TKI WIND OP ZEE
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Pathways to potential cost reductions for offshore wind energy

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Summary

To investigate the potential cost reductions for offshore wind energy a study has been conducted by TNO and BLIX Consultancy. The research has been commissioned to TNO and BLIX Consultancy by RVO[1] and TKI Wind op Zee.

The study has been divided into three phases, phase I aimed at potential cost reduction to be achieved by scaling up present technology, with 10 – 12 MW wind turbines, to 15 MW (2025) and 20 MW (2030) wind turbines. Phase II focused on cost reduction potential applying incremental innovations, qualitative assessment of these innovations and quantitative predictions of the effects of some of these innovations on the Levelised Cost of Energy (LCoE). In phase III a list of break-through/disruptive or emerging technology innovations has been inventoried and evaluated qualitatively.

The wind farm zone IJmuiden Ver has been selected as reference zone. The present technology (10MW), and future 15 and 20 MW wind turbines have been modelled in wind farms varying in size between 750 MW, 1 GW and 2 GW. The wind turbine and farm characteristics are scaled, applying recent trends in wind farm and wind turbine design. The TNO offshore wind farm cost model, including EEFarm - TNO install and TNO O&M calculator - have been applied to determine the Capex cost of the wind turbine, support structure and balance of plant. The yield of the turbine and wind farm in the conditions at IJmuiden Ver has been determined applying simplified models determining the wake effects.

The results have been applied in the simplified approach LCoE model described in an IEA recommended practices for wind turbine testing, see [1].

The results for phase I show that by “simply” upscaling the wind turbine and wind farm, the LCoE cost reduction will be up to nearly 25% in 2030 compared to the baseline, 2020. Applying learning curve effects assuming the road map for offshore wind energy from Wind Europe, see [2], an additional cost reduction of 8% (2025) and 12% (2030) can be predicted with a learning curve coefficient of 6%. This leads to a total cost reduction of nearly 33% in 2030.

Workshops and interviews have been conducted for phase II and phase III to create a long list of innovations, phase II for incremental innovations which are assumed to be implemented in a relatively short time, i.e., between now and 2030 and in phase III break-through/disruptive innovations that are assumed to lead to cost reductions after 2030. Both in phase II and phase III, a selection has been made on qualitative assessment to rank the innovations with respect to the potential cost reduction, effort to implement the innovation and other qualitative criteria.

A selection of the incremental innovations of phase II have been analysed with the LCoE model by applying the assumed cost reduction estimated for each specific innovation, e.g., an increase in energy yield of 0.5% leads to a factor of 1.005 times the yield determined in the reference cases of phase I.

Phase II innovations are listed in section 4. The most promising incremental innovations are increasing the design life to 40 years and/or increasing competition for the major capital expenditures as well as for the operational services required. The LCoE reductions are estimated up to nearly 8%, which is in addition to cost reduction due to larger turbine size. Some phase II innovations can be applied in parallel leading to a substantial higher total cost

[1] Dutch Enterprise Agency RVO

reduction however some innovations might probably also be included in the learning curve approach.

The phase III innovations assessed in a qualitative way are:

1. Robust, self-diagnosing and healing wind turbines
2. Alternative wind turbine concepts
3. Turbine load control/Lifetime extension
4. Smart wind energy
5. Optimised wind turbine including smart turbine design
6. Wind energy and P2X e.g., Hydrogen

These innovations cannot be quantitively analysed in the LCoE model due to completely different nature of wind farm and/or wind turbine concept. Most of the innovations in the long list are already under development for a longer period, some already for more than 20 years. These emerging concepts (still) have the promise of potential cost reduction and at the same time are not that easy to bring to the market. This is for a part due to the fact that the standard, most used concept, has seen large cost reduction over the past 10 years.
A concept that will most certainly come to the market is floating wind turbine. Due to scarcity of shallow water locations and the trend that the floating support structure, including mooring system, is reaching cost levels that are favourable comparing to bottom mounted support structures in water levels of 50 – 60 m the floating concept will see a swift development. Still several concepts of floating wind turbines are under development, the best concept, if there is one, still needs to emerge. It is however also expected that at least two concepts, one for intermediate depth, up to approximately 100 m water depth and a concept for deep water, i.e., more than 100 m to a few 100 m water depth will stay.
For most emerging innovations fundamental as well as applied research will be required to reach to a Technology Readiness Level (TRL) 9 to be able to implement these innovations with sufficient confidence.

The overall conclusion is that even though offshore wind has gone through a steep cost reduction in the recent past this study shows that the potential to reduce cost via R&D, innovations, is still available and that the present cost level is not the limit.

