenance; knowledge is needed on what the best strategies are for such extremely large components
- **Cost modelling** – Having technically designed the optimal wind turbine, it is necessary to investigate the financial aspects of the construction, installation and operation of this optimal size wind turbine, particularly with respect to project financing. What larger technical designs are still resulting in more positive business plans and what is the limit?
- **Standardization** – Agreeing as an industry on a certain standardized turbine platform allows further industrialization of the supply chain and may lead to a lower overall LCOE. It also avoids the cost and risk of R&D into larger size turbines

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2 – Alternative drivetrain designs

Authors

Jianning Dong, Pavol Bauer, Simon Watson

Objective

Alternative drivetrain designs for larger, more reliable and lower cost turbines

Beacons

- Low cost from larger turbine size
- Low cost from standardized turbine platform
- Supply chain efficiency

Background

Successful offshore wind generation requires the wind turbine drivetrain to have high reliability, high availability, high power, low logistics and maintenance costs, and a fast development cycle. Accurate and reliable modelling and design tools are needed to accelerate the development of offshore wind turbine drivetrains. To continue driving down the LCOE, drivetrains for larger wind turbines with rated power of 12 - 20MW or alternative wind turbines should be developed. Innovative drivetrain concepts, such as a hydraulic, permanent magnet-free and modular generator system, can reduce costs, enhance reliability and provide fault tolerance for the wind turbine drivetrain.

Current state-of-the-art

Current wind turbine drivetrains consist of a rotor connected to a main shaft which is then coupled either directly to a large multi-pole generator or via a gearbox to an induction generator, commonly a doubly-fed induction generator or a permanent magnet synchronous generator. Many recent European and national projects have looked at potential future designs of larger wind turbine drivetrains with an emphasis on improving wind turbine reliability[11]. In those projects, concepts including (water) hydraulic transmission systems, superconducting generators, hydraulic, pseudo-direct-drive generators, brushless doubly-fed and modular generators have been investigated. However, key limiting factors for large offshore wind turbines, e.g. the electro-magneto-mechanical coupling of the wind turbine drive train, reliability-oriented drive train system design and modelling, are not investigated. To enable fast and low levelized cost development of offshore wind energy in 2020-2030, not only alternative generation technology with the potential to reduce costs and improve reliability, but also technology and tools to design and model them, should be further developed.

Proposed R&D topics

- **Tools to accelerate development of the offshore generation system –** Technology to model key limiting factors of offshore wind turbine drive trains including electro-magneto-mechanical coupling, reliability and lifetime will be investigated and synthesized as a toolset to accelerate the design and development of offshore wind turbines
- **Alternative generator systems to reduce cost and improve reliability** – Innovative concepts and emerging technologies including superconducting elements, modularity and multi-rotors should be investigated as alternative designs. The objective of the research is

[11] Some examples: WINDRIVE (http://www.bdfig.com/), EU project on brushless generator; INNWIND (http://www.innwind.eu/), EU project on 10-20 MW wind turbines; D4REL (https://www.d4rel.nl/), Dutch project on reliability of offshore wind farms

to propose new solutions to enable larger wind turbines, enhance reliability and reduce LCOE compared to existing technology

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3 – Alternative designs for turbine topology

Author
Simon Watson

Objective
Alternative designs for turbine topology, for both generator and support structure

Beacons
- Low cost from larger turbine size
- Low cost from standardized turbine platform
- Supply chain efficiency

Background
Large modern turbines have converged towards a relatively standard design, i.e. three-bladed horizontal axis, upwind with either a direct-drive generator or generator and gearbox producing power through a converter connected to the local grid. This has served well and the design has been scaled up from the kW size to today's multi-MW machines. However, as machines get larger, this presents a challenge in terms of structural design, control, the materials used and deployment. Alternative designs may provide a more cost-effective means of generation, particularly if machines continue to be scaled up.

Current state-of-the-art
As mentioned in the background, large turbines are generally three-bladed horizontal axis, upwind with either a direct-drive generator or generator and gearbox producing power through a converter connected to the local grid. Blades are pitched for control using either electrical or hydraulic actuators. Blades are made of composite materials and towers are normally tubular and made of steel. Foundations for offshore are either monopile, tripod or jacket. Floating structures (semi-submersible, tensioned leg platforms or spars) are at the development and demonstration stage.

Proposed R&D topics
- **Research into alternative generation topologies** – This research effort should consider whether it is preferable to either scale up the existing topology in the current state-of-the-art, to standardize on a fixed rated power, or to develop a new topology. New topologies should include (though not be confined to): airborne wind systems, multi-rotor designs, secondary rotor designs, two-bladed downwind designs, vertical axis designs, etc.
- **Research into alternative support structures** – There is a potential to reduce the volume of materials required for support structures and for structures which are easier to deploy. It may also be beneficial to move to floating structures due to standardization and lower installation costs

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4 – Modular approach for turbine design

Author
Simon Watson

Objective
Modular designs for foundation, tower, blades and drivetrain components

Beacons
- Low cost from larger turbine size
- Low cost from standardized turbine platform
- Supply chain efficiency

Background
As turbines get larger, the logistical challenge in terms of installation offshore (and onshore) becomes greater. Larger components such as blades, towers and generators require larger boats and cranes for transportation and lifting. This can slow down the rate of installation as such larger vessels and lifting equipment are (and will be) scarce. At the same time, most modern large turbines are bespoke designs. Although some common elements across machines may be used, other parts such as foundations are particular to a turbine or indeed to a site. The logistical challenge and the overhead of bespoke design could be overcome by making turbines modular as far as possible, so that a larger number of smaller, common components and subassemblies can be standardized, mass produced and assembled on site using smaller, cheaper and more available installation vessels. Standardization into smaller modules is essential for a more industrialized supply chain.

Current state-of-the-art
Turbines are generally of a bespoke design with components and subassemblies manufactured especially for a particular machine. Offshore conditions (such as the seabed) can vary significantly from site to site, requiring specific solutions. Bespoke solutions add costs. In addition, as turbines become larger, subassemblies such as towers and generators need larger installation vessels and cranes with higher lifting capacities. The availability of such equipment is limited and can require reservation many months (or years) ahead. Such equipment can also command high prices in such a market-driven process. All of the above leads to potentially unnecessary costs and a restriction on offshore installation rates. Recent examples of modular design include the development of the modular steel tower by Lagerwey and the demonstration of a 45 kW prototype HVDC generator with three generator segments and three converter units in series.

Proposed R&D topics
- **Produce modular foundation design** – Research is required to provide a relatively small number of commonly used foundation designs that can be used at a variety of offshore sites. Such designs should be capable of being mass produced, easy to transport and easy to assemble on site. This would be primarily bottom-mounted solutions. Floating foundations offer even more opportunity to standardize in modules, as they do not have to be tailored to water depth and soil conditions
- **Produce modular blades** – Blades have become extremely long (>100 m) and could be more easily transported and installed in parts. This has had some attention for a number of years but presents quite a challenge in terms of overall structural integrity. Research is

required to come up with a modular design that can be scaled yet meet the fatigue life and strength required for long-term operation (see milestone 35)

- **Produce modular towers** – With ever taller turbines, a solution needs to be investigated with a modular design which can easily be erected on site, e.g. lighter lattice type towers, self-erecting towers, etc.
- **Produce modular drivetrain components** – In particular, this should focus on the production of modular generators. There are possibilities, for example, to manufacture the rotor and stator in sections which can then be assembled on site. However, to produce a design which can do this and adhere to the very strict design tolerances required (e.g. airgap) will be a challenge

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5 – Optimal dynamic equilibrium for support structures

Author
Andrei Metrikine

Objective
Develop "vibration-friendly" structural design and new materials and joints that are able to withstand much higher numbers and amplitudes of fatigue cycles

Beacon
- Low cost from larger turbine size

Background
Wind turbines are currently designed such that the optimal energy yield and the longest service life are achieved when the support structure and the blades of the turbine are fatigued as little as possible (i.e. when vibration is minimized). Present-day design prefers that the support structure remains as static as possible and that the number and amplitude of blade fatigue cycles are minimized. The fundamental idea of this current design may become too costly in the future given that the size of the turbines will increase, and it will become very difficult, if not impossible, to keep the level of fatigue cycles within the required limits. Therefore, it may be advantageous to drastically change the fundamental idea of the design and develop wind turbines which will function optimally when in certain dynamic (oscillating) equilibrium.

Current state-of-the-art
While active control is part of all the modern designs of offshore wind turbines [1], which makes these structures smart and adaptive, no designs exist as yet in which the wind turbines would operate in a dynamic equilibrium. On the contrary, the current state of technology will facilitate the realization, testing and implementation of such fundamentally new designs by 2030.

Proposed R&D topics
Research effort will be focused on the "vibration-friendly" structural design of the major components of wind turbines as well as on the development of new materials and joints that are able to withstand much higher numbers and amplitudes of fatigue cycles. The non-steady aerodynamics, thrust and energy yield of blades which vibrate while rotating will also be focused upon. The first steps will be applied to floating foundations as the steady oscillations of those in waves and, if specially designed, in wind, are relatively straightforward to realize.

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6 – Active control devices for support structures

Author
Andrei Metrikine

Objective
Develop and test active loading control devices to be installed in support structures, for both bottom-mounted and floating solutions

Beacon
- Low cost from larger turbine size

Background
Loads on wind turbine foundations increase with the increasing size of wind turbines. In order to cope with the loads and ensure that the service life of the foundations is increased to 50 years, the dynamic response of the foundations to the environmental loads should be actively controlled. If this is not done, the size and weight of the foundations may increase to prohibitive values.

Current state-of-the-art
While active control of the rotor and blades is part of all the modern designs of offshore wind turbines [2], nearly all foundations are designed to be passive. Recently, a number of design solutions have been proposed which incorporate semi-active control devices in the tower of the wind turbines [1, 3]. These devices may help in both installation and operation. However, no truly active control designs have been implemented, which would allow significant extension of the service life of the foundations.

Proposed R&D topics
The research effort will be focused on the development and testing of active control devices to be installed in and on the foundations, for both bottom-mounted and floating solutions. The main effort for bottom-mounted foundations will be placed on the control units that will be able to suppress complex vibration patterns of the foundations of the very large wind turbines as well as to deal with the slamming loads. The focus in the latter case will be on suppression within one vibration cycle. For the floating foundations, active vibration suppression will be achieved with the help of self-powered external devices such as underwater rotors or drag inducers based on the vortex-induced vibrations (VIV) principle.

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7 – Scalability of floating structures for wind and solar

Authors
Olaf Waals, Erik-Jan de Ridder

Objective
Novel high-fidelity design models which accurately model the complete systems of floating structures for offshore wind and solar

Beacons
- Low cost from larger turbine size
- Optimal integration into energy system
- Supply chain efficiency

Background
Currently the renewable offshore market is dominated by shallow water bottom-mounted offshore wind solutions. Development of other renewables like floating wind solutions will unlock access to deeper waters and to more steady and higher wind speed regions in the ocean. However, floating wind is still a very costly solution due to limited experience in the field. One of the critical aspects is the development of the next-generation floaters, which should be efficiently scalable towards ever larger turbine size and harsher environmental conditions. This development will help offshore wind integrate with floating offshore solar energy, which needs less carrying capacity but has many other challenges to be resolved to be installed in harsh offshore conditions.

Current state-of-the-art
The key issues with the current state of technology for floating wind and solar farms that have to be overcome to reduce the LCOE are; scalable low-cost floaters, mooring systems, and dynamic power cables. The installation and operation of the systems should also be further developed to reduce overall costs.

Proposed R&D topics
Research efforts should focus on novel high-fidelity design models which can accurately model the complete systems. In addition, they should be able to model the complete wind and solar farm in all relevant stages of its lifetime. The models and knowledge will provide the required basis to design novel scalable floaters with the lowest LCOE, both for offshore wind and solar.

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8 – Critical failure state design of support structures

Authors

Tim Raaijmakers, Maxim Segeren

Objective

Optimize support structure design, exploring the critical failure limits, to achieve minimal material use

Beacons

- Low cost from larger turbine size
- Low cost from standardized turbine platform

Background

Wind turbine support structures are sub optimally designed, leaving a lot of room for further material (and hence cost) reduction. In current design practice, the individual safety factors used on loads and strengths have a chain effect on the increase of material needed in the support structure, from nacelle to the base of the foundation. Furthermore, current load cases consider worst-case scenarios with a very low probability of occurrence.

To achieve an integrated, cost-efficient and technically optimal design, several disciplines need to be connected; each has its own governing processes, calculation models and experimental setups with corresponding scaling laws, which makes a fully integrated design complex. Offshore pilot sites, where these processes can be measured in conjunction at field scale and in real conditions, are therefore considered indispensable.

However, in the present setup of pilot sites, innovations are often incremental and only focus on certain individual design elements. The reason behind this is believed to be a combination of regulations, finance ability, insurability and certifiability. These requirements should be adapted for one turbine so that breakthrough innovations can be facilitated. Such breakthrough innovations should be piloted in future offshore wind farms, using a turbine that is similar to the other turbines of the wind farm, so that the effects of the innovative support structure can be isolated.

Current state-of-the-art

In the design of support structures, safety factors are added to wind and metocean forces to obtain conservative loads; safety factors are added to material characteristics and soil properties to obtain cautious values for the strength. These safety factors on loads and strengths make up for the fact that the governing processes are not fully understood. Besides, since the designs of tower and foundation are not integrated, material thicknesses are discontinuous at the interface, indicating that large savings can be obtained, if the entire support structure is designed as one structure. Recently, several detailed studies have been performed on including probabilistic methods in support structure design [2, 3], assessing remaining fatigue life in relation to joint probability of loads [4] and based on sensitivity analysis [5], including non-linear wave loads in aero-hydro-elastic calculations [1] and analysing uncertainties in pile-soil interaction [6]. However, to achieve significant optimization in support structure design, a (joint-)probabilistic, fully integrated design approach needs to be developed together with a prototype in the field for validation of the new design method.

For future wind turbines (> 10 MW), foundation diameters will further increase, resulting in wave loads becoming (even more) dominant over wind loads. Irregular wave loads in the diffraction regime as well as breaking wave loads, especially for foundations located on morphodynamic seabeds, require further research. Furthermore, dynamic pile-soil interaction and dynamic behavior of the support structure for larger diameter monopiles (e.g. through load identification) need further exploration, which is expected to be significantly more valuable when it is performed on a structure that is designed for failure and therefore will experience stronger dynamic behavior. Installation effects on the soil related to the selected installation method and the effect of scour on the dynamic behavior of the support structure should also be included.

