Lifecycle and decommissioning offshore wind

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March 2016
ECN-E--16-009

Acknowledgement

ECN would like to thank the following persons and companies for their contributions to this report.

Van Oord, Energy Solutions B.V. (Ralph Luijken), Prysmian (Wilco Veldkamp), Nuon/Vattenfall (Henk Kouwenhoven), NEN (Martijn Geertzen), Fabricom, BLIX Consultancy B.V. (Hennie Veldhuizen), TenneT.

From ECN the following researchers have been involved in writing the report:
ECN, Ashish Dewan (Installation and O&M)
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Executive Summary

In this desktop study ECN explores three end-of-life options for offshore wind farms: lifetime extension, re-powering and decommissioning. Combining a literature study with input from external experts and own experience, the outlines for a roadmap on these topic are sketched.
Lifetime extension and re-powering are end-of-life options that consider continuation of operation with original components and replacement components respectively. The study shows that lifetime extension requires monitoring of all components of the wind farm except the electrical infrastructure, which typically shows less wear and has a life up to 40 years. All other components of a wind farm are typically designed for 20 years of operation. To be able to decide on continuing operation, the owner requires information on the state of the farm, the permitting and safety conditions. Moreover, the business case for lifetime extension currently relies heavily on an extended subsidy programme. Existing wind farms are not designed for lifetime extension and are insufficiently monitored.
Re-powering typically considers installing state-of-the-art turbines on existing foundations and electrical infrastructure. Again the technical trade-off is based on the actual state of the components at the commercial end-of-life of the farm. This requires continuous monitoring of at least the foundations and electrical infrastructure in the farm. Operational wind farms are currently insufficiently monitored and not designed for re-powering, especially when considering increasing the capacity of the farms in the “second life”. Such intentional over-dimensioning will only take place when the residual value of the farm after 15-20 years is considered high enough to justify continued operation for another 15-20 years. The incentive for farm owners to design for re-powering, must be formed by a new governance model. Legislation must be in place before 2025 to grant extended permitting and a renewed subsidy scheme. Developing such governance models require instant action, as they will effect operation of wind farms 40 years from now.

When lifetime extension and re-powering are not considered viable, or when the wind farm has reached technical end-of-life, the wind farm must be decommissioned. Decommissioning requirements are defined in the contract and may include removal of the electrical infrastructure. Level of re-use or recycling are yet to be defined by the authorities. As the first UK wind farms are being decommissioned, we see the industry is in need for a dedicated decommissioning strategy, as the farms are currently being dismantled in reverse installation order. Special equipment is being developed and innovation within this sector has not yet reached its peak. Being very strong in the installation of wind farms, the Dutch industry can play an important role in the (international) decommissioning of the wind farms. The opportunities are significant and very relevant. We suggest to prioritize research into this field of wind energy.

The road map provided, shows that developments both on a technical level and on a governance level, must be finalized and implemented by 2025. The 9 years give us the possibility to prepare for making choices for the currently operational wind farms (which requires monitoring) and the wind farms that are to be designed after the Energy Agreement. These developments start with a stakeholder dialogue with all nationally parties involved.

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Introduction

1.1 Background

In the SER Energy Agreement on Sustainable Growth, an implementation agreement on (renewable) energy has been included. For offshore wind an important role has been foreseen in the agreement. It is agreed to have 4450 MW of wind energy operational in 2023 while at the time of the agreement 950 MW was in the pipeline or already installed. The government decided to install the additional 3500 MW in 10 sites of 350 MW each. The development sites will be clustered, e.g. 4 sites in the Borssele area, 4 sites at the Hollandse Kust South and 2 sites at the Hollandse Kust North. These sites will be tendered between 2016 and 2020 (5 times 2 sites of 350 MW each) and concessions will be granted for a period of 30 years.

Within this period of 30 years all activities of the developer have to take place, including the removal of the installed offshore wind farm components.
Nowadays, the technical lifetime of an offshore wind farm is calculated and certified to be at least 20 years, probably profitably extendable to 25 years.
It is to be expected that a longer economic lifetime of an offshore wind farm can help reduce the levelised cost of energy (LCoE). By taking extended lifetime, re-powering or decommissioning into account during the development and design phase of an offshore wind farm, costs can be avoided or environmental risks limited.

This study will briefly look into the effect of lifetime extension, re-powering and decommissioning of offshore wind farms. It will map the possibilities, through a literature study and quantifies, where possible, the cost saving potential per TKI WoZ R&D program line.

Secondly, the study will provide a research roadmap for the development of knowledge and policy related to the three before mentioned topics.

1.2 Definitions

Lifetime extension
Extending the lifetime of a wind farm literally means operating it for a longer time than it was economically designed for. In practice the economic design life shows a close correlation with the length of the subsidy scheme.

Re-powering
Having proved remaining life-time of wind farm components, 15 year old technology can be exchanged for state of the art. Re-powering potentially increases the efficiency of the farm, while lowering the cost of energy through re-use of components.

Decommissioning
Once a wind farm reaches end-of-life, most components require removal. The decommissioning requirements are often an integral part of the contract. Recycling of components is currently not a prerequisite.

1.3 The research questions

There are 12 questions that provide guidance in this research study:

1. What is the current design lifetime and expected lifetime of (components of) offshore windfarms (cables, foundations, wind turbines)?
2. What is the expected development in the area of lifetime extension, repowering and decommissioning, both for existing as for future (purposely designed) parks?
3. How far can we go in recycling of components and what might be value of the rest materials for both existing concepts and materials as well as new designs that anticipate recycling?
4. What would be the possibilities for cost reduction through life time extension, improved decommissioning methods, recycling and repowering?
5. How big are the cost reductions?
6. What are the expectations on the development of regulations that have impact on dismantling and re-cycling?
7. How do non-technical stakeholders face the idea of re-powering and life-time extension (mostly the investors, insurers and policy makers)?
8. What are the topics of research in this area?
9. What are the opportunities for product development?
10. What could a roadmap (research topics, budgets, timing, stakeholders etc) look like to support the aforementioned developments?
11. What measures are required from the government?
12. Strategy to gradually take down wind park

1.4 Providing the answers

Information in this report is based on three sources.

a) Literature study
b) ECN expertise
c) Consultation of external experts

The information that forms the answers to the research questions will be a mix of the three, unless a single source can be named. The literature sources are provided in

Appendix A, the external experts are listed in Section 1.5.