Acknowledgments

The following experts are acknowledged for their support creating this report by participating in interviews and workshops organised to create the long list of innovations and helping to determine the potential impact of the innovations on the LCoE.

We acknowledge from BLIX Consultancy (in random order), Maarten Timmerman, Albert van der Hem, Stefan Segers, Tim Drummen and associates Willem Schellingerhout, Henk de Pater. From TNO (in random order), Feike Savenije, Wouter Engels, Gerard Schepers, Chao Liu, Iratxe Gonzalez Aparicio, Clym Stock-Williams, Edwin Jan Wiggelinkhuizen, Aliene van Veen, Robert de Kler, Stoyan Kanev, Edwin Bot, Bo Hu and Peter Eecen. Technical experts from Van Oord Offshore Wind, Vattenfall, Shell, Ørsted, MHI Vestas, SiemensGamesa, Jos Beurkens SET Analysis, Green Ducklings, and Enersea Consultancy.

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1 Introduction

This report presents investigations of potential cost reductions for offshore wind energy which is assigned by RVO to TNO and BLIX.

In the recent past the cost reduction targets for offshore wind energy, as set during the “Energieakkoord 2013”, have been realised and even surpassed. In the Energieakkoord 2013 the cost reduction was targeted at 40% by 2020 compared to price levels in 2010. The target price for 2020 was set to 100 €/ MWh. However, in 2016 the price level for Borssele I & II was already substantially lower than the target for 2020. The latest tenders for the Hollandse Kust Zuid and Noord resulted in prices even without subsidy, only grid connection cost are subsidised/publicly funded, see Figure 1.

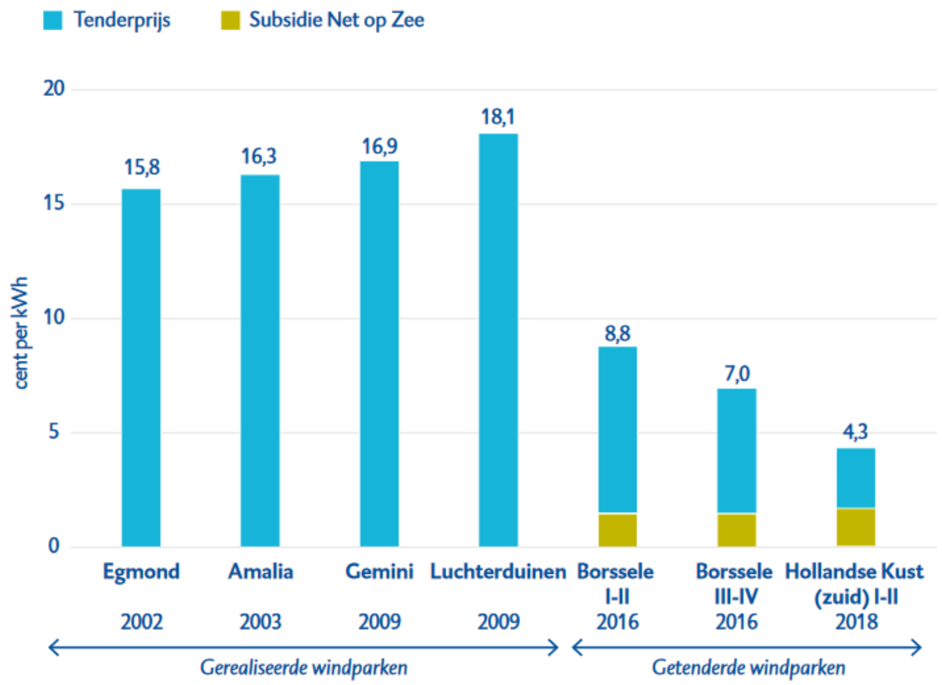

Figure 1 Offshore Wind Energy prices for wind projects since 2002. For the projects Borssele and Hollandse Kust Zuid the grid connections cost is included in the price as subsidy grid at sea. The Hollandse Kust Noord will have a comparable energy price as Hollandse Kust Zuid where the subsidy is only based on grid connection cost. Figure from [3].

Even though the cost of wind energy has gone down substantially faster than targeted, there is an increasing uncertainty whether the costs have gone down enough to ensure that future offshore wind farms will be cost effective and the business case for offshore wind remains positive at “zero” or no subsidy[2], see discussion in [4]. Due to the profile of the power generation of the renewable energies, mainly solar PV and wind, the value of electricity produced with wind and solar is lower than the time-based average electricity prices. This gap between the value of wind and solar electricity and the average value of all electricity will increase with increasing penetration of these renewables in the electricity grid.