Proposed R&D topics

In order to investigate the feasibility of a support structure that is designed for failure, not only the technical aspects and the potential cost savings should be addressed; equally important is a study on a feasible offshore innovation model which allows for integration of innovations in "normal" offshore wind farms. Research topics are therefore twofold:

- **Technical feasibility of "design for failure" support structures** – This R&D would prepare a design without any safety factors on loads and strengths, with best-estimate values for all parameters, using joint probabilities for a multi-parameter space (in order to avoid conservative combinations of several parameters). The support structure (tower and foundation) will be designed in an integral way. The design life will be deliberately chosen to be about 10 years, which is considerably shorter than the surrounding wind farm. This choice will not only make sure that several load conditions will occur that are close to or even exceeding the design conditions, but also that the dynamic behavior of the support structure can be observed around its end-of-life (e.g. to investigate its residual strength, if any). This R&D should also provide first estimates of material savings and give insight into the potential cost savings in support structures. These cost savings can be related to lower material consumption as well as to more cost-efficient installation (e.g. smaller and cheaper installation vessels)
- **Offshore innovation framework** – The success of this project will be partly determined by non-technical aspects. Topics that need to be addressed are:
  - Potential setup of innovation sites integrated into the tenders for new offshore wind farms
  - Permitting for structures with a flexible lifetime and a higher risk of failure
  - Certification for a design based on new design methods without any safety factors
  - Financial structure that divides benefits and costs between developer and government
  - Governance structure during design, construction, O&M and decommissioning phase

When the innovation project is considered technically feasible with sufficient envisaged cost savings and is also considered feasible from a financial, regulatory and governance point of view, then the higher TRL levels can be covered by an offshore pilot.

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9 – Characterization of wind inflow fields

Author
Sukanta Basu

Objective
Experimental and numerical characterization of metocean fields. Rigorous validation of simulated metocean fields for optimal design of turbines as well as spatial planning of wind farms

Beacons
- Optimal wind farm design
- Strong support from stakeholders
- Net positive impact on the environment

Background
As the growth of North Sea wind energy development steadily continues, it is anticipated that forthcoming wind farms will be deployed in more complex settings: farther away from the coastlines and in deeper waters. Under this scenario, in order to remain cost effective, unscheduled maintenance operations have to be reduced dramatically. Since weather events (both site-specific benign phenomena and extreme events) are often a precursor for incidents leading to unscheduled maintenance, the next-generation offshore wind turbine (OWT) design should be structurally more resilient against the harsh environmental conditions of the North Sea. At the same time, in order to reduce the LCOE, the engineering design of OWTs should not be overly conservative. To devise such an optimal turbine design, access to site-specific, high-resolution, three-dimensional turbulent inflow fields and underlying wave fields is of paramount importance. Since the next-generation OWTs are expected to reach heights of 300 m, inflow fields should also provide correspondingly large spatial coverage in both vertical and span-wise directions, while capturing the temporal correlations accurately.

It is needless to point out that the anticipated growth of the offshore wind energy development will eventually lead to collocation (and perhaps congestion) of numerous wind farms given the limited space in the North Sea. Thus, there is a dire need for a better understanding of physical interactions among turbines, as well as between wind farms. Accurate quantification of deep-array effects, global blockage, and other interactions will definitely aid in the reduction of LCOE.

Current state-of-the-art
The contemporary design standards and recommended practice documents for wind turbines (e.g. IEC 61400-3) provide specific guidelines for the generation of synthetic turbulent inflow. In recent years, the scientific community has clearly pointed out various fundamental issues associated with these guidelines. The wind energy industry is also beginning to recognize underlying limitations of the conventional approach and recently launched a joint industry project (JIP) to validate the existing turbulence models which are used for inflow generation. Lately, the wind industry has expressed serious concern over the global blockage and deep-array effects and has started providing some support for new research on these intriguing topics. New-generation coupled wave-atmosphere-wake modelling approaches are also being developed by a handful of alliances between the industry and academic and research institutes.

Proposed R&D topics

Research is urgently needed in order to generate a comprehensive turbulent inflow repository for the North Sea region which will facilitate the improved design of next-generation OWTs. Advanced coupled modelling frameworks (e.g. encompassing mesoscale motions, micro-scale turbulence, wave, and turbine aerodynamics) should be developed to accurately simulate wave-atmosphere-wake and farm-farm interactions. In the longer term, such coupled physical modelling frameworks (likely assisted by deep learning-based techniques) should be improved further to enable continuous operation in a short- and medium-term forecast mode.

Substantial research effort should be dedicated to the validation of numerically generated inflow fields and turbine loads. Intensive field experiments involving next-generation sensors (e.g. 3D wind scanner, spinner lidar, load monitoring sensors) should be conducted at various offshore locations.

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10 – Optimal turbine design, layout and control within wind farm

Author

Han la Poutré

Objective

Incorporate the character of atmospheric conditions in the design, layout and control within wind farms, using novel techniques from computational science, stochastics and optimization

Beacons

- Optimal wind farm design
- Strong support from stakeholders
- Net positive impact on the environment

Background

Given a collection of wind turbines, the design and spatial layout (or topology: how turbines are placed over an area) of the individual wind turbines and the wind farms as a whole are essential for their operation and energy revenue. The techniques for obtaining the proper designs, layouts and control are therefore essential.

Current state-of-the-art

The design and spatial layout of individual wind turbines within a wind farm has gained attention in the academic and industrial worlds. Several first results have been achieved, with promising perspectives.

Recently developed wind farms, such as the offshore Borssele farm, are designed based on engineering models in which the effects of climate, weather, wake effects, sea conditions and the associated uncertainties are only partially considered. With increasing turbine sizes, the interaction with the environment becomes increasingly important, and with the planned wind farms on the North Sea, the interaction between wind farms requires consideration.

Proposed R&D topics

Novel techniques from computational science, stochastics and optimization are required in order to incorporate the character of atmospheric conditions in the design and spatial planning of wind turbines within wind farms. Research must address the following challenges:

- How can atmospheric conditions (e.g. mesoscale models), wake models and farm-farm interaction effects be simulated and connected? How can reduced-order models and multiscale techniques in computational science be developed that enable the design and control of wind farms?
- Can one develop optimal control strategies using deep reinforcement learning (dRL). Since one has access to detailed engineering models for simulation, dRL might be a viable option for learning optimal control policies from data (observed or simulated)
- How can the stochastic nature of atmospheric conditions and wakes be modelled and taken into account? What is the effect on damage, wear, and operation and maintenance?
- How can the increasing amount of measurement data, such as lidar measurements, be efficiently assimilated to improve and calibrate model predictions?
- How can the design of wind farms incorporate the marine environment and marine activities?

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11 – Wind farm and turbine integrated design

Author
Richard Stevens

Objective
Optimal integrated design of wind farms and their individual turbines

Beacons
- Optimal wind farm design
- Strong support from stakeholders
- Net positive impact on the environment

Background
Nowadays, wind farm design is seen separately from wind turbine design. Typically, one first designs a wind turbine by considering it as a separate operating unit. During wind farm design, one selects the most suitable wind turbine available on the market. However, this approach does not take into account that wind turbines inside the wind farm experience very different operating conditions than turbines at the edge of the farm. For example, the mean wind speed and shear, turbulence intensity, and wake effects are very different for turbines located at different locations in the wind farm, and this may have significant consequences for their optimal design. Therefore, it is questionable whether this is the best possible design approach. Most likely, a better design is possible when a comprehensive, integrated design approach is used.

Current state-of-the-art
Wind turbine and wind farm design are strongly multidisciplinary, with strong couplings among the various disciplines, as many often competing aspects need to be considered. The disciplines involved include, but are not limited to, aerodynamics and flow physics, structures and materials, dynamics and controls, as well as hydrodynamics in the case of offshore applications. State-of-the-art wind turbine design requires an evaluation of the aerodynamic performance, loads, dynamic response and stability in normal and extreme operating conditions. Even after decades of enormous developments in wind power technology, there are still many areas where improvements can be made which can lead to significant performance improvements. The wind turbine design process is based on iterations among discipline-oriented specialists. Each group addresses a sub-discipline, such as aerodynamics, structures, controls and systems, and proposes solutions for their specific sub-discipline that are passed to the next group. Iterations among the groups are used to compromise on a solution that satisfies all requirements and constraints. This approach limits the design space that can be explored and probably leads to suboptimal design choices, already at the turbine level. For turbines located inside the wind farm, the operating conditions are very different from the standard atmospheric conditions that are considered during turbine design, which further limits the optimization of their design.

Proposed R&D topics
New approaches will be explored to achieve an optimal integrated design of wind farms and their individual turbines.
The development of an integrated design approach, in which all relevant aspects are considered, is necessary. An integrated design approach might require modifications to algorithms and specific design tools used by various sub-disciplines, and strong coupling

among disciplines is necessary. For example, blade design not only affects aerodynamic performance and power production but also indirectly the loads and the size of structural components and the generator. It is crucial that the operational scenarios considered in the design process faithfully represent the conditions that will be encountered by the turbine throughout its lifetime. Current design and certification guidelines focus on the operating conditions for single turbines. However, these guidelines should be updated to include more details on atmospheric conditions and phenomena like low-level jets, and provide an accurate description of the turbulence, wake and shear effects within a wind farm.

The design problem does not stop at the wind turbine level but should include the entire wind farm in which the turbines operate together and interact with each other and with the environment. Such an integrated design will require the combination of wind turbine and wind farm design tools. An integrated design may result in paradigm shifts in how we design wind farms. Would it, for example, be possible to design wind farms in which the turbines are more densely packed to reduce sea surface use and cost of connections by designing unique rotors and controls adapted to the wake conditions encountered in wind farms? Alternatively, should components like the drivetrain or tower be adjusted to account for the wake conditions encountered by turbines inside the wind farm?

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12 – Optimal wind farm spatial planning

Author
Richard Stevens

Objective
Understand large-scale aerodynamic interactions between wind farms to better design extended wind farms and wind farm clusters

Beacons
- Optimal wind farm design
- Strong support from stakeholders
- Net positive impact on the environment

Background
The ambitious plans for offshore wind power will require a significant portion of the North Sea area. Offshore wind developments need to share space with other sea users like fisheries, oil and gas exploration, shipping and the military, as well as with recreational users. The assessment of the suitability of wind farm sites depends on the wind conditions but can be limited by constraints based on environmental legislation, social aspects and exclusion areas. For example, wind farms cannot be built in protected national parks for environmental reasons or close to cities due to social acceptance. In some cases, spatial planning can promote complementary use of the available space; for example, offshore wind farms may act as artificial reefs for fish and other sea organisms, which can improve the marine environment. In other cases, spatial claims of wind farms may conflict with other users. Spatial planning of wind farms requires meticulous planning as aerodynamic interactions within and between large wind farms need to be considered. An appropriate geographical distribution, i.e. building wind farms at different locations, can improve the availability of wind power as it is less likely that wind resource is low at two places that are far apart.

Current state-of-the-art
Before wind farms are commissioned, the wind conditions at the site of interest are characterized. While these measurements provide crucial insight into the available wind resource, they do not provide information on long-term variations in the wind resource or effects caused by nearby wind farms. For example, the operation of an offshore wind farm downwind of another wind farm influences the mean wind speeds and turbulence levels and therefore affects the performance of the downwind wind farm. Also, recently, it was found that due to blockage effects, performance estimates for extended wind farms can be inaccurate, but detailed insight into this phenomenon is still lacking. Insight into such phenomena is crucial to improve wind farm design and appropriate design of wind farm clusters. Estimates for wind conditions at a wind farm site are obtained from field measurements or weather models. A better understanding of how the conditions at different locations are correlated can provide insight into the benefit of building wind farms in different geographical locations.

Proposed R&D topics
The optimal design of extended wind farms and wind farm clusters necessitates detailed insight into the large-scale aerodynamic interactions between wind farms, which need to be better understood. For example, understanding the development of the wake behind a large wind farm is crucial to predict the performance of downwind wind farms accurately. Also, wind farm

blockage needs to be better understood and modelled. The development of high-fidelity simulations and physical models is necessary to achieve this and get a better understanding of these effects. Also, new experiments are required to validate the simulations and modelling findings on these large-scale flow phenomena.

The implications of the geographical distribution of wind farms need to be understood. Developing wind farms in different locations can improve the availability of wind power as variation in the wind resource at different sites can level each other out. Simulations and field measurement campaigns are required to get insight into the best distribution of wind farms in the North Sea area.

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13 – Optimal design of grid connection

Authors

Mohamad Ghaffarian Niasar, Pavol Bauer

Objective

Optimal design of the connection of the wind farm to the power grid

Beacon

- Optimal integration into energy system

Background

An important aspect of offshore wind farm design is optimization of the offshore wind farm capacity with respect to the capacity of inter-array and export electrical infrastructure. The so-called overplanting (installing a small number of extra wind turbines compared to grid connection capacity) results in higher energy yield at lower wind speeds but leads to power curtailment at higher wind speeds. Higher initial investment in extra wind turbines has to be balanced with the extra revenue gained by extra energy yield due to overplanting [2, 3]. To properly perform such optimization, dynamic modelling of inter-array and export cable connections is needed to identify the limits so that such connections can be better utilized (by means of temporary overloading).

Current state-of-the-art

Optimization of offshore wind farm capacity and overplanting has been studied over the last decade. Different countries have suggested different values of overplanting as the optimum choice. The UK electricity transmission grid operator (National Grid) has set 12% overplanting as the optimum setup, while Ireland has raised the cap to 20% and the Dutch Ministry of Economic Affairs has allowed up to 8% of overplanting in the Borssele wind farm [1]. Such a considerable spread between optimal overplanting levels shows the strong dependency between wind farm technology, geographical location, electrical infrastructure used and the regulatory framework that the wind farm is embedded in. As such, an accurate level of overplanting and capacity optimization of the wind farm requires the development of advanced models and tools that take into account the limitations imposed by different components of offshore grid electrical infrastructures.

Proposed R&D topics

- Development of tools and methods to accurately calculate dynamic rating of electrical components of an offshore grid, in particular subsea AC and DC cables and their accessories as well as transformers and converters in offshore substations and wind turbines
- Development of optimization routines for optimal wind farm design, taking into account overplanting and current rating of electrical infrastructures
- Development of alternative solutions to increase capacity of the offshore grid, e.g. submarine electric pipeline, improved cable design with higher current rating, possibility of using dynamic voltage rating, improved cable insulation material to achieve higher capacity

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14 – Grid redundancy through modularity

Authors
Pavol Bauer, Pavel Purgat

Objective
Define the modules and platform with interfaces such that grid redundancy is maximized, maintenance costs are minimized and further technology innovation of modules is enabled

Beacons
- Optimal integration into energy system
- Supply chain efficiency
- Zero breakdown

Background
Modularity was the key concept in the commercial success of the IBM System/360 or Volkswagen vehicles. A modular approach proved to be an astonishingly powerful tool to beat complexity, especially in lower-volume industries [3]. The main benefits of modular designs across industries are increased portfolios with tailored solutions, reduced costs in design and production and, specifically in power electronics-intensive applications, increased system availability [5].

Offshore wind generation is known for high maintenance costs and harsh conditions in which the hardware must operate. Therefore, research has focused on predictive maintenance and design of robust power electronics systems that enable operation under harsh conditions and allow for well-planned maintenance [4]. However, a comprehensive approach to define a platform with modules is lacking. Therefore, the gains in availability of energy stemming from previous research can be considered limited.

Current state-of-the-art
Power Electronic Building Block (PEBB) was a successful research project financed by the US Navy to define functional power electronics blocks that can be used to increase the power availability and system resiliency of warships [1]. A second very successful project in modular power electronics was Integrated Power Electronic Module (IPEM) from the Centre for Power Electronic Systems (CPES) [2]. Both concepts brought to the field concurrent engineering and faster design and manufacturing. These results could be of benefit in wind energy research.