1.5 External experts

ECN has contacted the several external experts during the inventory phase of the project. The list below shows them categorized per programme line of TKI WoZ:

Table 1: Consulted external experts per programme line

1. Support structures	R. Luijken, Van Oord
2. Wind power plant and its components	H. Veldhuizen, BLIX Consultancy BV
3. Electrical infrastructure	R. Koning, Energy Solutions B.V. W. Veldkamp, Prysmian
4. Transport, logistics and installation	H. Kouwenhoven, Nuon/Vattenfall, NEC88 Commission M. Geertzen, NEN, NEC88 Commission M. Kradolfer, Fabricom Offshore services B.V. (GDF SUEZ)
5. Operation and maintenance	H. Kouwenhoven, Nuon/Vattenfall M. Geertzen, NEN, NEC88 Commission M. Kradolfer, Fabricom Offshore services B.V. (GDF SUEZ)
6. Facilities and experiments	Not assessed

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Inventory results

This section presents the results from the inventory phase of the project. The information that was gathered during the literature study and the data from the consultation rounds was combined with ECN’s own input and grouped per subject. As one subject can greatly influence the other two, we find overlaps in several topics.

2.1 Lifetime extension

2.1.1 Wind farms in operation

Lifetime extension considers operating a wind farm beyond its design life. The design life of current offshore wind farms is regarded to be at least 20 years and quite often to be 25 years.

The most critical components defining the lifetime of an offshore wind farm are the wind turbines and the foundation. Both the wind turbine and foundation are designed for fatigue where there is always the balance between additional investments at the beginning and the value of additional lifetime at the end.

The electrical infrastructure however, can typically operate up to 40 years assuming that it is installed and operated within the boundaries of its capacity. However it must be mentioned that this “expected lifetime” is never given as a warranty by suppliers, although it is often mentioned in discussions and presentations of suppliers. The industry does not have any practical experience with actual the lifetime of the electrical installations.

At the moment the technical lifetime exceeds the economic lifetime. Due to e.g. the duration that subsidy is granted to the produced electricity of about 15 years. The project developers and operators of the offshore wind farms assume 15 years in their finance plan to be the project lifetime.

In the present situation in the Netherlands, Germany and Denmark, where the TSO, TenneT in the Netherlands, is responsible for the substation at the site and the export cable to the main grid on shore it is the question whether that system cannot be used, economically and technically, for 40 years or even longer.

When considering lifetime extension of an offshore wind farm, the condition under which it has operated must be known. The condition of the wind farm in turn determines the net remaining value of the wind farm, which forms the most important element in the trade-off whether or not to extend operational life of an asset. This indirectly implies that throughout the operational life of the wind farm, the farm must be monitored continuously. The generated data will give essential information on the loading of the components of the wind farm in the past and what could be the residual life of the main components. Important information is e.g. the fatigue damage summation compared to the fatigue design limit and how many times has it been loaded up to its static limits?

The business case for extending the lifetime of a wind farm is based not only on the technical condition of the assets, but also on the financial proposition that comes with it. Currently, subsidy schemes are typically 15 years. For the net present value of a project this is a crucial point in time. When the subsidy scheme has ended the value of the produced electricity is solely depending on the market value of electricity. This reduces the business case substantially due to the fact that O&M cost tend to go up after 15 years of operation and the generated income goes down dramatically. A change in subsidy scheme could be helpful in this to make extension of the operational life of a wind farm substantially. O&M cost go up at the end of the lifetime of a project due to the fact that major components will require substantial maintenance or need to be replaced. Another issue is that spare parts will not always be available after 15 to 20 years due to the fact that there is no demand at present for these spare parts.

After the initial subsidy scheme period of 15 or 16 years the Capital Cost (CAPEX) of a wind farm is reduced to zero or close to zero. That leaves the cost of energy to be determined solely on Operational Cost (OPEX). However when the is higher than the expected income for the generated electricity the business case is negative and there is no incentive to keep the wind farm operating, even though the required income per MWh is much lower than for a new project. This problem is much more prominent for offshore wind farms than for onshore wind farms due to the much higher OPEX cost of offshore wind farms.

Another item that should be taken into account for projects that operate longer than initially foreseen is that the permit given for the projects requires that the wind turbines and the other components that make up the wind farm have a valid certificate on national or international (IEC) standard. At the moment the industry is investigating what should be formally required to extend the certificate for the period after the period that the certificate has expired. The wind turbine industry is also investigating how to write lifetime extension into the design and safety standard, see 2.1.

2.1.2 Design, installation and operation for lifetime extension

In general to design an offshore wind farm for a period longer than at present 15 -20 years does not require changing the design process substantially. Design lifetime is a parameter in nearly all design activities. However the implications of changing the design lifetime from e.g. 20 to 25 years or even longer will have a substantial effect on the outcome of the design. It can or probably will mean that the initial investment cost will go up but due to longer depreciation assumptions the annual capital cost will go down. Other subjects that should also be taken into account are that some of the main components might require additional major overhaul or even replacement. So in general, the whole execution of the project must take lifetime extension into account.

Electrical infrastructure

During the planning and the preparation phase of the project, it becomes even more important to perform a thorough marine survey so that obstacles, steep slopes and harsh environment are identified and potential damage of the cable during laying and operation is prevented. Lowering cost of energy by reducing the budget for this phase of the project can therefore be limiting the options of lifetime extension, or even increase the costs per kWh before lifetime extension can be discussed.