[2] i.e., only the grid connection cost are socialised/subsidised.

This report contains an investigation in cost reduction potential of present technology focussing on further upscaling of wind turbines, wind farms and learning curve effects. Secondly it is investigated what are potential benefits that deal with incremental innovations including project finance and organisational innovations. Finally, it is investigated whether breakthrough innovations which are in an early stage of development can lead to cost reductions in the long run, i.e., after 2030.

The following simple LCoE formulation will be used through-out this report

$$LCoE = \frac{\frac{Capex}{a} + Opex}{AEY}$$

Capex	Total investment, including interest during construction
Opex	Annual operational expenditures including maintenance and reservation for retrofitting or decommissioning
a	Annuity factor = $a = 1/\sum_{t=1}^{n}(1+r)^{-t} = (1-(1+r)^{-n})/r$
r	Real discount rate
T	Year index
AEY	Annual Energy Yield

The Capex, Opex and AEY depend on technology choices like turbine characteristics, location depending conditions and wind farm design choices.

The study is performed in three phases. Phase I investigates the cost reduction potential by upscaling both the wind turbine and the wind farm. To predict the cost reduction by upscaling, TNO's Wind Farm Cost model is evaluated for a 10, 15 and 20 MW wind turbine in wind farms between 0.75 GW and 2 GW. In phase I, the cost reduction potential that can come from learning by doing or learning curve cost reductions is also investigated. The results of the cost study are applied in an LCoE model to determine the influence of cost reductions. In Phase II an inventory of innovations with a relatively short period to implementation is created via interviews and a workshop. The long list resulting from the inventory is evaluated and a selection of the innovations is evaluated with the LCoE model. In Phase III an inventory of emerging / disruptive innovations is created in 3 workshops. The most promising innovations are evaluated in a qualitative manner.

In Appendix A, a short summary of cost reductions studies performed in the past decade has been reported.

2 Reference case

2.1 Reference wind turbines and wind farm

To measure the value of innovations it is required to define a reference and it is our choice to use a virtual wind turbine that has realistic characteristics of a wind turbine that is available on the market 2020.

The dimensions and power are listed in Table 1. The hub height is determined to be ½ rotor diameter + 30 [m]. The rotor speeds are scaled from existing wind turbines where the nominal rotor speed is based on a tip speed of 85 m/s.

Windturbine		**2020**
P_{nom}	[MW]	10
D_{rotor}	[m]	193
H_{hub}	[m]	126.5
Rotor PD	[W/m2]	342
RPM_{min}	[RPM]	3.5
RPM_{nom}	[RPM]	8.4
Windfarm		
P_{nom}	[GW]	0.75
WF PD	[MW/m2]	6
Export cable	AC/DC	DC
Economic Liftetime		20
Overplanting	[%]	0

Table 1 Dimensions and nominal power of the reference wind turbine and wind farm in 2020.

It has been decided by the research team to model a DC export connection to shore for the reference wind farm although that is not common or realistic in 2020 terms, especially for a relatively small size wind farm of 750 MW. However, to prevent cost differences due to technology changes with respect to the grid connection, the DC connection has also been modelled in the 2020 reference project.

2.2 Reference economic/financial parameters

Cost of Debt	3.0	%
Cost of equity	10	%
Ratio Debt/ Equity	4	80% debt
WACC (nominal)	4.0	
Inflation rate	1.5	%
Real Discount rate	2.86	%
Corporate tax	25%	%
Economic lifetime	20	Years
Annuity	15.1	Years

Table 2 Financial and economic reference values applied in the LCoE

The annuity is calculated with the following equation:

$$a = 1/\sum_{t=1}^{n}(1+r)^{-t} = (1-(1+r)^{-n})/r$$

The real discount rate, r, is based on cost for equity and debt and the corporate tax level in the following way:

Real discount rate (WACC)

$$WACC = \left(R_d \cdot (1-TC) \cdot \frac{D}{V}\right) \left(R_e \cdot \frac{E}{V}\right)$$

V	sum of Equity and Debt
Re	return on equity
R_d	interests on debt
TC	Corporate Tax
E	Equity
D	Debt

This results in an annuity of 15.1 years for the reference case 2020.

2.3 Reference site conditions and wind resources

The location chosen for the yield analysis is wind farm zone IJmuiden Ver (IJver). The Weibull wind coefficient at the zone, based on DHI analysis are: Weibull scale factor is 11.189 [m/s] and the shape factor is 2.177 resulting in an average wind speed of 9.91 m/s at an altitude of 120 above MSL.