Redundancy can be achieved via modularization based on functional division. So far, three distinct possibilities for the availability increase of wind energy have been investigated. Firstly, a converter which consists of *N+1* paralleled modules can positively contribute to higher availability. The second option is to connect one converter per phase and then cascade the converters. Redundancy is achieved, and in the case of failure, a faulty phase can be bypassed. The last option is to use multilevel converters with inherent redundancy.

Proposed R&D topics
- Module lead (scale and innovation)
    - Define and develop basic building blocks based on identifying technical commonalities across subsystems (e.g. generator subsystem, grid converter subsystems)
    - Generator subsystems

- Generator modularity – Explore physical modularity of the generator to reduce the maintenance time
- Cooling system modularity – Explore options of an increasing lifetime via active cooling of physical generator modules
- Generator drive modularity – Investigate possible commonalities with grid converters
- Grid converter subsystems
  - Active modules – Develop intelligent switching modules designed for predictive maintenance
  - Active filter modules – Design active filer modules to reduce total filter size, increase filter lifetime, ensure simple and fast maintenance
  - Passive Modules – Develop integrated passive modules to reduce size and reduce maintenance time
- Platform lead (architecture and integration)
  - Multi-objective optimization of defined subsystems to analyse the trade-offs of highly modular systems. Examples of possible trade-offs are the total cost of ownership vs. lifetime, availability vs. efficiency, modularized subsystems vs. integrated subsystems (e.g. generator drive)
  - Ensure feedback to the module lead for knowledge reuse

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15 – 100% stable DC connection

Authors

Pavol Bauer, Laura Ramirez Elizondo

Objective

Control strategies and suitable converter design to ensure 100% stable DC connection

Beacons

- Optimal integration into energy system
- Full international connectivity
- Zero breakdown

Background

The electrical power system is facing new challenges due to the increasing amount of distributed energy resources with stochastic behavior, with offshore wind as one of the most prominent ones. While the grid has traditionally been operated with alternating current (AC), HVDC is seen to be preferable for applications such as the interconnection of offshore wind farms and the main grid for long-distance connections.

For example, HVDC has technical benefits in relation to HVAC offshore wind connections. An HVDC system has lower losses than an HVAC system. The CIGRE Technical Brochure 483, "Guidelines for the Design and Construction of AC Offshore Substations for Wind Power Plants", states that HVDC is a more economical solution for a wind power plant located more than 50 to 100 km offshore and larger than 200 MW. In terms of protection, a DC link can limit fault propagation from the wind farm to the main grid, and from the main grid to the wind farm.

Nevertheless, many challenges have to be tackled in order to achieve a 100% stable connection, for example more flexible coordinated control, stable transition between connection and disconnection of offshore farms, and suitable converter design to reduce the losses further and allow more flexibility in the network. Little attention is paid to offshore wind farm electrical infrastructure with completely DC connection between the wind turbine generators.

Current state-of-the-art

Line commutated converters (LCCs) and voltage sourced converters (VSCs) have been proposed for offshore wind farms. VSCs have been widely used in HVDC-connected offshore wind farms. Some of the advantages obtained from using these two technologies are: independent control of active and reactive power, ability to connect to weak AC grids, capability to black start, more compact converter station with less or no filtering, etc. Other options for connecting HVDC have been proposed in recent years to reduce the complexity of the offshore substation and increase flexibility, however more research in this field is required. Modularity and coordinated control mechanisms can serve as a way to transform networks with high participation of offshore wind power systems into more flexible and resilient ones. Offshore wind farm electrical infrastructure with completely DC connection between the wind turbine generators is not addressed yet due to lack of experience and lack of appropriate components. However, complete DC wind farm electrical infrastructure has the potential for higher modularity, flexibility and lower costs.

Proposed R&D topics

- Developing control strategies that account for the negative effects of communication delays and stochastic nature of wind power generation. This will facilitate more flexibility and resiliency in the network
- Developing a suitable converter design to reduce the losses further and allow more flexibility in the network. Modularity concepts should be implemented to enable further flexibility of HVDC connection and also DC electrical infrastructure
- Executing stability studies focused on the connection and disconnection of offshore wind farms to identify the effect of these transitions on the network. This will help to further improve the control mechanisms and converter requirements

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16 – Grid harmonics mitigation and resonance damping

Authors
Zian Qin, Pavol Bauer

Objective
Grid harmonics mitigation and resonance damping through wind farm model development, interconnected system analysis and advanced control strategies

Beacons
- Optimal integration into energy system
- Zero breakdown

Background
The Grid Code specifies power quality requirements with regard to the harmonic distortion at the point of common coupling (PCC) of connections. Most new wind farm connections will include significant cable lengths, which may amplify already present harmonics. In addition, the replacement of thermal generation by converter-based technologies may result in more generation of harmonics. The combination of these factors will have a negative effect on power quality [1].

Current state-of-the-art
During the harmonic assessment of a new offshore wind power plant connection, it is current industry practice to rely on numerical models, which do not offer clear insights into the actual relationships between certain design choices or parameters and the global behavior of the farm at the PCC. Understanding is drawn mainly from simulations in an attempt to gain insight into the cause-effect relationships in the farm. Whenever a harmonic problem is detected at a certain frequency (e.g. a very under-damped resonant point or a very high emission at a certain harmonic), an overdesigned passive filter is then installed at the PCC. However, the passive filter only depresses the harmonics injected into the grid, while the resonance issue inside the farm will still remain. Moreover, the passive filter has a very high cost, and provides no flexibility so their adaptation to new situations (e.g. wind farm expansions) is challenging.

Proposed R&D topics
To achieve grid harmonics mitigation and resonance damping, it is essential to explore the potential of other solutions that might help to avoid the installation or to reduce the size of these passive filters in certain situations. The first step will be the development of an analytical model, which aggregates wind power converters, transformers and array cables in the offshore wind farm. Moreover, with the developed model, the impact of different design parameters on the harmonics and resonance of the wind farm can be analysed [2, 3]. On top of that, recommendations for design requirements of the offshore wind farm for harmonics mitigation and resonance damping can be given. Consequently, the harmonics and resonance issues in offshore wind farms are expected to be mitigated in the design phase, or even by means of advanced control strategies of the wind turbines, which compared with the passive filter approach will be much more flexible and cost effective.

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17 – Mitigating physical failure of cables

Authors
Olaf Waals, Erik-Jan de Ridder

Objective
Mitigate physical failure of cables through load alleviation and monitoring during installation, operation and maintenance

Beacons
- Optimal integration into energy system
- Zero breakdown

Background
Failures of inter-array and export cables of offshore wind farms can result in significant loss of revenue, which particularly holds for power cables in highly dynamic environments. Therefore, the offshore wind industry requires innovations that make power cables less susceptible to failures, fatigue, wear and tear during both the cable installation and the operation of the project.

Current state-of-the-art
As of January 2017, around 4,600 subsea cables were laid and are serving fixed offshore wind farms worldwide. Research on insurance claims has been performed by insurance specialist Genillard & Co GMBH [1], which claims that "there are around 10 declared incidents annually of cable failure, with an average cable downtime of 100 days". Furthermore, it is stated that subsea cable incidents account for between 70% and 80% of the total global cost of offshore wind farm insurance losses and account for only 10% of the overall cost of an offshore wind project.

Proposed R&D topics
These cable failures will increase even further when the industry also develops floating wind farms due to the dynamic loading of the cable during the O&M phase. Therefore, this milestone will focus on cable load alleviation and monitoring during installation, operation and maintenance. The following research topics will be addressed here:

- Installation procedures
- Fatigue load due to vortex induced vibration (VIV), trenching, wave motions, sand waves, etc.
- Unmanned installation and maintenance using autonomous underwater vehicles (AUVs)
- Extreme load mitigation: emergency disconnect/connect systems

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18 – Strong, lightweight, durable composites for blades

Authors

Clemens Dransfeld, Julie Teuwen

Objective

Novel, coated composites with high strength, low weight, good processability, high fracture toughness and supreme durability

Beacons

- Low cost from larger turbine size
- Supply chain efficiency
- Zero breakdown

Background

Fiber-reinforced polymer composites are of great importance for the construction of wind turbine rotor blades. Their high strength- and stiffness-to-weight ratio makes them ideal for highly tailored engineering applications. The lifetime of such blades, however, is limited by the fatigue damage of the composite and by erosion, which may lead to premature blade exchange or repairs in offshore conditions.

Current state-of-the-art

Such fiber-reinforced polymer composites are supremely effective when exploiting their properties in the fiber direction, however, the thermosetting polymer matrix is typically brittle and has a limited fracture toughness. Known methods to increase the toughness and hence the fatigue life of the matrix comes at the cost of processability and compromises the manufacturability of the large-scale structures, or the heterogeneity of the matrix, leading to processing limitation [1]. In nature, structures achieve outstanding performance by intricately structuring soft and brittle phases in a hierarchical manner [3], but limited approaches [2] are known to translate these biological design principles to synthetic materials.

Proposed R&D topics

- Novel thermosetting matrix systems with tailored heterogeneous and hierarchical structures from the molecular level up to the mesoscale, overcoming the paradigm of processability and structural performance
- Erosion coatings with self-assembled bioinspired brick-and-mortar architectures and structure gradient for supreme durability
- Discontinuous multi-scale composites, synergistically exploiting intrinsic and extrinsic toughening mechanisms, resulting in high fracture toughness in spite of dominant brittle constituents

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19 – Self-healing and healable materials

Author

Santiago J. Garcia

Objective

Realize more reliable, durable and sustainable components for wind farms through the development and implementation of processable and healable (dynamic) polymeric matrices for composites and thin films, and sensors integration

Beacons

- Supply chain efficiency
- Zero breakdown

Background

Maintenance of (offshore) wind farm structures is currently at its infancy as, in practice, they are often described and treated as "black boxes". In other words, manufacturing and maintenance practices have not yet been fully translated from metals to composites; for instance, patching or bolting of composite materials is common practice in structural repairs [2].

The growth of wind farms will inevitably increase maintenance and related costs. Self-healing or healable materials could help to increase reliability of such structures and components of wind farms as well as decrease related maintenance costs [1].

This milestone will develop the structural or functional components of the future that are able to respond to damage in a smarter way, using integrated detection-heal concepts or detection-light active human intervention.

Current state-of-the-art

The self-healing materials field is a mature field where application-driven research parallels the development of new chemical approaches and deeper scientific and technological understanding of the healing process. The Netherlands has a strong international position in several application areas, such as concrete and asphalt that have reached the market. Our strong position in characterization of polymeric healing materials and development of strong healable polymeric systems [3] is a unique starting point to redirect our research efforts towards application-driven research in the largely unexplored area of wind energy structures and functional components.

Proposed R&D topics

Self-healing and healable components will be developed and implemented through:

- Development of processable and healable (dynamic) polymeric matrices for (fiber) composites and/or thin films (e.g. coatings, adhesives), fully or partially based on sustainable raw materials
- Development and integration of healing strategies and sensors in functional components and structures for wind farms
- Development of sense-heal strategies and prediction models for reduced maintenance, making use of the self-healing concept

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20 – Direct measurement of fatigue life in support structures

Author
Andrei Metrikine

Objective
Magnetic, electric and electro-magnetic sensors that allow for the direct measurements of the inner structure of metals and the level of fatigue at large scale

Beacons
- Low cost from larger turbine size
- Zero breakdown

Background
It is fatigue that usually drives the design of foundations of offshore wind turbines [1]. By means of advanced monitoring of vibrations of the foundations, the remaining fatigue life can be estimated and a decision can be made as to whether an intervention is needed and/or removal of the foundation is required [2]. The accuracy of this estimation is questionable, and in order to enable significant extension of the service life, methods and hardware should be developed that allow for the direct measurement of fatigue state at a large scale while the turbines are in operation.

Current state-of-the-art
Strictly speaking, direct measurement of fatigue in metals can be done only with the help of inspection techniques that use very short waves capable of resolving the micro-structure of the metal. It is unlikely that such a technique can be used offshore at a large scale. Therefore, devices that are sensitive to small changes in the material (domain) structure of the metal should be used. Such techniques are necessarily associated with the use of the electromagnetic field. While extremely sensitive sensors of the electromagnetic field have become available on the market in recent years, no use has been made as yet for identification of the fatigue state of offshore structures.

Proposed R&D topics
Research effort is proposed on the development and testing of magnetic, electric and electromagnetic sensors that allow for the direct measurement of the inner structure of metals at a large scale. The fundamental challenge lies in the identification of the changes in the electromagnetic field around a metal structure that can be one-to-one associated with the level of fatigue of the metal.

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21 – Characterization of composites resistance

Author
René Alderliesten

Objective
Energy-based concept to derive constant fatigue life diagrams. Strain energy density theory for damage tolerance evaluation of structural composite details

Beacons
- Low cost from larger turbine size
- Zero breakdown

Background
To enable production of larger turbine sizes, current limiting factors in upscaling the size must be tackled. These limiting factors relate either to mass, in terms of material weight and density, or they relate to margins of safety and safety factors. To reduce the weight of turbine blades, more efficient use of materials must be achieved, while reducing the required safety factors in design. For this aim to be realized, however, better understanding and predictive methodologies for durability and damage gradation are required.

Current state-of-the-art
Structural integrity and durability are currently addressed by selectively evaluating long-term material behavior and damage resistance of specific details identified as potential damage initiators. This implies extensive material testing, generating fatigue life curves, allowing interpolation over constant life data to predict the fatigue lifetime of the materials used. Additionally, this requires extensive testing of multiple detailed design solutions, like ply drop-offs, load introductions, etc., to estimate the corresponding lifetime.

This lack of a generalized approach to a better estimate of material and structural detail response is attributed to the empirical and highly phenomenological level of state-of-art fatigue and fracture assessment. A more intuitive physics-based concept to understand and characterize materials and details is needed.

Proposed R&D topics
- **Durability** – Developing an energy-based concept to derive constant fatigue life diagrams. Instead of stress life, fatigue should be considered physically in terms of (cyclically) applied work (energy) and the dissipation of that energy through fracture mechanisms (intrinsic material resistance) [2]. This topic aims to develop a more intuitive physics-based methodology to describe the durability of composite materials
- **Damage tolerance** – Developing a strain energy density theory for damage tolerance evaluation of structural composite details. Instead of phenomenologically relating damage growth to linear elastic fracture mechanics (LEFM), parameters like strain energy release rate and strain energy density will be considered to identify the onset of fracture [1, 3], while energy dissipation mechanisms will be developed to characterize the intrinsic resistance to damage growth

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22 – Life-cycle assessment of composite blades

Authors

Clemens Dransfeld, Julie Teuwen

Objective

Life-cycle assessment of novel thermoset and thermoplastics manufacturing processes for large-scale fiber-reinforced polymer composites and their joining methods for comparison with alternative materials and technologies

Beacons

- Strong support from stakeholders
- Net positive impact on the environment

Background

Fiber-reinforced polymer composites are of great importance for the construction of wind turbine rotor blades. Their high strength- and stiffness-to-weight ratio makes them ideal for highly tailored engineering applications. The increasing size of the components is currently approached by upscaling current design principles and manufacturing technologies. Considering the production volumes, size and offshore location of future wind turbines, the sustainability of this approach requires close attention [3].