The protection of the cables (mechanical and electrical) is crucial for the lifetime of the cable. The burial of the cable is recommended, especially in shallow waters where fishing activities and anchoring take frequently place. In order to prevent damage from anchors or fishing devices, cables are often buried at least two meters below the surface of the sediment.

A major challenge for wind farm operators is to extend the lifetime of the intra array cable system. The operator needs to optimize power capacity and assess condition of components. Further, the operator needs to prevent thermal overloading of the cables, which means that the conductor temperature should not exceed its design values. In addition, testing forms a crucial aspect, both for installation and operation. Superior simulation and optimization of the whole process is also essential to evaluate and update maintenance schedule when necessary.

The same holds for the substation and export transmission system, that is operated by the TSO for new projects. The need for lifetime extension will require a more strict enforcement of the thermal restrictions in all components to make sure that the desired lifetime can be met.

The installation and commissioning of the electrical infrastructure makes up ~15% of the total CapEx see [1; 2;3;4;5]. As most of the costs of the electrical infrastructure are defined by installation/burial of cables, lifetime extension will have potentially a significant impact on the reduction of the LCoE.

Support structures

The lifetime of the support structure of a turbine is mainly determined by the design dimensions and corrosive protection system that should manage the rate of degradation of the substructure. Typically over the course of time the lifetime of support structures has increased from 20 to 25 years. Further lengthening the lifetime, through design could be done by simply over-dimensioning the substructure (for example increased wall thickness), which will directly affect the stiffness properties of the complete turbine system. Higher support structure stiffness can affect the fatigue requirements of the turbine tower positively, leading to lower system costs.

There is still uncertainty on the eigenfrequency of the support structure in the design phase, mainly due to soil-structure interaction. In general, the eigenfrequency is underpredicted in the design. A 10 percent higher eigenfrequency found in reassessment has shown an increase of 88% of the predicted lifetime (25 → 47 years), in case of the Walney offshore wind farm [7], scour protection should limit the variability of the support structure eigenfrequency. However, soil conditions are still changing (by sand dunes for example).

Investing in improved corrosion resistance of the substructure or intensifying preventive maintenance will directly affect the remaining lifetime as well. Again, to be able to grant permits for lifetime extension, continuous monitoring and correct interpretation of the measurement data of the substructures is a requisite.

O&M and installation

Operation and maintenance costs make up around 20-30% of the LCoE of an offshore wind farm in the Netherlands. O&M can be well planned during the initial stage of the life (preventive maintenance) an offshore wind farm and becomes more challenging up to the end of the design life of the farm (reactive maintenance on top of the preventive maintenance).

Once the subsidy scheme ends, asset owners shall not be able to invest a substantial sum in lifetime extension of the wind turbine and / or support structure and it is expected that owners to let their assets produce with the minimum effort of maintenance possible. To be able to safely operate a wind farm beyond its lifetime it is therefore required showing that the safety is not in danger through additional requirements that are preferably prescribed in a standard, whether in a national or international format. Firstly, the operator must be able to prove safe operation, which can be proven to the authorities by having a certificate from an accredited certification body, resulting in a renewal of the permits. Secondly, standardisation can help e.g. ports, authorities and the Dutch industry to create a stable base for future farm servicing.

The NEN (Dutch Standardisation Institute) indicates the need for an “offshore guide for Safety Evaluation”, to outline the conditions and regulations that favour the logistics and transport industry. At one end, the Dutch industry wants to make Netherlands as an important market for offshore wind energy, however at the same time the labour law, building law and operational law are quite national and are not considering the European market as a whole. Overall, the operational conditions will need to be more flexible in terms of harbour usage and transport and logistics. It is pointed out that offshore wind industry is very global and all the big OEMs have their presence in international countries. When engaging internationally, the Dutch (O&M) industry can benefit from this as well. Different ownership of the different elements of an offshore windfarm, as will be the case in the Netherlands in the future, will influence the life-time extension possibilities.

The economics of life time extension for wind power plant and is components
Next to a number of technical / safety related issues that have to be dealt with to keep on operating an offshore wind farm after 20 years, it is important to look into the economic viability of extending the life for such projects. The economic feasibility for an offshore wind farm after the technical life has expired, is hampered by the fact that it is actually already difficult to keep on operating an offshore wind farm after 15 years, once the subsidy scheme has ended. Normally a project is financed in such a way that the capital cost of the project has been paid off after the subsidy scheme is ended and thus the only cost determining the LCoE is the OPEX. With the present price levels at the electricity market an OPEX of more than € 30 – 35/MWh is hardly economical.

So to continue operating offshore wind farms after the (initial) subsidy programme has ended it is definitely required to investigate the options to setup an additional subsidy programme to maintain it operational to 20 years, the technical lifetime of the project, or even longer when it is shown that the installation is capable to be operated longer.

Looking at lifetime extension for offshore wind farms the most obvious components that could be of interest for lifetime extension are infrastructure components. Firstly the electrical transmission line and substation that converts the energy to a higher voltage level before transmitting it to the grid on shore. Secondly the support structure could of interest.

Summarizing the previous section, the electrical infrastructure offshore far outlives the other wind farm components. The failure rate of offshore electrical transmission system is higher than the onshore system, mainly due to the environmental hazards it encounters. As long as the cable temperature is maintained within the limits it would be possible to extend the lifetime of these components to two projects.

To calculate the effect on the LCoE with the simple model described in Section 2.6 it is required to make some assumption to determine the relative influence on the LCoE.

The following assumptions made are:

CAPEX	€ 3.200,= / kW
Cost of ETS	15% of the CAPEX.
Average interest rate	6,4%
Depreciation time wind farm	20 years
Depreciation time ETS	40 years
Annualised CAPEX/OPEX	2.0

This results in an LCoE reduction of 2.2%.