Alfa [°]	Freq [%]	W-A [M/S]	W-k [-]
0	6.194	9.715	2.171
30	5.702	9.166	2.354
60	6.340	9.308	2.471
90	6.387	9.709	2.419
120	5.550	9.279	2.338
150	4.804	9.330	2.092
180	7.301	11.284	2.179
210	13.450	13.134	2.394
240	14.800	12.928	2.437
270	11.360	11.957	2.202
300	9.751	11.200	2.191
330	8.360	11.127	2.173
All	100	11.189	2.177

Table 3 The reference wind resource at IJVer at 120 m above MSL

The wind speed is assumed to vary with height, applying the power law formulation:

$$\overline{V_H} = \overline{V_{ref}} \cdot \left(\frac{h_H}{H_{ref}}\right)^{\alpha}$$

With the shear exponent α = 0.085.

The water depth is chosen to be 40 [m], which is close to the maximum water depth for the IJmuiden Ver location, with soil conditions assumed to be sand.

3 Phase I - Potential cost reductions of upscaling present technology

When upscaling present technology wind turbines to 2025 and 2030, the following assumptions are made:

- Wind turbines will continue to increase in nominal power, the assumption is that in 2025 it will be possible to build a wind turbine with a rotor diameter of 250 m with a nominal power of 15 MW and in
- By 2030, it is assumed that a wind turbine with a nominal power of 20 MW with a rotor diameter of approximately 290 m will be feasible.

In general, it is assumed that the trend of reducing the rotor power density will continue in the future. The reduction of rotor power density has a strong effect on the wind capacity factor which influences the revenue of a wind farm positively and reduces the need for future storage. The wind farm power density of the Dutch wind farms planned till 2030 is increasing, most probably due to scarcity of offshore space. This trend has also been applied in the upscaled wind farms of 2025 and 2030. Increasing the wind farm power density will however lead to a higher LCoE.

A previous study performed for the Ministry of Economic Affairs and Climate Policy indicated that the increase of LCoE due to increasing the wind farm Power Density from ~5 MW/km2 to 10 MW/km2is approximately 5%, see [5].

Windturbine		**2020**	**2025**	**2030**
P_{nom}	[MW]	10	15	20
D_{rotor}	[m]	193	250	290
H_{hub}	[m]	126.5	155	175
Rotor PD	[W/m2]	342	306	303
RPM_{min}	[RPM]	3.5	2.7	2.3
RPM_{nom}	[RPM]	8.4	6.5	5.6
Windfarm				
P_{nom}	[GW]	0.75	1	2
WF PD	[MW/m2]	6	8	10
Export cable	AC/DC	DC	DC	DC
Economic Liftetime		20	25	30
Overplanting	[%]	0	0	0

Table 4 Characteristic values of the wind turbine and wind farm

3.1 Cost model and cost model results

The Levelised Cost of Energy of the TNO offshore wind farm cost model has been applied to determine the cost of the:

- Wind turbine
- Support structure
- Electrical system in the wind farm
- Wind farm installation
- Electrical export system
- Operation and maintenance (O&M)

The results from the cost model have been reviewed and improved with BLIX knowledge and experience.

The yield of the wind farm has been determined on the basis of the yield of the wind turbine stand alone in the wind regime and wake losses and other losses, amongst also in-availability losses, are subtracted to determine the Net Energy Yield.

The cost model consists of simple engineering models, tuned with real cost data, or parametric relations based on theoretical scaling functions for components where the simple engineering models are not available. The parametric relations are also tuned with real cost data. The reliability of the actual cost data is assumed to be within 15 – 20 % of the individual components the total Capex is assumed to be within 10 – 15%. The ratios of the cost levels are assumed to be much more accurate.

The wind turbines modelled are virtual wind turbines. The 10 MW reference model is modelled with characteristic dimensions that are applicable for wind turbines that are presently on the market. The 2025 and 2030 wind turbines are based on expectations to be achievable on the basis of the present technology. In no way it is the intention to imply that the dimensions given here are the maximum achievable. The employed models are not capable to predict maximum engineering dimensions.

Wind Turbine		2020	2025	2030
P_{nom}	[MW]	10	15	20
D_{rotor}	[m]	193	250	290
H_{hub}	[m]	126.5	155	175
Rotor PD	[W/m2]	342	306	303
RPM_{min}	[RPM]	3.5	2.7	2.3
RPM_{nom}	[RPM]	8.4	6.5	5.6
Wind Farm				
P_{nom}	[GW]	0.75	1	2
WF PD	[MW/m2]	6	8	10
Export cable	AC/DC	DC	DC	DC
Economic Liftetime		20	25	30

Overplanting	[%]	0	0	0
Farm Area	[km2]	125	125	200
Turbines	[-]	75	67	100

The resulting cost of all components, for the reference and upscaled version for 2025 and 2030 are listed in appendix A.