Current state-of-the-art

An accurate assessment of such manufacturing technologies for large (composite) structures requires detailed modelling to evaluate direct costs and burdens [1], life-cycle analysis [4], environmental analysis, as well as health impacts. Little work is being undertaken in the public domain that focuses on the impact of novel manufacturing scenarios [2] in the technology assessment of large-scale offshore wind turbines.

Proposed R&D topics

- Accurate modelling towards a dedicated life-cycle inventory of novel thermoset and thermoplastics manufacturing processes for large-scale fiber-reinforced polymer composites and their joining methods for comparison with alternative technologies
- Assessment of technological and environmental impacts of novel manufacturing scenarios over the whole life-cycle, under consideration of different end-of-life scenarios

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23 – Recycling methods for fiber-reinforced polymers

Authors
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Objective
Circular design and recycling methods for glass- or carbon fiber-reinforced polymers

Beacons
- Low cost from larger turbine size
- Strong support from stakeholders
- Net positive impact on the environment

Background
Fiber-reinforced polymers based on carbon and glass fibers offer high strength and stiffness at low weight and are therefore key materials for the realization of very large wind turbine blades. With increasing size and manufacturing volumes, the end-of-life scenarios of such parts becomes a major concern [4] and could become a show-stopper for the sustainable growth of this industry. The current approach to shred and landfill used blades is likely to be prohibited by legislation, and carbon fiber-reinforced polymers are already being increasingly banned from incineration plants as the electrostatic precipitator for dedusting flue gases can be short-circuited from fiber residues. New recycling methods will mitigate the technological and legislation-driven challenges relating to the end-of-life of wind turbine blades and will enable the sustainable growth of this industry.

Current state-of-the-art
As carbon fibers are very energy intensive in their original production, increasing effort is dedicated to recycling methods which recover the fiber and combust the polymer matrix, e.g. via pyrolysis [2] or solvolysis [1] methods. In the latter method, a value stream for the polymer residue is still to be identified. Reclaimed glass and carbon fibers from existing recycling processes are always discontinuous, but efficient methods for realignment are still only emerging and not well understood in their processing and structural performance. In principle, thermoplastic matrix systems would offer the possibility to be reprocessed in the molten state, but limited approaches [3] have been identified due to the high fiber volume content and the lack of scalable processing for thermoplastic composite manufacturing methods.

Proposed R&D topics
- Development of circular design approaches for reclaimed fibers, addressing the aspect of resizing, recombination and high-fidelity realignment and impregnation as well as understanding and tailoring the discontinuous fiber architecture towards high-performance, damage-tolerant materials
- Development of circular design approaches for thermoplastic composites with potential scalability of size reduction methods and tailored performance of the reprocessed discontinuous mesostructures

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24 – Availability of materials

Authors

Ton Veltkamp, Novita Saraswati, Edwin Wiggelinkhuizen

Objective

Assess the future availability and cost of materials for offshore wind turbines

Beacons

- Low cost from larger turbine size
- Strong support from stakeholders
- Net positive impact on the environment

Background

Triggered by the unprecedented and dramatic increase in rare earth market prices in 2011, a global awareness arose on the availability of critical materials for high-tech technologies such as wind turbines and solar modules. Early studies in this field focused on short- to medium-term risks and effects of potential materials shortages and competition for materials [1-3].

Since 2011, offshore wind energy technologies have changed quite dramatically, as evident from e.g. the upscaling of wind turbines, the large-scale offshore wind deployment, and need for smart grid connection. Moreover, the wind turbine manufacturing industry has changed considerably over the last decade, showing consolidation in only a few very large companies in a few geographical areas. The costs of wind energy have dropped.

It is therefore imperative to provide a state-of-the-art critical review of materials availability and costs for the energy transition in the Netherlands, based on very large-scale offshore wind power deployment. The review will also include medium- to long-term risks and effects, such as on the competitive capacity of wind energy to access critical materials.

Current state-of-the-art

As mentioned, first studies addressed the short- to medium-term economic, political and geographical critical materials factors that could adversely affect large-scale deployment of renewable energy technologies [1-3]. Since 2010, the development of offshore wind energy has shown tremendous changes and this warrants an update of these studies and their basic assumptions.

While some material and alloys used in offshore wind turbines seems obvious, such as steel, magnetic materials, zinc, aluminium and copper, it is not so obvious how at the end of a wind turbines life these materials in large quantities can be reused or recycled.

In offshore wind turbines, some materials, especially metals and rare earth materials, are also used in different quantities depending on the wind turbine's size and design. Examples of these metals are chromium, boron, cobalt, lead, molybdenum, nickel and rare earth materials like dysprosium, neodymium, praseodymium and terbium. The environmental impact of the use of these elements is still under investigation. For example, current neodymium production and supply chains involve entwined economic, environmental and geopolitical challenges.

Proposed R&D topics

To assess the future availability and costs of materials for offshore wind turbines, the following topics will be addressed in a critical review of the available information:

- Update on installed capacity and future installed capacity scenarios relevant for Europe and the Netherlands
- Update on applied offshore wind turbine technologies (e.g. gearbox versus direct drive) and future technology scenarios. How does materials availability interact with wind turbine technology choices? Which technologies are most robust towards materials scarcity and costs?
- Update on global distribution of offshore wind turbine manufacturing and potential risks involved
- Update on competitive capacity of low-cost wind energy to compete (with other high-tech products, such as electrical vehicles and consumer products) on the free market for scarce materials. Or in other words, how will future materials scarcity affect the costs of offshore wind energy?
- Status (and importance for mitigating materials scarcity) of recycling offshore wind turbine components
- Effect of materials availability on grid connection and energy storage

The review will address the time period 2020-2100.

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25 – Flexible offshore wind farms

Authors

Richard Stevens, Simon Watson, Edwin Wiggelinkhuizen

Objective

Enhanced controllability/dispatchability through improved wind farm control methods, for optimal integration into the energy system

Beacon

- Optimal integration into energy system

Background

Current offshore wind farms are optimized for maximum annual production at minimum levelized cost of energy (LCOE). Developments in larger blade sizes and load mitigation techniques like storm control, as well as decreasing subsidy levels, have led to increasing wind turbine and wind farm capacity factors in recent years. This has increased annual energy production, especially at lower wind speeds where market prices tend to be higher. As offshore wind farms are getting bigger, there has to be a paradigm shift that extends from wind turbine control to wind farm (or farm cluster) control. With the increasing share of wind in the energy system, new challenges emerge as wind power will have to provide more ancillary services to ensure the stability and efficiency of the power grid. Also, offshore wind energy will be increasingly subjected to changing market dynamics, as the energy system will transition from fossil fuel-based energy sources to renewables. It will be essential to have reliable power production forecasts as well as the technical built-in features to increase reliability to achieve this. More accurate forecasts will also allow the development of control schemes that will allow "on demand" power production. New control algorithms will also facilitate the development of wind turbines that do not break down and reduce maintenance costs by reducing the load on and the fatigue of the turbines.

Current state-of-the-art

Modern wind turbines have controls that ensure that they are aligned with the main wind direction while the rotational speed of the blades is adjusted to maximize power production up to the generator’s rated output. Additionally, controllers to reduce structural loads on individual components are in place. Typically, control is performed on a turbine level, without taking information or impact on other turbines into account. However, for successful wind farm control, communication between turbines will be required. In addition, excellent insight and models to provide real-time prediction of the flow and wind farm power production will be necessary. Nowadays, wind power production forecasts are often provided by using statistical methods or by using simplified physical modelling approaches. High fidelity computational fluid dynamics simulations, which can capture the characteristics of the atmospheric boundary layer and the turbulent wind turbine wakes in detail, are in many cases only available for ideal conditions and not in real time. Even the analysis of these state-of-the-art simulations is often limited to average flow quantities.

Proposed R&D topics

- **Development of dynamic controllers** – Improving the integration of wind power into the energy system requires the development of dynamic control strategies, which require wind turbines to achieve power setpoints that are determined by the grid operator and the market, instead of just optimizing power production. The fundamental scientific challenge is to develop robust controllers that take the flow dynamics and turbulence characteristics inside the wind farm into account to allow wind farms to provide ancillary power services

- **Development of models that provide detailed information on the wind flow conditions at wind turbine and wind farm scale** – Achieving robust dynamic controllers requires better physical insight into the flow dynamics and turbulence characteristics inside the wind farm. Also, it will be crucial to realize controllers that can handle conflicting control goals to ensure that fatigue loads on blades and towers can be limited. Decreasing these loads will increase the turbine lifetime and lower maintenance costs. The rapid advancement of sensors will improve the quality and the quantity of data that can be used to inform the controller about the wind turbine, while machine learning and uncertainty quantification techniques can be applied using the available data to improve maintenance scheduling
- **Development of integrated and multiscale models for simulation and control** – Nowadays, the employed control schemes are often simple, taking input from a single sensor to control a single output. In the future, detailed high-fidelity simulations will drive the advancement of reduced-order and physical models that can be used to make real-time predictions of key wind farm performance indicators. Together, all these models can be used to construct digital wind farm twins, which can be used to develop and verify new control schemes. A digital twin can also provide useful forecasts for crucial wind turbine and wind farm performance indicators. Controllers can take advantage of these physically motivated predictions to ensure that the control does not only act on current performance indicators measured by sensors but also anticipates upcoming events. A particular challenge will be that the range of relevant time scales is enormous, ranging from sub-second turbulent fluctuations at blade level to large-scale weather variations that take place over days. Integrating all models that describe the relevant physics at the appropriate time and length scales in the digital wind farm twin such that the controllers can obtain real-time forecasts for key performance indicators in real time will be an incredible challenge

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26 – Innovative offshore energy storage

Author
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Objective
Innovative technology for the offshore storage of energy

Beacons
- Optimal integration into energy system
- Full international interconnectivity

Background
The storage of energy generated by offshore wind turbines is becoming an ever-growing challenge due to the increasing amounts of generated energy. Currently, the energy is mainly stored in electrical form using batteries. This needs to be diversified and new types of energy storage with significant capacity have to be developed, preferably at source (offshore).

Current state-of-the-art
Many technologies exist that could enable alternatives to electrical energy storage using batteries [3]. These are, to name a few, compressed air storage, pumped hydro storage, flywheels, supercapacitors [1, 4], and transformation of power into gas and/or liquid hydrogen that can be stored in tanks on old oil & gas platforms or on floating or artificial islands (see figure 21).

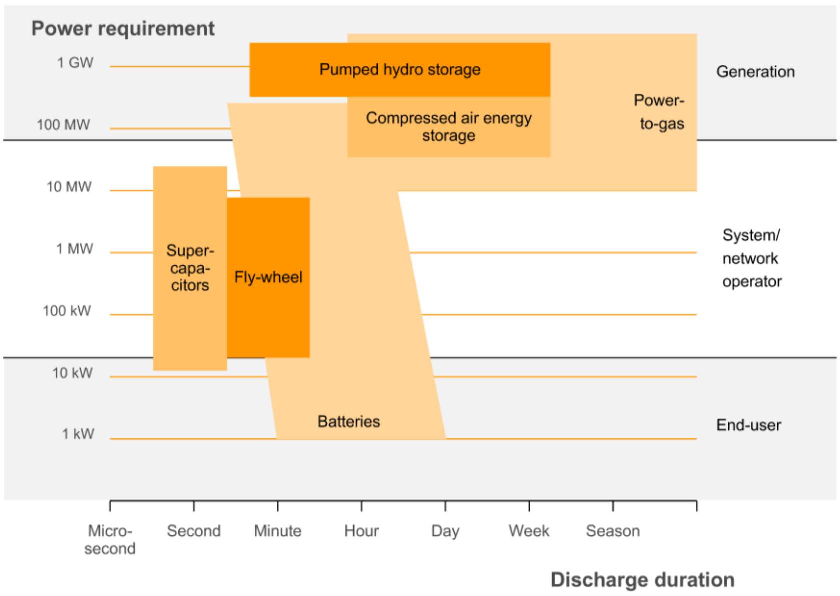

Figure 21 – Storage technologies [2]

The main unresolved challenges are associated with storage efficiency and possibilities offshore and the transformation of power to hydrogen offshore. These need to be addressed and resolved in the coming 10 years, parallel to the improvement of electrical storage capabilities.

Proposed R&D topics

Research effort is proposed on the development of high-pressure energy storage and the development of compact facilities for conversion of power into gas and liquid hydrogen, in both tanks and on artificial islands. Floating facilities for energy storage will also be developed. Research into electric, electro-mechanical, thermal and superconducting magnetic energy storage will continue as well.

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27 – (Re)design and maintenance of energy system infrastructures surrounding wind farms

Author
Han la Poutré

Objective
Computer-aided (re)design, extension, and maintenance of wind farm energy systems, including wind turbines, networks, storage, conversion, transportation and interaction with the larger energy systems it is part of (national, international)

Beacons
- Optimal integration into energy system
- Full international interconnectivity

Background
Wind farms, together with their related offshore and local onshore networks (e.g. infrastructures for electricity transportation), conversion and storage facilities (e.g. gas), and other assets, and with various players and stakeholders, form a complex energy system. Such wind farm energy systems (WFES) deal with power generation by several energy types (e.g. wind, gas, and possibly solar, tidal and wave energy) and, in addition, are part of a larger (national/European) energy system.

Such WFESs need to be designed, extended, redesigned and maintained, focusing on good overall system performance, e.g. in terms of energy supply, congestion and storage management, and control of the wind turbines themselves. Therefore, the (re)design and maintenance of these systems should be optimized.

Current state-of-the-art
In the past, (re)design and maintenance of energy network infrastructures has mainly been done for conventional energy systems (like electricity networks) with central, dispatchable generation and predictable consumption. (Re)design and maintenance of future energy systems is a current and future focus of research and development, when considering intermittent and uncertain energy supply and the use of storage and conversion. The energy (sub)system formed by a WFES thus faces many important (re)design challenges, such as for the network topologies, the location and capacities of assets (e.g. storage, converters, cables), etc. Issues are to (re)design a WFES dealing with e.g. intermittent power generation from a wind farm; using storage (of various types) and conversion (to e.g. gas); addressing efficiency, effectiveness, scalability, and stability; and being part (subsystem) of a larger (integrated) energy system (national, European). Last but not least, the (fully) automated optimization of (re)designing WFES is still a large, open challenge, where current approaches (for less complex settings) are usually still based on guidelines, simulation and trial-and-error, thus being costly, time-consuming and suboptimal.

Proposed R&D topics
Novel techniques and knowledge should be obtained in the areas of electrical engineering, physical sciences, computer science, control theory, and mathematics and optimization, in order to deal with the computer-aided (re)design, extension and maintenance of WFESs, thus including wind turbines, networks, storage, conversion, transportation and interaction with the

larger energy systems it is part of (national, international). This concerns the timespan from days to decades. Some of the challenges include:

- What are proper methods and tools for (re)designing, extending and maintaining the WFESs for periods ranging from days (maintenance) to decades ((re)design, extension)?
- How can (re)designing, extending and maintaining these energy networks and other assets be optimized automatically? How can such automated methods and tools be developed, e.g. in terms of algorithms, AI, data, models, objectives, and automated optimization and simulation systems?
- How can lifespan and failures of WFESs and their parts be modelled and forecasted, e.g. by using data, sensors, algorithms and AI?