The other case, the support structure requires some other assumptions. As mentioned, for the support structure to survive longer than 20 years in offshore conditions it will be required to increase the wall thickness of the structure or to maintain a very good anti-corrosion system during the lifetime. This impacts the CAPEX and/or the OPEX of the support structure or the complete offshore wind farm during the entire life span of the support structure. For simplicity in the LCoE analysis it is assumed that the wall thickness of the monopile with the extended life time has an additional wall thickness of 10 mm, assuming that every year of additional life 0.5 mm is corroded away [1]. In the analysis the following additional, conservative, assumptions have been made for 6 MW wind turbine in 25 m of water depth:

Cost of the monopile per ton	€ 3.500,=
Dimensions of the monopile: Diameter D	7 m
Length	70 m
Wall thickness	1% D
Depreciation period monopile (reference)	20 years
Depreciation period monopile (extended lifetime)	40 years
Installation cost monopile (both cases)	€ 250.000,=

These assumptions result in a mass of 840 Tons for the reference support structure and a mass of 960 Tons for the support structure that is reused for a second project. This will increase the CAPEX for the first 20 years from € 3.200/kW to €3.270/kW or an increase of the LCoE of 1.4%. For the second period when the there is no requirement to install a new monopile the CAPEX requirement will go down from € 3.200,= / kW to € 2.670,= / kW reducing the LCoE by more than 11%[2].

Final considerations on designed lifetime extension

As mentioned before the business case for extending the operational life of an offshore wind farm depends on the outcome of the project revenue minus the cost. This determines in combination with the assumed risk whether or not to continue operation of an existing wind farm. The subsidy scheme, or the nonexistence of such a supporting scheme, directly influences the business case for lifetime extension. Should it cover 15 years, 20 years, or full life time of the wind farm? There are several operational options related to this question:

(a) Lifetime extension could simply imply continued operation without further life extending expenses. Some turbines may not be operational, but the farm as a whole will continue to provide (limited) power. Based on new permits and support schemes.
(b) Lifetime extension could mean investing at certain end of design life components, to boost the existing assets for continued operation. Based on new permits and support schemes.
(c) Dismantle the farm partially and allow new parts or turbines in a new subsidy scheme, based on the original electrical infrastructure, new permits and support schemes.

[1] Other effects like changes in the frequency of the monopile and the consequently influence on the loading of the wind turbine are neglected in this analysis.

[2] A more detailed economic analysis, discounting future earning with an assumed inflation rate would show the true value of this option.

This last option tends towards re-powering, which is covered in the following section.

2.2 Re-powering

Re-powering a wind farm consists of re-using the existing electrical infrastructure and foundations by replacing the wind turbines by new modern ones. The constraint would be that the turbines do not generate more power than the rated power of the old wind farm and the loads on the support structure should not be higher than the support structures can carry. It could be that due to technology improvements the capacity factor of the wind farm will increase without loading the infrastructure to an unacceptable level.

Electrical infrastructure
With their design lifetime far exceeding that of other wind farm components, the cables can be used for future repowering of offshore installations (e.g. wind farms). The opposite can also occur. In specific cases, the power cables used for the powering of offshore platforms, could be used as part of the cable system for the power connection of operational offshore wind farms.

It would be interesting to consider, during the design phase, the installation of higher capacity cables for offshore wind farms. This would on the one hand increase the initial cost of the project. However, in the long term, this decision could be beneficial for two reasons:

(a) As long as the lifetime of the cables is longer than the lifetime of a wind farm, these cables could be used for future offshore farms, being compliant also with the trend of developing turbines with higher rated power.
(b) These cables could be capable of managing “overplanting” for existing wind farms. Furthermore, general overloading during the operation of offshore wind farms will prevent damage to the electrical infrastructure during the design life of the original farm.

Investing in a larger capacity cable or doubling the operational pay-back time of the cable through re-powering can greatly influence the cost of energy produced by that farm. If also the substation can be re-used at the same capacity level, the costs of engineering the electrical infrastructure for the re-powered wind farm can be reduced by 90%, when designing for it in the original farm.

Needless to say, these decisions should be made early on in the planning phase of the first wind farm, taking into account future usage of the area. Consultation of the local government should provide clarity or guidelines.

Support structures
The current wind farm installation industry does not design and build for re-powering. Even though design lifetime extension for support structures is relatively straight forward, it is assumed that in 15 to 20 years the turbine technology will have improved to such an extent that the foundations would be too small, too closely spaced for modern wind turbines in the future. The question is of course do we expect that the growth in size and power will continue, or do we expect that this growth will reduce to such an

extent that in 20 years we can still obtain commercially interesting wind turbines with a diameter and rated power equal to the present state of the art wind turbines.

When there would be no wind turbines available in 20 years that would fit the constraints of the infrastructure the additional cost made at the beginning is made for nothing. In order to re-power, innovations should be developed on the possibility to adapt modern turbines to the existing foundation structures, which depending on the assumed growth of size of wind turbines can be difficult. Perhaps there will be a special niche for retrofitting wind turbines of sizes similar to those of the existing windfarms.

As mentioned, current wind farms in operation have often not been designed nor installed for re-powering in the future. Normally a foundation lifetime is considered as 25 years. For older wind farms like Amalia and Belwind, the corrosion protection is less prevalent. However, for newer generations of wind farms like Luchterduinen, specific corrosion protection systems are employed. If health monitoring of these structures shows no degradation beyond the design values, re-powering up to 35 years may be an option, if similar size turbines and spare parts are available.

O&M and installation

Re-powering is a more attractive option from an O&M point of view. As components (and their spare parts) age, the common technology advances with all its benefits. Re-powering makes use of these new technologies, often requiring lower maintenance. Health monitoring, off-site maintenance assessments and design for maintenance are common aspects of state of the art turbines, lowering the overall maintenance cost and increasing the safety of maintenance personnel.