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28 – Control and operations of energy system surrounding wind farms

Author
Han la Poutré

Objective
Short-term automatic control and operations of wind farm energy systems, including wind turbines, networks, storage, conversion, transportation and interaction with the larger energy networks it is a subsystem of (national, international)

Beacons
- Optimal integration into energy system
- Full international interconnectivity

Background
Wind farm energy systems (WFESs) need to be operated and controlled. The operation and control should yield good overall system performance, e.g. in terms of energy supply and balancing, congestion management, network constraints, satisfaction, storage and conversion management, service level agreements between (external) parties, interaction with the external energy systems, and control of the wind turbines themselves. Therefore, the operations and control of these systems should be effective, efficient, optimized and digitalized.

Current state-of-the-art
Operations and control of smart energy systems is a current and future focus of research and development, when considering variable, uncertain energy supply and the use of storage and conversion. Some general (first) approaches have been developed, but advanced solutions for complex and dedicated, complex energy (sub)systems are still a challenge. Important open areas concerning future WFESs are how to deal with large, variable generators; various players (for energy services like storage and conversion); generators using multiple energy source types (wind, solar, tidal, etc.); addressing efficiency, effectiveness, scalability and stability; congestion and conversion management; and being part of (i.e. a subsystem of) a larger integrated energy system.

Proposed R&D topics
Novel techniques and knowledge should be obtained in the areas of electrical engineering, computer science, control theory, mathematics and optimization, and physical sciences in order to deal with the automatic control and operations of WFESs, including wind turbines, networks, storage, conversion, transportation and interaction with the larger energy networks it is part of as a subsystem (national, international). This concerns the timespan of seconds to minutes to hours. Some of the challenges include:
- What are proper automated solutions for controlling the network (e.g. congestion, supply security, energy balancing, network constraints) and other assets (storage, conversion) and (third-party) energy services, in timespans from seconds to hours?
- How to manage the limited storage and conversion capacities in an automated fashion, given that these need to be used over longer periods for storage (in case of excess supply) and supply (in case of excess demand) of energy?
- How to coordinate between multiple players and stakeholders in the WFESs? What kind of cooperation mechanisms, market mechanisms, or optimization and control methods can be obtained?

- What are proper techniques for the automation (digitalization) of control and management, e.g. algorithms, sensors, AI, data, simulation, modelling, etc.?
- How to control the wind turbines in the farm (with or without storage) to meet external requirements and service level agreements (SLAs), like active power control?

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29 – Combining wind energy generation with electrolysis to gas

Authors

Thiago Batista Soeiro, Pavol Bauer

Objective

Combining wind energy generation with electrolysis to gas through analytical modelling tools for the energy hub infrastructure, medium voltage megawatt power electronics of the hydrogen electrolyser, and intelligent power flow controller for the energy hub

Beacons

- Optimal integration into energy system
- Full international interconnectivity

Background

With a move towards a greener energy-based Europe, more distributed renewable energy generation based significantly on wind farms has been gradually replacing traditional high power synchronous generators powered by coal and gas. Unfortunately, the loss of these large synchronous generators raises concerns about system stability due to the loss of inertia. A decentralized virtual/synthetic inertia control strategy integrated into key grid-connected power electronics of the wind generators has been proposed to solve this issue [3], however the renewable generators may need to operate at a suboptimum level. That is to say, a renewable power plant such as a wind farm may need to generate power below the maximum power point available because a reserve level is necessary for fast recovery of the grid frequency and voltage stability during a fault. Alternatively, energy storage systems would allow all the renewable energy generation systems to operate at maximum power, optimizing the economical dispatch of energy while enabling the provision of grid ancillary services [2]. Among the energy storage technologies, fuel cells are particularly interesting because the derived hydrogen can be used as a fuel or stored to be employed later for production of electrical energy (seasonal storage). The hydrogen can be stored with the excess renewable energy and/or it can be transported to where it is needed via gas pipelines.

Current state-of-the-art

Due to the variable nature of renewable energy generation based on wind, its integration into the AC grid naturally requires additional ancillary service provision. This is typically performed by its integrated grid-connected power electronics [1]. This circuit can also be used to add synthetic/virtual inertia to the grid in order to assist in the frequency and voltage control during faults. Unfortunately, for the latter functionality, full control of the active and reactive power injected into the grid is necessary and the wind generation system may need to be operated at suboptimum power or below the maximum power point for long times. The integration into the grid of energy storage elements, commonly based on Li-Ion batteries, is done for energy congestion management, but it could also be used for participation in the ancillary service market. The usage of electrolysers for storage and use of hydrogen for grid support is less exploited than the previous options.

Proposed R&D topics

- **Development of analytical modelling tools for the energy hub infrastructure** – To accelerate the deployment of the energy hub infrastructure comprising wind generation and electrolyser systems, the derivation of accurate analytical models, economical and functional, for the system components is necessary for safe integration into the current European energy structure. This should focus on the definition of economical and efficiency trade-offs between the combination of conventional electricity grids and its components with renewable fuel with the required pipelines and tankers

- **Development of medium voltage megawatt power electronics of hydrogen electrolysers** – The objective of the research is to propose new power electronic solutions to enable the integration of low voltage DC electrolysers into the AC medium voltage grid. The impact and feasibility of incorporating virtual/synthetic inertia control and grid ancillary services into the power electronic functioning need to be understood. Circuit design merits such as cost, reliability and power efficiency need to consider while deriving circuits with superior performance than the current existing technology
- **Development of an intelligent power flow controller for the energy hub** – Power flow control becomes the heart of the energy hub infrastructure operation. This must understand and provide solutions to the variable wind power generation, the required system dispatch of energy, the necessary provision of ancillary service, and management of hydrogen storage/usage. Optimum economic and reliable operation is the main target of the power flow control

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30 – Meshed hybrid (AC-DC-H_2) offshore transmission system

Authors

Jose Rueda Torres, Pavol Bauer

Objective

Meshed hybrid (AC-DC-H_2) offshore transmission system through digital simulation and new coordinated control concepts

Beacons

- Optimal integration into energy system
- Full international interconnectivity

Background

Studies in existing literature show that combining energy carriers such as electricity and hydrogen can reduce offshore wind costs, and has the potential to contribute to managing the in-feed of variable offshore wind power generation 0. As acknowledged in the Infrastructure Outlook 2050 published by TenneT and Gasunie 0, a substantial research effort is needed to ascertain and understand in full detail the challenges of integrating and pursuing complementary operation of larger-scale offshore wind generation and large-scale power-to-gas (P2G) conversion and storage, which is essential for defining new techno-economic and operational principles for the offshore infrastructure needed for 2050.

Current state-of-the-art

The problem of simultaneous satisfaction of different objectives in a multi-energy hub (e.g. matching production and storage of hydrogen with variable renewable power generation, contribution of electrolysers to electrical network stability by demand-side response, minimization of operational costs, respecting the boundaries of power-to-gas conversion, storage and transportation) demands significant multidisciplinary research effort. Such a problem becomes even more complex considering the myriad of options associated with possible hardware design considerations, like the topology of the hub, rating and dynamic control capabilities of wind turbines and HVDC systems, necessary protection systems, the location, size and operational boundaries of large electrolysers, and facilities for transport and storage of hydrogen. Existing literature exclusively focuses on cost-benefit analysis of the feasibility of either using electrical renewable energy for production of hydrogen 0, or the design of the electrical infrastructure for offshore wind power generation and transmission based on available technology 0, which does not contemplate the necessary upgrades to tackle the large-scale nature of modular multi-energy hubs.

Proposed R&D topics

- Understanding the dynamic behavior of an offshore modular multi-energy hub, and definition of operational principles. Real-time digital simulation and hardware-in-the-loop tests as essential tools for accurate assessments for dynamic and non-linear phenomena
- Ensuring interoperability and reliability of multi-vendor power electronic converters used in an offshore transmission grid, offshore wind power plants, and large size electrolysers. Development of digital controls to interface and optimally coordinate components with different working, control and protection principles

- New control and protection concepts for an AC-DC offshore modular multi-energy hub, ensuring readiness for operation within a meshed offshore network with more multi-energy hubs (e.g. including H_2) as well as for interconnection with onshore systems
- New coordinated control concepts for provision of ancillary services on different time scales associated with multi-energy conversion and storage to safeguard the stability of onshore electrical power systems

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31 – Continuous, swarm-based autonomous subsea asset monitoring

Author
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Objective
Continuous monitoring of subsea assets through swarms of autonomous robots

Beacons
- Supply chain efficiency
- Zero breakdown

Background
Inspection is a crucial aspect of all asset management, especially in such an unstructured and hostile environment like the ocean. Wave action, currents, wind and corrosion are all complex to model, partly because of their stochastic nature. The interaction between these phenomena leads to even more complicated effects which can lead to accelerated failure of both above- and underwater assets, requiring repair or replacement. This is both costly and hazardous. Prevention is possible if such effects are detected in time. Swarm-based robotic monitoring could provide the means to efficiently and safely obtain data in the field. Swarms do not have single points of failure, as opposed to traditional robotic operations, thus making 100% uptime possible, and can operate 24/7 without human supervision [1].

Current state-of-the-art
Monitoring of offshore assets is considered a costly and dangerous task. A lot of shallow water operations are still conducted by human divers and classified "high hazard" by the HSE [2]. The industry is moving to more and more unmanned inspection and maintenance using remotely operated vehicles (ROVs), often equipped with hydraulic or electric arms and a range of end effectors. These robots are tethered to a topside support vessel, on which specialized personnel control the robots. Because of the winds and currents, these topside vessels tend to drift off, which can disturb their operation. Thus, these ships often have some sort of dynamic positioning system, costing a lot of fuel [3]. Because of the wave action and the heavy tethers, a tether management system is used to make sure the tether is not subjected to excessive forces. Overall, the above- to underwater interface tends to be very expensive to operate and maintain. Furthermore, despite the rugged (heavy) construction of the ROVs, failures are not uncommon, costing critical time. Autonomous underwater vehicles are starting to be used but often either remain limited in capabilities or prove unreliable.

Proposed R&D topics
To realize this milestone, R&D efforts should be focused on three topics: swarming, underwater communication and robust robotic navigation. Swarm robotics is a combination of swarm intelligence and robotics. The cooperation of nature swarm and swarm intelligence, and the special features of the swarm robotics, compared to a single robot and other multi-individual systems are important research topics. The modelling methods for swarm robotics and the algorithms need to be advanced in such a way that they can deal with dynamic unstructured environments, including cooperative control mechanisms in swarm robotics for flocking, navigating and searching applications.

(Underwater) communication is essential for swarm behavior and data transmission to the surface. Optical, acoustic and radio methods all have their advantages and disadvantages. A low-cost way to efficiently transmit and receive signals at high data rates is crucial to a reliable subsea monitoring system.

Due to the dynamic and unstructured nature of the sea and the sea floor and the limited (optical) sight, high satellite signal attenuation, underwater navigation and positioning are difficult. Both the sensors themselves and the algorithms used to fuse their output data need to improve significantly. Terrain-relative navigation using simultaneous localization and mapping (SLAM) is a promising research topic as it does not require any in-field infrastructure such as beacons, but rather relies on vision algorithms and predetermined bottom maps. This is a multidisciplinary challenge, as it involves challenges in hardware, software and signal processing.

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32 – Remote structural health and condition monitoring and diagnostics for turbines

Authors

Roger Groves, Simon Watson

Objective

Achieve more effective remote structural health and condition monitoring and diagnostics for turbines

Beacons

- Supply chain efficiency
- Zero breakdown

Background

Remote structural health monitoring (SHM) and condition monitoring (CM) of wind turbine installations is essential for increasing safety and reliability while reducing maintenance costs, by providing real-time information about system loading, detection and the emergence of damage for the prediction of the future structural integrity and the maintenance and repair needs of the wind turbine.

It is important to focus the attention of operators of wind farms on the total cost of ownership over the lifetime of the facility to maximize return on investment for companies and investors. Active and efficient maintenance also contributes to local job creation in the region where the wind farm is located and increases the sustainability of the wind farm.

Current state-of-the-art

The current practice in industry is to use a combination of inspection by personnel and data-driven or damage model approaches based on available sensor and operating data [1-3]. Inspection is costly, especially for turbines located at sea, due to difficult access and operating conditions for personnel, and weather-dependent scheduling uncertainty. Data-driven approaches are limited by lack of integration with domain knowledge in structures and materials behavior, and by ad hoc design and lack of focus in selecting sensor types and locations. Accurate damage models are difficult to define due to the complex loading conditions of a wind turbine and the commercial nature of information required to properly define the physical characteristics of a component.

The scientific and technological community has developed a wide variety of sensors which could potentially be used for SHM and CM. Commonly, companies and research groups focus on a single or a small number of sensor types, which they market across industry sectors. Modern sensor types include optical fiber sensors, ultrasonic, thermography, 3D inspection, terahertz, lidar, etc. A downside of this wide range of sensor technologies is that many commercial sensors use proprietary technology that is difficult to validate from a scientific or engineering perspective and requires extensive testing for each application.

A combination of available sensor technologies with data fusion and modelling algorithms has the potential to provide the required information for the predictive algorithms. The gap is in the integrated design of SHM or CM systems based on sound scientific and engineering principles and the combination of data-driven approaches with domain knowledge of structures and materials behavior.

Proposed R&D topics

- Advanced sensors – The monitoring of wind turbine components should provide the key information to determine accurate remaining useful life **(**RUL) and detect damage at a very early stage when low-cost remedial action can be taken. This involves multi-modal sensing and data fusion from both embedded sensors or non-destructive inspection
- Advanced prognostic algorithms – Sensors can provide key information, but the data needs to be analysed to determine the consumption of fatigue life, the prediction of crack growth, the probability of failure, etc. There needs to be research to develop better prognostic algorithms based on a combination of accurate physical models, machine learning and statistical methods. The development of algorithms should be focused on those components and subassemblies for which failure-related downtime has the greatest impact on LCOE. Algorithms should be incorporated into holistic models of wind turbines and wind farms: such models are sometimes known as "digital twins" and provide the capability to accurately simulate the operation of a system, e.g. a wind turbine, over its lifetime to provide insight into potential failures and how it and/or the wind farm might be optimized
- Setup of a working group to benchmark SHM and CM technologies for remote structural health monitoring with open discussion of sensor technologies and their theoretical and demonstrated capabilities – This working group should develop measurement standards for monitoring and data collection, as wind turbine systems are currently and frequently monitored differently from machine to machine. Taxonomies and standards are starting to be developed but much needs to be done to ensure consistent data sets across different fleets of turbines, with the correct coverage both in terms of components and sampling frequencies

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33 – Condition monitoring and diagnostics of HVDC offshore assets

Authors

Armando Rodrigo Mor, Pavol Bauer

Objective

Monitoring and diagnostics of HVDC assets through development of sensors for gas insulated systems, cable sensors and artificial intelligence (AI) based diagnostic systems

Beacons

- Optimal integration into energy system
- Full international interconnectivity
- Supply chain efficiency
- Zero breakdown

Background

Offshore wind farms require complex electrical infrastructure in harsh environments. The goal is to achieve a fully automated renewable energy generation system that works without the physical presence of people in the offshore facility. That goal can only be achieved by means of remote monitoring and diagnostic systems to ensure a continuous flow of electrical energy.

A monitoring and diagnostic system is a combination of hardware and software. The collection of sensors that monitor different parameters of the electrical assets is referred to as the hardware. This includes temperature sensors in transformers, vibration sensors for cable raisers, and electrical insulation sensors for partial discharges, along with the acquisition systems of the signals from the sensors. The software is the collection of algorithms that conditions the signals and prepares the data for inspection by an expert.

By means of monitoring and diagnostic techniques, it is possible to assess the status of the electrical infrastructure and predict potential failure. The prediction of faults increases the reliability of the system because it reduces unexpected failures. Furthermore, it reduces maintenance costs since maintenance can be scheduled in time according to a risk assessment based on the measurements and the diagnostics. Therefore, the provisioning of spare parts and the organization of the offshore maintenance works can be planned ahead, reducing the maintenance costs of the offshore platforms.

A relatively new technology that enables large-scale offshore renewable energy is HVDC. This milestone proposes monitoring and diagnostics specifically for HVDC assets.

Current state-of-the-art

Nowadays all the offshore HVDC substations are air insulated, while a few gas insulated systems (GISs) in HVDC substations are being experimented. GISs can decrease the substation footprint by up to 15%, cutting platform costs. However, there is no specification regarding the commissioning and testing of an HVDC GIS. It is known that some insulation defects in an HVDC substation can go undetected by conventional insulation monitoring systems. Therefore, new hardware and software need to be developed to overcome this issue and make the HVDC GIS as reliable as its AC counterpart.
Sensors in an HVDC cable will develop space charges in the long run due to temperature gradients and operational conditions. Nowadays, there is no available technology for space

charge monitoring of HVDC cables in offshore conditions. There are only a few laboratory prototypes for normal HVDC cables, used during type testing.

AI diagnostics insulation monitoring systems can create large amounts of data, up to dozens of gigabytes per minute in certain conditions. Nowadays, the data is processed and adapted for fast human inspection, as a sort of a data mining tool. The data inspection and assessment are done by an expert consultant manually.

Proposed R&D topics

- **Sensors for gas insulated systems** – There is a need to develop new partial discharge sensors with increased sensitivity to be able to detect insulation defects in HVDC GIS. The new sensors have to be developed alongside tailored electronics. The new sensors have to be resilient to the power electronics converter noise by means of a combination of hardware and software tools. Experiments with different types of defects in a GIS have to be conducted to design sensors that can detect them
- **Cable sensors** – There is a need to develop an online space charge cable measuring tool for offshore application. The system could be based on electroacoustic methods, using acoustic sensors for the detection and positioning of space charges. A pulsed voltage has to be injected into the cable, so it is worth studying the possibility to create the necessary voltage waveforms with the power electronic converter and coordinate the operation of the converter with the space charge cable monitoring system. In this case, the development of the monitoring tool has to consider the converter design and operation (from the system point of view). Intensive laboratory testing will be required to check the feasibility of the system
- **AI diagnostics** – There is a need to develop AI-based diagnostic systems. The focus will be the integration of AI technologies with the data interpretation. The goals will be the identification of invalid data, the discrimination of noise, the development of cluster techniques, and finally the development of the intelligence to automatically analyse the data and make an assessment and risk evaluation. The work will be a combination of laboratory work, to create artificial data representative of real-life conditions, and software programming. The goal is to have a fully autonomous and reliable offshore system.

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34 – Automation in blade manufacturing

Author

Julie Teuwen

Objective

Model and automate the production process to achieve higher production efficiency and blade quality and accuracy with higher throughput using advanced materials

Beacons

- Low cost from larger turbine size
- Low cost from standardized turbine platform
- Supply chain efficiency
- Zero breakdown
- Adequate availability of human capital

Background

Current wind turbine blades are based on thermoset composite structures made via vacuum infusion. Their lifetime depends on blade design, materials and manufacturing quality, as well as on the operating and environmental conditions. The challenges in long blades for large offshore wind turbines (25 MW or more) will be in making them more robust, reliable and tailor-made for offshore operations. In offshore wind farms, longer blades or variable blade lengths will be considered to increase power output of the wind farm.

Current state-of-the-art

As the complexity of geometry, production volumes and component size increase, the blade manufacturing industry will be driven towards more and more stringent requirements in terms of reliability, quality and efficiency. The production process of current blades is scarcely automated [1], with a lot of labour-intensive work and no inline monitoring systems to monitor the expected quality of the part after production. The production process of larger blades is typically based on the knowhow of the production of smaller blades, which is then scaled to the new length, which could result in conservative choices. Quality control is mostly done at the end of the production process, leading to repair work and potential scrap parts.

This means that large improvements in quality are possible, leading to higher production efficiency and speed in the manufacturing process in the future [2].

Proposed R&D topics

- Simulation and optimization of each step of the manufacturing process of the complex and thick substructures of the large-scale wind turbine blade, such as prediction of resin flow and cure cycles, to design the most efficient production process (cost, efficiency and quality)
- Creating a digital twin in manufacturing by coupling information from inline monitoring systems (for instance resin flow, pressure, residual strain, temperature, dielectric sensors) with the aforementioned production process models which can give corrective input during manufacturing when deviations are observed. This will ensure high-quality products
- Automation of the relevant production steps for increase of throughput and quality assurance

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35 – Joining methods for modular blade designs

Author
Julie Teuwen

Objective
High stiffness, strength and fatigue-resistant joining methods for modular blade designs to accommodate the logistics of ultra-long blades

Beacons
- Low cost from larger turbine size
- Low cost from standardized turbine platform
- Supply chain efficiency
- Adequate availability of human capital

Background
While milestone 4 gives an overview of the potential benefits of a modular design of all turbine parts, this milestone focuses on the joining methods that need to be developed for modular blade designs. As turbines get larger, the logistical challenge in terms of assembly and installation becomes greater. Larger components such as blades, towers and generators require larger vessels. This can increase the cost of installation as such larger vessels are (and will be) scarce. To ensure the use of large wind turbine sizes and reduce the logistical challenge significantly, it will be paramount to develop blades which can be manufactured in several sections that can be assembled at - or on a marshalling yard near - the installation site [1]. Modular design for wind turbine blades will be beneficial not only for logistics but also in the selection of the best materials and most optimal manufacturing technologies for the different sections of the blades, or in offering a scalable blade architecture.

Current state-of-the-art
Several split blades have been tested by wind turbine blade manufacturers where splits were made at the root, middle or tip section of the blades [2]. The connections for the root and middle sections (highly structurally loaded) were typically quite heavy (bolted joints) and not implemented in service. Tip-split blades are currently under investigation and pose fewer structural requirements. The joints for these parts could be based on co-cured or adhesively bonded connections (composite connections rather than bolted joints). The quality assurance and speed of the joining process, as well as controllability of the on-site conditions, will be of critical importance.

Proposed R&D topics
To fully tap into the potential which modular blades for larger turbines would bring to the market, the modularity needs to be taken to a next level. The blade will be separated in more than two pieces (logistics) and the material and manufacturing technologies will have to be tailored to the specific operating and manufacturing conditions of the specific parts. For instance, the material choice for the leading edge (impact damage due to erosion) will be different than the material choice of the load carrying structure (high strength, high stiffness, high fatigue resistance). Joining dissimilar materials and creating a high-performance structural joint is however not straightforward [2]. The objective of this milestone is to develop high stiffness, strength and fatigue-resistant joining methods for modular blade designs to accommodate the logistics of ultra-long blades. To meet this objective, we propose the following topics:

- Study on circular product design in terms of optimal selection of parts of the blades to be joined on site, optimal choice of materials and manufacturing and joining technologies for each of the parts, while taking into account the end-of-life solutions at the design stage of the blade
- Study on feasible joining methods of two structurally dissimilar materials (going from micro-/meso- to macro-scale assembly), as well as potential separation methods and on the most efficient manufacturing technologies for the different parts to be joined on site, including automation of the manufacturing and joining technologies

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36 – Optimal integrated installation method for tower, nacelle and rotor assembly

Author

Andrei Metrikine

Objective

Semi-active and active control devices integrated in the tower, nacelle and rotor assembly of offshore wind turbines to enable their optimal integrated installation method

Beacons

- Low cost from larger turbine size
- Supply chain efficiency
- Adequate availability of human capital

Background

The current practice of a bottom-mounted wind turbine installation is based on the sequential approach [2]. First, the foundation is installed. Thereafter, sometimes after a significant time window, the tower is installed. The nacelle and the rotor (hub and blades) are then mounted on top of the tower. While it is challenging and, perhaps, hardly possible to install the future generation of mega-size bottom-mounted wind turbines in one piece (foundation, tower, nacelle and rotor assembly), it is definitely desirable to develop an optimal installation method that includes installation of two pieces only, namely the foundation and the integrated tower, nacelle and rotor assembly. In order to enable such installation, fundamentally new installation strategies need to be developed and/or integrated. Vibration-mitigating devices should be integrated into the tower, nacelle and rotor assembly ("top side") in order to meet very strict criteria that will be introduced should the integrated top side be shipped to the location and installed in one piece. The latter measure is necessary both for bottom-mounted and floating solutions.

Current state-of-the-art

Assembling the tower, nacelle and rotor of offshore wind turbines onshore and shipping it to the location in one piece has always been desirable but not yet practically achievable for the offshore engineering community. The main obstacles are the space available on the transport vessels and the strict conditions in terms of allowable mechanical stresses and accelerations that must be ensured during transportation and installation. It is becoming clear to the research community that it is unlikely that the desirable minimization of stresses and accelerations can be achieved in the framework of passive mitigation solutions. Therefore, the main fundamental challenge of this milestone is to develop semi-active or active control devices that ideally reduce stresses and accelerations of the wind turbine components during transportation, installation, and, desirably, operation, as well [1].

Proposed R&D topics

The research effort will be focused on the development and testing of semi-active and active control devices that will be integrated in the tower, nacelle and rotor of offshore wind turbines such that the stresses and accelerations can be kept at an acceptable, very low level in all three phases of the active service of a wind turbine, namely in transportation, installation and operation. The fundamental challenge of this milestone lies in the development and integration of the control devices, which will be able to operate successfully under fundamentally different types of excitations that are experienced by the turbine in the above-mentioned phases of the service life.

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37 – Supply chain efficiency through digitalization

Author
Wouter Beelaerts van Blokland

Objective
Further supply chain efficiency improvement in installation and operation of wind farms through digitalization

Beacons
- Supply chain efficiency
- Zero breakdown
- Adequate availability of human capital

Background
Operation and maintenance costs for offshore wind farms account for approximately 30% of the total costs over the lifetime of a wind farm. Installation costs are also important. These costs can be reduced significantly through further digitalization of the logistics in the supply chain. Up to 2050, wind farm owners and owners of installation vessels, land-based facilities (hubs), turbine manufacturers and supporting service providers face the following problems or shortcomings regarding installing and operating far offshore wind farms:

- Asset owners of wind farms experience a lack of coordination and matching of transport capacities. The link between onshore or land-based and offshore or marine-based activities is missing
- Undisclosed or fragmented information silos cause underutilization of assets and resources

Current state-of-the-art
Optimizing the matching of onshore with offshore transport capacities can reduce operational costs and reduce the costs for offshore wind energy. This helps the economic viability of renewable energy and its role in the energy transition.

Proposed R&D topics
The desired results of the proposed research into digitalization of the logistics is to improve efficiency by reducing or eliminating:
- Transaction complexity
- Waiting time between hubs, vessels, vehicles and wind farms
- Transaction costs between parties
- Time to market of energy (TTM-E)
- Downtime of wind farms
- Transaction errors
- Ship movements
- Emissions

It is expected that a further cost reduction towards 5% of the LCOE is possible for the installation and operational phase altogether. Two R&D topics are proposed:
- **Digital chain and platform for real-time information processing and sharing** – The aims are: (1) the assignment of assets (vehicles, vessels/lifting equipment, harbor location, wind turbine systems, spare parts) and resources (certified personnel), and behavior of

stakeholders (e.g. negotiation between stakeholders, benefit system, sharing benefits); and (2) trade-offs between vessel/vehicle capacities investment, purchasing, chartering and transport costs. R&D is proposed towards the design of the Digital Wind Chain and platform, AI (IoT and blockchain) driven data information platform to process data and make available on-offshore transport engineering-related information for real-time matching and planning between multiple stakeholders. The platform is designed around a dappstore (distributed appstore) infrastructure for development and deployment of (third-party) distributed apps (dapps). A dedicated dapp can be part of the development to support demand-supply chain efficiency

- **Innovative AI real-time matching and planning** – For land- and marine-based logistic and engineering-driven operations for installation and maintenance of wind farms. The aim is innovative real-time matching and planning of on-offshore logistics by simulating real-time construction and maintenance requests and through optimal resource and assets allocation to enable anticipatory shipping, involving yards, ships, personnel, vehicles, cranes, systems and components. For maintenance operations, machine behavior of turbines needs to be connected with supply chain operations to mine supply chain efficiency enabled by the digital chain, or R&D topic 1. The R&D here will be towards an innovative, AI-driven, real-time choice matching and planning model (MPM) to optimize land- and marine-orientated logistic services for multiple wind farm installation sites and operations performance of installed wind farms. Different supply chain efficiency scenarios can be laid out, including spatial and temporal variations in e.g. construction and maintenance requests from multiple turbines' behavior and derived demand for spare parts, wind farm location, increasing number of turbines over time (scalability) and harbor hubs. For each of the scenarios, the simulations with the numerical model will result in an optimized matching and planning of the land- and marine-based logistic services as a response to the construction and maintenance requests over time

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38 – Optimization of standardization throughout supply chain in ramp-up phase

Authors

Henk Akkermans, Roland van de Kerkhof

Objective

Guidelines for setting standards throughout the supply chain in ramp-up phase without limiting innovation too much

Beacons

- Low cost through standardized turbine platform
- Supply chain efficiency
- Zero breakdown
- Adequate availability human capital

Background

Standardization is a double-edged sword. On the one hand, standardization can vastly increase the efficiency of ramp-up and management of the offshore wind supply chain. On the other hand, standardization limits innovation. Standardizing too soon would result in the ramp-up of suboptimal technology. Ideally, the offshore wind sector reaches agreement about standards just before the ramp-up really takes off. This includes standards for:

- Design of offshore wind assets, such as wind turbines, electricity grid, etc.
- Manufacturing processes of these assets
- Installation processes of these assets
- Data collected from these assets
- Maintenance policies for these assets

At this time, it is unknown what the optimal standards will look like. If the standards are to maximize the net gain from the offshore wind supply chain, we have to take trade-offs into account. Larger wind turbines, for example, might provide more power, but are harder to produce, transport, construct and maintain. Additional research is required to identify these trade-offs and determine what standards will be optimal for the offshore wind ecosystem as a whole.

Current state-of-the-art

The benefits and downsides of standards have been studied extensively in the past, focusing on economies of scale, network effects, switching costs, etc. [4]. In addition, research on standards adoption and competition between standards has identified multiple forces that lead to the adoption of a standard, such as engineering, the market, competition, consortiums, and government [1, 2].