Wind power plants and its components

Re-powering of a complete windfarm can only be done based on monitoring reports and new permits/extended subsidy schemes. If these prerequisites are fulfilled, the technical challenges remain.

Some examples from the field:
Böckstigen wind farm in Sweden is a near shore wind farm, installed in 6m water depth. The Momentum Gruppe is now considering whether the original monopiles can be re-used, in case they are forced to install similar size turbines.

In the Netherlands, wind farm Lely, owned by Nuon is out of operation since December 2014. There are no plans for repowering. Irene Vorrink, also owned by Nuon is being assessed for repowering.

Taff Ely Wind farm in the UK is an onshore wind farm. The advancement in the modern turbines has led RWE to think that they can generate almost twice as much power from the same site, being able to reduce the number of turbines on the site by almost two thirds.

2.3 Decommissioning

Decommissioning of a wind farm can be ordered for various reasons. To name but a few: the assets making up the farm can be at the end of their commercial life. The business case for continued operation may not be closing anymore (e.g. alternative energy costs, O&M costs vs yield). Permits allowing exploitation of the area or safe operation of the wind farm may be discontinued. Whatever the reason may be, when decommissioning a wind farm, there is a final expense and revenue to be made.

Electrical infrastructure

In general, the financial benefits of decommissioning the electrical cables do not outweigh the costs (around k€90./km [6]) Therefore, power cables are more typically abandoned in place than removed. Whether the sub-sea cables need to be removed or not depends on the contract for the windfarm and on the requirements of the national and local authorities.

If the cables stay buried there is a potential for contamination from the metal parts of the cable. Even though the installation may have initially caused habitat disturbance in the area, over the life of the wind farm, the habitat will have been colonized once again. The seabed around the cable trajectory may have become feeding grounds for predators over its 20 year operation. It may now provide a refuge to fish and shellfish and an anchor point for benthic flora and fauna. Moreover, it may have proven to enhance populations of certain species by providing shelter. In short: removing the cable may cause more harm than leaving it untouched. The precise risk of exposure of the cable itself will be established by monitoring cable burial depth over the life of the wind farm. When required by contract, offshore cable removal is likely executed by one of the following methods:

- peel-out: using a grapnel to pull the cable out of the seabed
- under runner: pulling an under-runner by a steel cable to push the electrical cable from the seabed
- jetting seabed material from the cable using a water jetting tool similar to that used during cable installation

The method used for removing the cable directly affects the re-usability of the cable itself. When the intention would be to re-use the cable for a new location, retrieval techniques are required that are currently not available in the industry. As cable cost only for a very small part of the total installation costs of the electrical infrastructure, re-use seems unlikely.
If the cable is destined to be recycled into its basic materials, the removal can be done with relatively rough methods (pulling/cutting). Once unburied, the cable will be winched, in parts, onto a vessel similar to that used during installation and taken to shore for recycling.
Work has started on developing a 100% recyclable cable, using High Density Polyethylene. Currently the insulation is made of XPLE, which is not recyclable.

Current cable recycling companies (most equipped for land cable) are not located for easy access to the vessels used for decommissioning. Having a recycling plant near a deep-sea harbour will help in this. Future wind farms can be designed for decommissioning by for example using 100% recyclable cables and "bury-for-easy-retrieval" options. The current decommissioning projects will provide the input for this.

Support structures

The current requirements on decommissioning turbine foundations vary per authority, but all of them state removal is compulsory. Typically, monopiles are to be cut 3 to 5 meters under the "mudline". This requires dredging. For the cutting operation, relatively light vessels are required. Due to the limited accuracy needed to cut a monopile, the weather windows are less strict. Contractors are looking into developing decommissioning tools that do not require divers. As the seabed is a dynamic environment, shifting sand dunes can expose the once buried stumps. These are easy to locate with radar. Monopile pulling, or possibly newly developed methods, to retrieve the complete monopile provides challenges caused by soil compaction leading to huge required crane capacities. The retrieval becomes a financial trade-off. Is the 200-300 tons of steel worth it?

In case of OWEZ, the foundations are filled with concrete to account for the settling grout issue. This increases the challenge of decommissioning. In theory however the pile could be lifted with the internal concrete plug in place.

Limitations in lifting a jacket support structure are based on dimensions, and less on the weight. The same decommissioning strategy is applied as for monopiles, by cutting the foundation piles. Stability of the jacket on the ground is maintained to some degree when the piles are cut, so in that sense it is easier than monopile cutting and lifting.

It is unclear at this point why the costs of decommissioning are uncertain. The vessels that can do the job are present in the current capacity so the investment needed for the decommissioning plan can be worked out closely to the actual procedure by those that are experienced installers. Reducing costs of decommissioning is a hot topic, with industry suggesting to lower costs by easing the requirements on cutting below the "mudline". Another way of reducing costs, is to leave the foundations as-is, and provide them with an artificial reef function.

With the Dutch industry so well-equipped for the job, the technical challenges do not form a hurdle for the decommissioning projects, neither here nor aboard. The question is who is picking up the bill: the utilities or the local authorities/governments?

O&M and installation

A US study shows installation costs to be typically 5 to 15% of overall capital costs and that decommissioning costs are roughly half of installation costs, or roughly 100,000 to 160,000 $/MW. Decommissioning costs and financial assurance depends on the methods developed for decommissioning and regulations concerning the circumstances under which components may be left in place [11].

Furthermore, the Federal Offshore Wind Lease T&C- Decommissioning Plan requires:

- All facilities must be removed to a depth of 15 ft. below the mudline when they are no longer used for operations but no later than 2 years after the termination of the lease, ROW[3] grant, or RUE[4] grant.
- Facilities include turbines, foundation structures, pipelines, cables, and other structures and obstructions.
- Lessees and grant holders must verify clearance within 60 days after a facility has been removed.

Each decommissioning project is unique in terms of the requirements of the operation, structure and site characteristics, equipment used, market conditions, contract terms, time of operation and operator preferences.

Offshore decommissioning operations in the oil and gas industry are for the most part low-tech and routine involving standard equipment and procedures. Same is expected for the offshore wind case as well, although the operation is estimated to be performed on a much larger spatial and temporal scale than oil and gas projects.

From the operator's point of view, decommissioning activities represent a cost to be incurred in the future, while from the government's perspective, decommissioning represents an uncertain event and financial risk if the operator becomes insolvent or cannot meet its financial obligations under the lease. For this reason, state and federal governments require companies to post a decommissioning bond at the time of construction to ensure that adequate funds exist to remove infrastructure in the future.

Wind power plant and its components

Decommissioning of a complete farm has been assessed by 3 case studies:

In developing a capital cost for the project, Gwynt y Môr Offshore Wind Farm Ltd has made an estimate for the future decommissioning of the wind farm. In a study for Decommissioning, Climate Change Capital Ltd (CCC) estimate net decommissioning costs to be around £40,000 per MW [12; 14] (based on interviews with stakeholders using a 240MW wind farm as a model). Considering this assumption for Gwynt y Môr project, it indicates a net decommissioning cost of approximately £23 million for the installed capacity of 576MW. The CCC estimate of decommissioning costs includes the complete removal of an offshore renewable energy device, including foundations and cables 1-2 metres below the seabed. However, it does not take into account the pre-decommissioning surveys that are required, management of the waste and any monitoring that may be required. Therefore, Gwynt y Môr Offshore Wind Farm Ltd proposes a decommissioning budget in the region of £400,000 per turbine or approximately £64m (for 160 turbines).

For Horns Rev III wind farm, it is expected that two years in advance of the expiry of the production time the developer shall submit a decommissioning plan. A part of this decommissioning program an EIA will be required to be completed. The method for decommissioning will be to follow best practice and the legislation at that time [15].

Vattenfall's Yttre Stengrund offshore wind farm, located in Kalmar Sound, Sweden was recently decommissioned. Work on dismantling the five wind turbines with a total capacity of 10 megawatt (MW) began at the end of November. The wind farm had been in operation since 2001 and had been owned by Vattenfall since 2006. The reason for the

[3] ROW is Rights of Way

[4] RUE is Rights-of-Use and Easement

decision to dismantle the entire wind farm rather than replacing the turbines with new, more modern ones was both financial and technical. Giving an insight on the reason of dismantling operation, the project manager Ms. Maria Hassel mentions- “The turbines that were installed at Yttre Stengrund were an early model and only about 50 of them in total were actually produced. The difficulty of getting hold of spare parts and the huge cost involved in upgrading the turbines and gearboxes meant that it wasn’t financially viable to replace the turbines.” Vattenfall plans to restore the site in such a way that any trace of the former wind farm will be negligible. Underwater cables will be removed in the summer of 2016 [17].

2.4 Recycling of components

Another topic is whether recycling of decommissioned parts can be of interest from a LCoE or environmental point of view. The industry agrees that recycling of metal component, the vast majority of the parts, is relatively straight forward. To reduce costs, it would be beneficial to keep transport on land of large decommissioned parts to a minimum. For the metal components, the recycle industry is well equipped to be able to reduce the waste to a minimum.

Recycling of polyester/epoxy blades is more challenging. Several studies have been conducted into recycling of composite materials, but they have yet to lead to a standardized procedure to re-use, or recycle blades. Currently, land fill is the most cost effective method of processing the blades. It will be important to reduce the carbon footprint of wind energy by innovation in polymer recycling. There is a potential in energy production, gasification and reclaiming of reinforcements. Chopped glass fibre and carbon fibre can be sold for reasonable prices.

We do not expect a second hand market for offshore wind turbines, or turbine parts to evolve as it did on the onshore market. The costs for offshore installation are too high and there is no possibility to place the equipment onshore.

2.5 The effect on LCoE

It is investigated whether by extending the technical and economic lifetime of wind farm and or its components a cost reduction can be achieved. For some of the components it is fairly safe to assume that there technical lifetime is not in line with the economic lifetime of the wind farm. For example the electrical infrastructure in the wind farm or the transmission lines connecting the wind farm to the shore can probably be used for much longer than the 20 years that a project is now foreseen to generate electricity.

Wind turbines and wind farms are designed for more severe conditions than the actual site conditions that are often encountered during the life of a farm. This means that all components have additional, technical, life left at the end of the project. What this remaining lifetime is, is difficult to quantify. Reason for that are the differences due to location inside a wind farm. Effectively this means that every turbine in the farm has a different potential technical lifetime left after design lifetime. For example a wind turbine at the outer edge of a wind farm in the dominant wind direction has had less wake effects than a wind turbine in the centre which did experience maybe lower wind speeds but a lot more turbulence.

To make use of the potential additional technical lifetime it would be required to measure the loads in the major components in a few wind turbines in a wind farm. This would lead to additional cost in the first phase or lifetime of a project. Only if lifetime extension or re-powering is planned prior the tendering process, the financial trade-off can be made that should support this decision process.

It is relatively easily to show how using a component beyond its design life affects the Levelised Cost of Energy (LCoE). The LCoE is calculated in its most simple form, including the economic lifetime effect amounts to the following:

$$LCoE = \frac{\frac{CAPEX}{a} + OPEX}{AEP}$$

In which:

CAPEX total capital required to install the project
OPEX Annual operation cost
a Annuity - = $(1-(1+r)^{-n})/r$
r average discount rate
n economic lifetime
AEP Annual (net) Energy Production

To include different economic lifetimes for specific components this formula can be extended to:

$$LCoE = \frac{\left(\frac{c_1}{a_1} + \frac{c_2}{a_2}\right) CAPEX + OPEX}{AEP}$$

Where

c_1 is the fraction of the capital cost with the annuity a_1 and
c_2 the fraction of the capital cost with the annuity a_2.