Proposed R&D topics

- Explore the interdependencies within the supply network to elicit standardization trade-offs with multiple cases. How is the design of offshore wind assets related to the production, construction and maintenance requirements of these assets?
- Design standards that are optimal for the supply network as a whole. A design science approach [2, 3] is most suitable here. Typically, design science research seeks to create innovative artefacts that are useful for coping with human and organizational challenges through an iterative process of development and testing

- Design guidelines for the supply network on how to deal with standardization: how to use standardization most effectively in the offshore wind sector without limiting innovation too much? To what extent should standards be enforced and to what extent should they be allowed to emerge out of market interactions?

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39 – Sufficient turbine manufacturing, transportation and installation capacity

Authors
Henk Akkermans, Roland van de Kerkhof

Objective
Model and plan for sufficient manufacturing, transportation and installation capacity expansion for wind farms for 2030-2050 period

Beacons
- Supply chain efficiency
- Adequate availability human capital

Background
A steep ramp-up is required, especially between the years 2030 and 2050, to achieve 240-450 GW of offshore wind capacity in the EU by 2050. A successful ramp-up of offshore wind power capacity therefore requires sufficient supply network capacity from 2030 onwards. However, with ramp-up targets this high, it is inevitable that capacity constraints become an issue. Managing and aligning capacity in the offshore wind supply network is expected to be especially complex for multiple reasons:

- **It is organizationally complex** – Many different capacities are involved, capacities for e.g. designing, building, operating and maintaining the wind turbines. These capacities are managed by different, independent organizations which have no natural way of aligning their capacity planning
- **It is technically complex** – The designs of wind turbines are still changing, placing new demands on e.g. production, transportation and construction capacities. This makes it hard to develop capacity
- **It is dynamically complex** – Dependencies exist between the different capacities (e.g. the quality of design affects the ease of construction and the need for maintenance) and most capacities change over time (e.g. aging workforce). Managing the individual capacities thus requires a dynamic "picture" of the system's capacities

Current state-of-the-art
Prior research has studied ramp-ups of production and service supply chain capacities [5]. These studies have provided insights into the challenges of ramp-ups and gave rise to mechanisms for aligning the stakeholders' capacities: integral planning with suppliers [3] and sales and operations planning [4]. It is currently not known how these mechanisms can also be translated to the supply network level and whether they can be used for managing capacities throughout the offshore assets' lifetime, also including the operations and maintenance phase. Fortunately, the methodology employed by these studies can also be used to analyse other types of ramp-up systems.

Proposed R&D topics
- Identify what main capacities are required for design, production, transport, construction, operations and maintenance of an offshore wind supply network, how these are related, and where bottlenecks can be expected. Understanding "the whole elephant" [1] can be gained via group model building sessions with the organizations involved in the supply network [2]

- Develop new tools and collaborative planning techniques to manage capacities in the offshore wind sector during ramp-up. These will give rise to design guidelines that can be tested and refined in a number of empirical settings in the sector, and validated and tested for robustness with system dynamics simulation models

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40 – Design guidelines to increase learning capability throughout ramp-up

Authors
Henk Akkermans, Roland van de Kerkhof

Objective
Integrated design guidelines to increase learning capability throughout ramp-up: which parties have to cooperate to increase the speed of identifying flaws in the designs? What methods are best for identifying these flaws: simulations, prototypes, etc.?

Beacons
- Supply chain efficiency
- Zero breakdown
- Adequate availability human capital

Background
No design is perfect from the start. Basic designs and detailed designs are flawed, so organizations make use of laboratories, prototypes and pilot plants to identify the flaws in their designs before scaling up production. However, within the offshore wind ecosystem, designs are related. The design of the wind turbine, for example, affects the requirements for the design of the transportation and construction ships. These designs therefore need to match, and adjustments in one design can create flaws in another design. How fast the ecosystem learns – the learning capability – determines how fast designs improve, and thus how fast the offshore wind ecosystem can ramp-up.

Current state-of-the-art
There is a vast body of research in management literature about organizational learning, a change in the organization's knowledge that occurs as a function of experience [3]. This knowledge is institutionalized in a variety of ways, including changes in cognitions, routines and behaviors [2]. Prior research has identified under what conditions learning takes place [4], what the optimal timing is for moving from prototyping to full-scale production [1], and how flaws can be identified in later stages of the development process [5]. However, so far studies have focused on a single design – not on multiple related designs – and on learning by a single organization, not by an ecosystem.

Proposed R&D topics
- Explore what learning is required within the offshore wind sector. How are the designs of wind turbines, the electricity net, and transportation and installation vessels related? What requirements do the designs of wind turbines put on the design of the electricity net for example? What flaws can enter the designs? And finally, how, when and by whom can these flaws be detected?
- Develop an integrated model of learning and learning guidelines that improve the learning capability of the sector as a whole: which parties have to cooperate, or at least communicate, to increase the speed of identifying flaws in the designs? What methods are best for identifying these flaws: simulations, prototypes, etc.?

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41 – Assessment of system risk (unk-unks) and how to manage it

Authors

Henk Akkermans, Roland van de Kerkhof

Objective

Methodology to assess supply chain system risks (unk-unks) and how to manage them.
Evaluate and improve methodology on an ongoing basis

Beacons

- Supply chain efficiency
- Zero breakdown
- Adequate availability human capital

Background

New product development efforts, such as the development of new wind turbines, are typically characterized by unknown unknowns (unk-unks) [1]: the inability to recognize and articulate relevant variables and their functional relationships. At the start of a project, you do not know what you do not know. The same is true for the offshore wind supply chain: at this moment in time, it is unknown what the system risks will be and how they can be best managed. Therefore, it is wise to develop methodologies for assessing and managing the risks within a system simultaneously with the development of the system itself.

Current state-of-the-art

Risk management involves the identification, evaluation and prioritization of risks. Specific methodologies have been established, for example, for dealing with natural disasters [8], managing IT security [9], process safety [5] and supply chains [2]. In general, theories have been developed of how to foster so-called high-reliability organizations [4]. In addition, multiple methodologies have been developed recently for identifying and tackling unknown unknowns within projects [6, 11]. To date, no method has been developed for the assessment of risks at the ecosystem level.

Proposed R&D topics

- Create a methodology for assessing risks at the ecosystem level, including low-likelihood high-impact events, so-called "black swan events" [3]. This methodology can build upon the methodologies from related risk management fields, but should be developed in interaction with the organizations active in the offshore wind supply chain
- Conduct a comprehensive risk assessment of the offshore wind supply chain. Since disasters are rarely caused by the breach of a single barrier, it is useful in this stage to map the causal interdependencies between risk factors in multidisciplinary sessions

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42 – Ecological effects of large-scale offshore wind capacity rollout

Authors

Han Lindeboom, GerJan Piet

Objective

Ecological effects of large-scale offshore wind capacity rollout identified, measured and modelled. Optimize and predict the effects of mitigation, compensation, development of new habitat types and ecosystems and offsetting

Beacon

- Strong support from stakeholders
- Net positive impact on the environment

Background

Today's nature in the North Sea is degraded. Large parts of the seafloor have been disturbed, intensive fishing threatens a number of fish species, and certain sea bird populations are struggling, e.g. large tern, auk and lesser black-backed gull. There is also good news: several commercial fish populations are thriving, large-scale waste dumping has been stopped, and the number of seals and porpoises is increasing in the Dutch part of the North Sea. Still, at present, none of the policy objectives related to biodiversity have been achieved, and at the current levels of exploitation it is unlikely to happen in the future.

Therefore, a large-scale capacity rollout of offshore wind power capacity, potentially covering ~20% of the Dutch EEZ by the year 2050, needs to be executed in an ecologically responsible way. The installation, operation, maintenance and decommissioning of wind farms have potentially both direct and indirect effects on flora and fauna above and below sea level [1]. Offshore wind farms can also impact winds, currents, waves, stratification and turbidity. On the other hand, wind farms also offer compelling opportunities to improve the ecology: in particular, the prohibition on disturbance of the seabed in wind farms can facilitate the redevelopment of the characteristic North Sea substrate and fauna. All ecological effects of the offshore wind capacity rollout need to be identified, measured and modelled [1] Thus, effective measures can be taken to mitigate negative effects, if necessary, take compensative measures, and develop new habitat types and ecosystems among the wind farms. Ultimately this must lead to a net positive environmental impact, which is essential for strong public support of the large-scale offshore wind capacity rollout.

Current state-of-the-art

In the last decade, many wind farms were installed in the North Sea, and their short-term ecological effects have been extensively investigated [1]. However, the potential ecological effects of a large-scale capacity rollout are largely unknown. Risk-based approaches, together with more specific models, have been developed to estimate those effects on the whole ecosystem and its components, specifically certain endangered species. However, for these approaches to inform decision-making they need to be made more robust through improved parametrization and validation from experiments and further measurements in the field. In situ data is scarce or missing and an elaborate monitoring and research program both within and around the wind farms is a prerequisite for further large-scale development of wind farms. Moreover, there are surely still several unknown unknowns: for instance, it was only recently discovered that certain endangered bat species use migration routes over the North Sea that may be affected by wind farms. The effect of mitigation measures also requires further research. For instance, it is not yet known what the full effect of noise mitigation screens is on underwater noise and its effect on sea mammals. Impacts of large-scale development on winds, currents, waves, stratification and turbidity and its impacts on the ecosystem have hardly been studied and need immediate attention. Finally, there is only limited experience with the development of new habitat types and ecosystems among the wind turbines.

Proposed R&D topics

Explorative research is proposed to discover and estimate potential ecological impacts from the large-scale rollout that are not known today. To that end, we need more in situ research. We need to further develop risk-based approaches and models that allow a first scoping of all the potential impacts that may occur and assess their relative importance in order to guide the initial planning process as well as the subsequent steps, including the distribution of wind farms across the Dutch part of the North Sea. This requires detailed information on e.g. spatial and temporal (e.g. seasonal) distributions of all the relevant marine ecosystem components, with a focus on the most vulnerable species as well as an understanding of how specific configurations in the design of the offshore wind farms (e.g. positioning, height, type of scour protection) differ in terms of their effect on the various ecosystem components. Over time, these approaches can be further improved as information from the subsequent steps becomes available.
Development is also proposed in new and improved measurement methods (eDNA, radar, sonar) and more robust models to be able to assess and predict the effect on all relevant ecosystem components, i.e. birds and bats, marine mammals, fish and cephalopods as well as benthic invertebrates, with a focus on endangered species or species of commercial interest. This includes research focused on how changes in the non-living aspects of the ecosystem (hydrography, wind fields, coastal waves) may have unwanted impacts on the biota. For instance, the recent insight that the presence of many monopiles with their scouring protection may have significant impact on the physical features in the North Sea, of which the overall effects are largely unknown, calls for much more research. Finally, the competition for space between fisheries and wind farms requires more research into how fishermen’s behavior determines their reallocation to other areas, with potential knock-on effects on the benthic community or commercially important species, like sole and plaice.

- **Mitigation** – Today, several methods have been developed to mitigate the ecological impact: e.g. bubble curtains to reduce the noise during piling, and radar that detects a large bird migration so that wind turbines can be shut down. Further research is necessary to improve these methods and to measure their effectiveness. This should then result in improved parametrization of the existing risk assessments and models
- **Compensation** – Certain measures can be taken to compensate the effect of a wind farm on certain species. For instance, a comparable habitat can be created at another location. Further research is necessary to predict the effect of such measures
- **New habitat types and ecosystems** – Wind farms offer the opportunity to develop valuable new habitat types and ecosystems. Experiments are currently being done with e.g. artificial substrates and oyster beds. Further experimentation and measurements are necessary to be able to predict the effect of the development of such habitat types and ecosystems
- **Offsetting** – If it turns out that it is not possible to meet our ecological commitments when the large-scale rollout of offshore wind is added to the current configuration of the different marine activities, then offsetting could offer a solution. Cumulative effects assessments can be used to identify those human activities that cause similar impacts that may otherwise

prevent the large-scale rollout of offshore wind power capacity. Mitigation of the impacts of those other human activities could be economically more profitable while also allowing the large-scale rollout. An example is the offsetting of additional mortalities of marine mammals from noise while bycatch in fisheries or effects of ghost-nets could well be causing much higher mortalities

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43 – Changing impact on coastal erosion

Authors

Tim Raaijmakers, Sukanta Basu

Objective

Potential coastal impact and effect on flood risk of large-scale rollout modelled and predicted. Optimal spatial planning of wind farms developed for minimal impact, or effective mitigation measures developed

Beacons

- Optimal wind farm design
- Strong support from stakeholders
- Net positive impact on the environment

Background

Given the planned large-scale developments of offshore wind farms, energy hubs and grid infrastructure, at some point during this development stage potential coastal impact on flood risk can occur. At this time, it is unknown for which installed offshore wind capacity and at which locations these effects become noticeable due to complex, not completely understood interactions between wind fields, hydrodynamics, sediment transport and coastal changes. On a similar spatio-temporal scale, processes related to climate change and (consequential) sea level rise will interact with the processes related to large-scale development of offshore wind. Therefore, there is a need for a better understanding of how local effects introduced by individual wind turbines and complete wind farms can potentially evoke a chain reaction (often referred to as "cascade effects") which eventually leads to coastal impacts and effects on flood risk.

Current state-of-the-art

Currently, it is largely unknown what the potential coastal impact of a large-scale rollout of wind farms in the North Sea may be, and what effect it can have on flood risk.

The coastal profile is affected by both cross-shore and alongshore sediment transport. In the cross-shore direction, sand is eroded from the upper part of the coastal profile and the dunes during storm conditions, which is then deposited in the lower part of the coastal profile. During milder conditions, sediment is transported in the upward direction and, by aeolian (i.e. wind-driven) processes, sand is further transported from beach to dunes. In the alongshore direction, sediment is transported related to the angle of the coastline in relation to the hydrodynamic forcing which is driving this sediment transport. In general, net sediment transport is from southwest to northeast along the Dutch coast, although locally around infrastructure (such as harbor breakwaters) differences exist. Where the current position of the Dutch coastline is not in equilibrium with the alongshore and cross-shore sediment transport, the coastline is maintained by regular sand nourishments. Presently, the annual nourishment volume is around 8-12 million m^3.

Due to climate change and related sea level rise, the annual nourishment volume is expected to increase to 50-480 million m^3 by 2100, depending on the climate change scenario. These estimated volumes are excluding any effects related to large-scale development of offshore wind power capacity. At some point, these developments are expected to start affecting the wind, wave and current climate at the coast. Some studies have investigated the potential effects of individual wind farms on coastal impact [1, 2]. However, research on the effects of a large-scale rollout of offshore wind power capacity is still in its infancy [3]. It is important to realize that even if coastal wind speeds and wave heights are reduced due to extraction of wind energy, the cross-shore sediment transport processes responsible for building up the coastal profile may be affected, resulting in different coastal equilibrium profiles. Alongshore sediment transport may be affected by the chosen locations of offshore wind farms, resulting in certain parts of the coastline becoming more out-of-equilibrium, requiring more coastal nourishments.