And $c_1 + c_2 = 1.0$

Investigation must show how the design requirements for the wind farm components change. For example, the additional material requirement for lifetime extension or re-powering must be offset to the additional costs needed at the start of the first project. This will indicate whether either of the two is interesting from a techno-economical perspective.

2.6 Other considerations

The three end of life options presented in this report are new ground, but not unexplored. For example, this report has shown that the United Kingdom has well defined requirements on decommissioning of offshore renewable energy installations. With the first wind farms nearing end of life, it will be interesting what is reported by their owners. .

Re-powering offshore wind farms has been considered for existing wind farms but no wind farm has been designed for re-powering. The lessons learned from onshore re-powering operations can be employed for offshore wind farms although most experience onshore is to rebuild the entire wind farm with (much) larger wind turbines.

Moreover, guidelines have to be framed by the government for lifetime extension, re-powering and decommissioning. From the applicable subsidy schemes to required percentage of recyclable components.

Standards need to be developed, both for technical and safety related topics. Here we can learn from the oil and gas industry. Related to safety: cutting cost may be one option to reduce the LCoE, but increasing revenue is another one. In Denmark offshore wind farms, such as Middelgrunden have become a tourist attraction, from a safe distance.

Certification of components is usually granted for 20 years of operation. It will be required to re-certify components after the life of the first project or to certify components for a 40 year life. Permitting of wind farms also require a safety certificate according to NEN or IEC. At the moment obtaining such a permit for a lifetime longer than 20 years is not performed although not impossible.

3

Working towards a roadmap

Summarizing the previous section, we can identify specific areas of interest that currently hamper lifetime extension and re-powering. As the Dutch industry will play an important role in the decommissioning of not only national projects, this topic requires prioritization.

Lifetime extension - current status
Wind farms are operated up to their economic lifetime. Limited monitoring is taking place. There is no financial incentive to operate a wind farm beyond its design life, as risk increase as well as the O&M costs.

Lifetime extension - what is required?
Thorough knowledge and information is needed on the condition of a wind farm before lifetime extension is considered. For this we need to measure more extensively, also in currently operational wind farms. This way we can generate information on remaining life in a wind farm, which provides input for future wind farm designs.
Moreover, if lifetime extension is to be considered, a legal and financial framework will need to be set-up and implemented that supports the extended operation of a wind farm beyond its design life. Safe operation, also for the O&M personnel is extremely important. Standardization and regulation need to help here.

Lifetime extension – what are the specific research topics?
- Further development of health monitoring with Condition Monitoring Systems
- Develop O&M strategy to lifetime extension
- Development, modelling and validation of extended life designs through monitoring/measuring
- In-depth overview of governance requirements
- Identify gaps in the standardization structure that will have to support LE.

Lifetime extension - what is the time scale?
2017 – 2025 (also see page 29)

Re-powering - current status

Re-powering a wind farm that is currently operational bring large risks with it. If the condition of the wind farm components is not monitored throughout the lifetime of the farm, it will be hard to find financial support for a re-powering investment.
If re-powering at equal capacity, the costs of the electrical infrastructure are significantly lower (up to 90%).

Re-powering - what is required?

Like for lifetime extension, it is important to confirm the remaining life of the farm at the end of life. This can only be done by monitoring the technical condition of the farm throughout its lifetime. If a wind zone is to be developed for re-powering, the farm design will need to be specifically tuned to that. Especially if re-powering is planned at a higher power capacity than the initial project.
As design and installation for re-powering requires additional costs, a governance structure needs to be in place that can guarantee permit granting, safe operation and an extended subsidy programme.

Lifetime extension – what are the specific research topics?

- Further development of health monitoring with Condition Monitoring Systems
- Development, modelling and validation of re-powering designs through monitoring/measuring
- In-depth overview of governance requirements
- Identify gaps in the standardization structure that will have to support RP

Lifetime extension - what is the time scale?

2017 – 2025 (also see page 29)

Decommissioning - current status

Wind farm owners are expected to produce the area in the same state as it was when the lease started. The requirements and exact conditions are defined in the tender contact. Experience in efficiently decommissioning an offshore wind farm is very limited. First reports are done on UK farms that have reached their end-of-life.

The Dutch industry is eminently equipped for performing the decommissioning task of European wind farms, as their largely require the same equipment as used for installation.

Decommissioning - what is required?

We need to observe closely what is happening in the UK and use the Dutch wind farms OWEZ and Amalia as research projects to become experts on decommissioning offshore wind farms. In parallel, innovation is required in specific decommissioning equipment and planning of decommissioning activities.

Governance is required on the requirements of waste handling. Perhaps CO2 footprint of wind energy can be further reduced when promoting recycling of specific parts of the wind turbine, foundation or electrical infrastructure.

Decommissioning – what are the specific research topics?

- Innovation in decommissioning equipment
- Optimizing of planning of decommissioning activities
- Innovations in recycling of composite materials
- LCA of wind power, including decommissioning