Proposed R&D topics
Research is needed to model and predict the potential coastal impact of a large-scale rollout of wind farms on flood risk. This research should focus on setting up a framework of coupled large-scale models for atmospheric and hydrodynamic processes, coupled to (detailed or parametrized) small-scale models representing the effects of construction of large-scale offshore wind, energy hubs and other related infrastructure which are needed for energy storage or conversion. Since the temporal scales are related to several decades, scenarios for offshore energy developments need to be combined with climate change scenarios. The presence of field measurement data is paramount for validation of these models. Data obtained in a field measurement campaign such as data from measurement stations (e.g. lidar data, ADCP data) and bathymetry measurements (e.g. multibeam seabed data and JARKUS rays at the shoreline) will have to be combined with remote sensing data (e.g. obtained by satellites, such as shoreline positions for various water levels and seabed features at shallow water depths).

Research results are expected to provide input for future marine spatial planning: which wind farm location will have the smallest impact (or even a positive impact) on future required sand nourishment schemes. Or, if coastal impact cannot be avoided, effective mitigation measures need to be developed. Also, developments of SWIPs (sand wind parks) in which sand extraction and renewable energy production are combined in the same offshore area, are a potentially very interesting opportunity for symbiosis, although the morphodynamic response of the seabed to sand extraction and the corresponding effects on foundation fixation levels and cable burial depths require a good understanding of these processes and a smart design of these SWIPs.

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44 – Mitigating negative environmental impact of offshore installation and operation

Author
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Objective
Optimal integral installation methods and mitigation measures developed to mitigate effect on environment. In order to achieve this, the high-frequency but narrow-frequency-band vibratory installation techniques will be implemented along with mitigation techniques that are focused on the specific narrow frequency bands of vibrations and noise

Beacons
- Strong support from stakeholders
- Net positive impact on the environment

Background
Installation of offshore wind turbines can have a negative impact on the environment. The major negative impact in installation is associated with the noise emitted during the construction activities, especially during the pile driving. The noise and vibrations emitted by wind turbines also disturb the environment, but the level and consequences of this disturbance are yet unknown. Long-term effects of various types of scour protection on the environment need to be analysed, as well.

The impact of the construction activities, especially the level of underwater noise, should be minimized and the effect of the noise and vibration pollution should be studied along with the long-term effect of the scour protection measures [2].

Current state-of-the-art
Installation of the foundations of offshore wind turbines is associated with high levels of underwater noise and vibrations of the seabed. The noise is currently mitigated by means of various mitigation screens, while the vibrations are considered to have minor effect on the environment. A major effort is currently underway in the development of vibration (instead of impact) installation techniques. While these techniques do reduce the sound exposure level, the level of vibrations of the seabed as well as the energy of the low-frequency noise are likely to increase [1]. The consequences of the shift of the frequency band of the noise and vibration pollution are unknown. The level of technology nowadays is such that it is possible to develop and implement new mitigation techniques, which, together with the vibratory methods of pile driving, will enable a very significant reduction of the noise and vibration pollution.

Proposed R&D topics
Research effort is proposed on the integral development of installation methods and mitigation measures, which will allow the localization and reduction of the environmental impact of construction activities. In order to achieve this, the high-frequency but narrow-frequency-band vibratory installation techniques need to be implemented along with mitigation techniques that are focused on the specific narrow frequency bands of vibrations and noise.

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45 – Ethical issues of large-scale implementation of offshore wind

Author
Behnam Taebi

Objective
Fully understand the ethical issues associated with large-scale implementation of offshore wind power

Beacons
- Strong support from stakeholders
- Net positive impact on the environment

Background
Wind energy is considered one of the key renewable energy technologies for a successful energy transition. Yet its implementation could give rise to public resistance and controversies, due to the impacts on wildlife, noise pollution for nearby residents, as well as aesthetic objections. Moreover, transmission lines create impact on land in a larger area. These objections mostly relate to onshore wind farms in densely populated countries such as the Netherlands, where they have too often led to the failures of major onshore wind projects. The offshore wind farms have been proposed from the perspective of more efficient use of "open space" in the sea, but also to avoid some of the objections (i.e. noise and aesthetic objections for nearby residents) and the associated controversies.

Offshore wind farms have, however, given rise to controversies too; opponents consider them to be inefficient and unprofitable but also a threat to landscape qualities, regardless of location and proximity to residential areas. While the objections due to lack of efficiency and profitability seem to be mostly resolved – as the technology is maturing, offshore wind energy is becoming increasingly less dependent on subsidies – moving wind farms from (densely) populated areas to the sea has not yet proven to be an effective way to circumvent controversies.

Current state-of-the-art
It has been argued that the controversies associated with offshore wind power often emanate from a problematic public participation process in the planning and implementation; for instance, when one fails to acknowledge the imbalance in the bargaining power of different stakeholders (e.g. fishermen versus wind energy developers). Moreover, controversies could also emanate from an inappropriate inclusion of stakeholders' opinions and values in their design. A large-scale capacity rollout, if not done properly or in close and timely collaboration with the relevant stakeholders, is potentially a source of major controversies, all of which could stop or seriously slow down this rollout. A rollout of major offshore wind farms must therefore acknowledge and include the opinions and values of stakeholders, not only in the design of the technology, but also the institutions surrounding it [3]. It has been argued that offshore wind farms must be designed for values that go beyond the technical and economic values like efficiency and profitability, for which energy systems are typically designed [1]. Values such as environmental benevolence (from both an anthropocentric but also non-anthropocentric point of view) seem to become increasingly relevant. Wind farms in the North Sea offer an opportunity to improve the ecology; in particular, the prohibition on disturbance of the seabed in wind farms can facilitate the redevelopment of the characteristic North Sea substrate and fauna. More specifically in the Dutch context, there are ongoing negotiations for a North Sea agreement for spatial planning.

Learnings from these negotiations can be used to further develop knowledge about co-development models for the long term.

Large-scale wind parks must not only be accepted by the stakeholders, but they should also be ethically acceptable, meaning that their ethical issues beyond the direct scope of participation (as mentioned above) need to also be taken into account [5]. Among those issues are the climatic issues associated with large-scale implementation of wind energy on the atmosphere and the sea, which are not yet fully and properly understood. It has been argued that wind turbines create a "wind shadow", which means that air will slightly slow down after hitting the blades; this could cause long-term impact (e.g. surface warming) in the long run [6]. Similarly, a substantial increase of wind turbines placements into the seabed could have an impact on marine life, the ecosystems but also the sea currents. The short-term and long-term climatic impacts of large-scale wind farms need to be properly understood. Socially and ethically acceptable offshore wind must take into account the type of technology (e.g. floating turbines), the pace and the size of development in the near future (2030) and beyond (in 2050).

Proposed R&D topics

- Identify stakeholders who play a role and understand which values they uphold, how those could change if we move forward with a major upscaling, and whether upscaling would give rise to the emergence of new stakeholders (e.g. new exploitation purposes for fisheries) or perhaps new values (such as non-anthropocentric environmental benevolence)
- Ensure not only the social acceptance but also the ethical acceptability of large-scale wind farms
- In conjunction with the above, offshore wind farms should also comply with the basic principles of the tripartite model of energy justice: recognition, participation and distribution of burdens and benefits [4].

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46 – Optimal regulation for infrastructure and market design

Authors

Annelies Huygen, Edwin Wiggelinkhuizen

Objective

Achieve optimal regulation for offshore wind infrastructure and market design

Beacons

- Optimal integration into energy system
- Full international interconnectivity
- Strong support from stakeholders
- Net positive impact on the environment

Background

The envisioned large-scale capacity rollout of offshore energy in the Dutch EEZ of the North Sea can lead to inefficient solutions and/or significant public resistance: the cost can be or be perceived to be to be too high, both in terms of actual economic costs as well as cost to the environment and society. The challenge for the authorities is to design regulations that will lead to the optimal infrastructure for energy generation in the North Sea, and an optimal market model to achieve the highest added value, including a net positive impact on the environment.

Current state-of-the-art

The development of offshore energy is a rather new subject in regulatory theory. Over the past two decades, many governments worldwide have devised a wide variety of regulatory systems and incentives to stimulate and to manage the energy transition. Also, there has been an attempt to assess the full societal cost and benefits of energy transition developments in the long term.

However, for application to offshore energy, these techniques should be adapted. At sea, there are other stakeholders and other bottlenecks, for example. Therefore, adapted analytical methods, other regulatory measures and other ways of monitoring seem to be necessary.

Proposed R&D topics

- **Assess full societal cost-benefits** – We need to develop and/or adapt and validate methods to measure the full societal cost-benefits of the rollout of offshore wind energy capacity. The development of offshore wind farms has a multitude of societal and environmental effects: impact on household energy cost, reduction of greenhouse gas emissions, negative effects on the marine environment (e.g. bird collisions, piling noise impact on sea mammals), positive effects on the marine environment (e.g. prohibition of sea floor disturbance, opportunity to develop new ecosystems), impact on the consequences for the maritime sector and sometimes for the view from the coast. We need to develop and validate methods to measure such effects, and to be able to make trade-offs between the individual effects and other public interests
- Devise effective regulatory measures to optimize environmental impact – Effective regulation of offshore energy promotes the efficient development of energy resources. To devise regulation, we need to elaborate all public interests that are involved. We have to consider whether and how these interests may be affected by the activities at sea. In a next step, we will examine the possible remedies and regulatory measures. We can make a

framework to evaluate these measures and to prioritize them. In this framework, we can include factors such as simplicity, barriers for innovation, extra costs of performance, costs of monitoring, etc. We also can learn from theory and practice in other countries

- **Devise support regimes for flexible offshore wind farms** – Zero-subsidy tenders, enhancing wind power plant flexibility, are becoming more prevalent as a means to stabilize revenues and support the energy system (and lower integration cost). While tender mechanisms should continue to ensure a fair price for the energy delivered, future tenders may include possibilities for an integrated industry approach to support the emerging flexibility options. That means tendering wind farms including a support option for conversion or storage. Alternatively, the tenders may include additional criteria that reflect certain environmental or societal values, like compensation for land or sea use or measures to avoid bird deaths, including monitoring mechanisms or enhanced market and grid support
- **Devise appropriate network tariffs to stimulate efficient use of the grids** – Tariffs for use of the transport and distribution network also stimulate an efficient use of these grids. Flexible tariffs stimulate storage or conversion at the right time and the right places. Total grid costs are reduced when the costs of the networks are borne by the parties that cause them
- **Devise coordination mechanisms for integration into the energy system** – New multi-objective coordination mechanisms to integrate offshore wind in the energy system, including markets for power-to-gas, storage and ancillary services. Ensure successful interplay with other developments onshore like distributed generation and storage, prosumers, micro-grids and onshore multi-energy hubs
- **Devise flexible, tailored incentives for technological innovation** – 3-bladed bottom-mounted turbines seem to have become the optimal technology to generate offshore wind energy. Stimulation of further optimization of this technology is necessary. Meanwhile, innovations in alternative offshore wind technologies (e.g. 2-bladed, kites, floating) also need to be stimulated, as those alternative technologies may lead to even better performance. Likewise, the development of alternative offshore energy technologies like tidal current and wave energy need to be monitored, and the support regime needs to be flexible in case such other technologies offer better solutions. Low-TRL research into such technologies by universities and research institutes needs to get public funding. Start-up companies that develop such new, disruptive technologies need to be assisted in their struggle to get through the valley of death, facing competition from large incumbent companies that benefit from the scale advantages of established technologies. Regulation needs to guarantee a level playing field between existing and new technologies, and between incumbents and new entrants to the market

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47 – Design of dedicated market model mechanisms

Author
Han La Poutré

Objective
Achieve optimal coordination between the players and stakeholders in the energy system around offshore wind farms through optimal design of market model mechanisms

Beacons
- Optimal integration into energy system
- Full international interconnectivity
- Supply chain efficiency
- Strong support from stakeholders

Background
Offshore wind farms, together with their related offshore and local onshore networks (e.g. infrastructures for electricity transportation, also for interconnectivity between North Sea countries), conversion and storage facilities (e.g. gas), and other assets, and with various players and stakeholders, form a complex energy system: a wind farm energy system (WFES). Various different players (or stakeholders) are usually involved that own assets or devices or can deliver energy services.

In order to obtain good system performance, coordination between the players and allocation of energy services (including supply, demand, flexibility, storage, conversion and other network services) is necessary. Important coordination mechanisms are market mechanisms, especially for the allocation of energy supply and demand and of energy services (like flexibility and other network services).

Current state-of-the-art
Large-scale (wholesale) energy markets already exist in conventional energy systems. Energy markets for future (smart) energy systems in a more local setting, like for WFESs, are not yet available. Some first solutions for smart grids are available, but these are not tailored for the complex settings of WFESs. Here, the specific diverse components of such systems and variable power generation make the market settings more complex, and dedicated solutions are required. In addition, such market mechanisms should be automatic, and thus must (be able to) be digitalized.

Proposed R&D topics
Novel market mechanisms should be investigated and developed in order to deal with allocation and coordination in WFESs. Such market mechanisms should be automatic, and thus be able to perform and operate by ICT. In addition, such market mechanisms should satisfy societal and economic objectives, with respect to e.g. business as well as end-users. Different settings or objectives can demand different market mechanisms. This requires research and development in the areas of e.g. computer science, economics, game theory, artificial intelligence (AI), electrical engineering, and physical sciences. Such market mechanisms deal with e.g. supply and demand matching, flexibility services, congestion management, network stability, risk sharing, and they work between various (autonomous) players and stakeholders. In addition to

the market mechanisms (i.e. market and allocation rules), bidding and planning strategies should be available to the players in the form of software players (agents) acting on their behalf.

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48 – Methodology to assess and accelerate technological innovation

Authors
Olaf Waals, Bob Meijer

Objective
Methodology for a reliable screening and selection process in an early stage of the potential value of new concepts and ideas for harvesting offshore wind energy

Beacons
- Low cost from larger turbine size
- Low cost from standardized turbine platform
- Optimal wind farm design
- Optimal integration into energy system
- Full international interconnectivity
- Supply chain efficiency
- Zero breakdown
- Strong support from stakeholders
- Net positive impact on the environment
- Adequate availability of human capital

Background
The objective of this milestone is to accelerate innovation for harvesting wind energy at sea. At present, there are a lot of new ideas and concepts for harvesting offshore wind energy. This milestone aims to develop a reliable screening and selection process for the potential value of new concepts and ideas in an early stage. By developing an indicator for the potential success of a concept, it will become easier to select which ideas to focus on in the future.

Current state-of-the-art
The current state-of-the-art is to value the levelized cost of energy (LCOE) for wind concepts at sea. Besides the cost aspect, other parameters will start to play a role in the success of new concepts. These include impact on the environment, social acceptance and the efficient use of space at sea.

Proposed R&D topics
Much like risk assessments where risk is defined as the product of probability and consequence, innovation potential could be valued as a product of feasibility and impact. Research should therefore focus on how to quantify feasibility and impact of a certain innovation on various parameters:
- Economics (e.g. estimated development cost versus potential to reduce LCOE)
- Life cycle CO_2 emissions
- Impact on environment
- Circular material use potential
- Maturity of supply chain (can the market deliver on a large scale)
- Spatial use (value created per km^2 of ocean)
- Social acceptance in the short and long term

As a result, this may lead to an innovation potential index (IPI) for offshore wind.

Reference
[1] Patterson F. The innovation potential indicator. Manual and User's guide. Oxford: OPP Ltd; 1999.

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