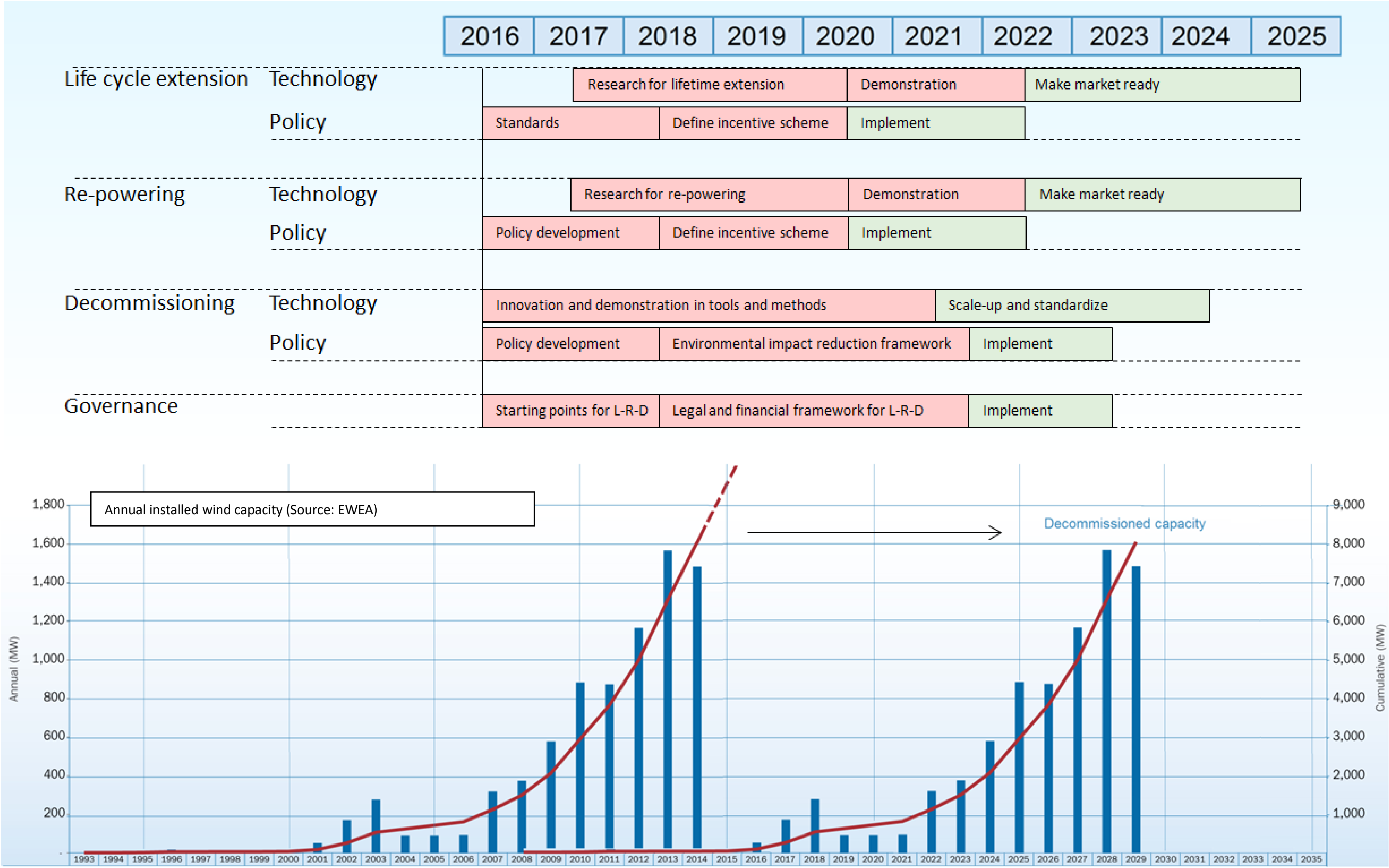
Decommissioning - what is the time scale?

Now – 2025 (also see page 29)

The roadmap depicted on the next page provides a clear image: in 10 years from now, the first operational wind farms will reach their end-of-life. If the Netherlands is well prepared, we will have 3 options: extending the operation of the Dutch wind-farms, re-power the same wind farm or decommission it efficiently. The foundation for these three options will have to be laid within the coming 5 years. This will provide enough time to demonstrate well in advance that we have overcome the technical and governance challenges that accompany lifetime extension, re-powering and decommissioning.

This roadmap is formed as a spark for discussion with the stakeholders in this field of expertize. We believe priority should be given to decommissioning, as this is a sector that the Dutch industry is well prepared for, and is most relevant for the moment. The potential cost effects of life-time extension and re-powering can however not be neglected and should receive more attention in the coming years. The previously mentioned list of research topics is by no means exhaustive. Again a dialogue with the stakeholders will promote involvement and broadly supported agreement on the various topics.

Figure 1: : Roadmap until 2025



4 Conclusions

Business cases developed for the state-of-the-art wind farms of today, are looking at a commercial horizon of 15 years. The initiative for lifetime extension, re-powering and recycling of components, must come the local authorities. One can imagine that governance models, supporting lifetime extension and re-powering, will need to be in effect prior to the design and installation of a new wind farm. This is partly because it potentially requires over-dimensioning of the components, but also due to the fact that additional costs are made for monitoring the technical status of the farm throughout its "first" lifetime. These extra costs need to be financed in the first contract and should be covered by the authorities.
Innovation in decommissioning also requires support from a national programme, as the most cost effective options not always represent the options with the lowest carbon footprint. As the Dutch installation industry can and will play an important role in the decommissioning of operational wind farms, both nationally and internationally, ECN suggests to focus on research and development in the field of decommissioning.
Governance and policy development form the fourth main area of importance for implementing lifetime extension, re-powering and advanced decommissioning. Not only should the financial incentive be reliable, it should be available in time, to provide the possibility of continuing operation of wind farms.
Standardisation is an important part for granting permits (both for lifetime extension and re-powering). Safety legislation will form the corner stone for extended operation of any wind farm. Operational and maintenance work performed at the wind farm will intensify, especially for wind turbines that operate beyond their design lifetime. The effect of lifetime extension, re-powering and effective decommissioning is a reduction of the levelised costs of wind energy. Providing concrete numbers proves to be difficult as the band width of estimations are large. It is important to further look into the potential of each of the 3 options, in order to be able to prioritise more accurately.

The road map provided shows that developments, both on a technical level and on a governance level, must be finalized and implemented by 2025. The 9 years give us the possibility to prepare for making choices for the currently operational wind farms (which require monitoring) and the wind farms that are to be designed after the Energy Agreement. These developments start with a stakeholder dialogue with all nationally parties involved.

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