The installation cost is determined with the TNO install software tool. The annual O&M cost are determined with TNO O&M cost model.

The Levelised Cost of Energy (LCoE) are determined applying the simplified LCoE model as described earlier.

		2020 (10 MW)	2025 (15 MW)	2030 (20 MW)
# of wind turbines		75	67	100
Pnom of wind farm	[MW]	750	1005	2000
Distance to shore	[km]	70	70	70
Distance to grid	[km]	100	100	100
year		2020	2025	2030
WACC[3]	[%]	3.80	3.88	3.88
Single turbine	[M€]/turbine	7.41	13.05	19.02
Support structure	[M€]/turbine	4.97	8.50	11.38
Electricity total	[M€]	735.97	926.83	1766.74
Project fixed cost	[M€]	45.00	60.30	120.00
Installation total	[M€]	110.31	131.39	205.75
Total Capex	[M€]	1819.8	2563.0	5132.4
Total Opex	[M€]/year	63.90	70.59	107.96
Yield	[TWh]/year	3.5407	4.7775	9.4704
LCoE 2020	[€/MWh]	**55.2**	**48.7**	**42.3**

Table 5 The overall characteristics, cost, performance and levelized cost of energy

[3] Corporate tax level changes in 2021 to 21.7% from 25% in 2020.

3.2 Learning curve cost reduction effects

A substantial part of the cost reduction in any manufacturing process is achieved by making more items, in this case more wind farms. In engineering technology this is called learning curve cost reductions. A simple, and the most popular, model, created by Wright in 1936, see [6], described a fixed cost reduction rate for each doubling of the cumulative production. In aircraft technology the learning rate was determined to be ~17%.

The applied “learning by doing” relation is: $\log Y = \alpha + b\,(\log x)$

Where Y is the unit cost, e.g., the cost of per MW of installed wind capacity.
b is the learning rate and
x is the cumulative installed wind power.

Cost reduction achieved by learning are not autonomous. To achieve the learning curve cost reduction still a substantial effort in R&D to develop and implement improvements in manufacturing, logistics, installation and operational process is required!

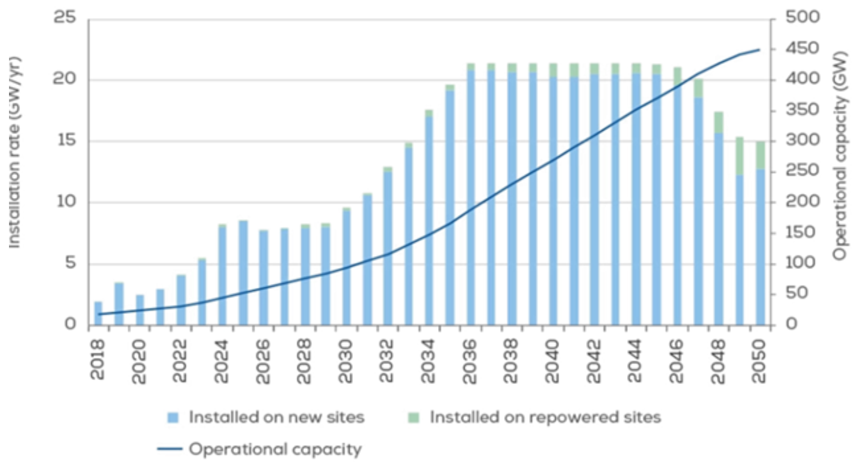

Figure 2 Installation rate required to meet the target of 450 GW installed capacity by 2050, copied from [2][4]

In 2019 Wind Europe published a road map for offshore wind in European seas (including the UK), see [2], in which the deployment of offshore wind has been estimated to make sure that the target set by the European Commission of 450 GW in 2050 will be met. The installation rate is based on new installations and repowering of existing sites. The operational power is based on existing installation minus decommissioned power plus the newly installed power, see Figure 2.

The learning rate for offshore wind power has been analysed in several studies. A large discrepancy between recent and older studies has been found. This could be due to the fact that the cost of first offshore wind farms have been reported too optimistically (low). The first offshore wind farms, like Horns Rev and Near Shore Wind Farm Egmond aan Zee, needed substantial technology adaptions immediately after installation which were not accounted for the

[4] These numbers still include the installed capacity in the UK.

total Capex of the project or have been paid for by the wind turbine supplier. Due these cost overruns of the first offshore wind projects before 2005, later projects, between 2005 and 2010, reported more realistic cost levels resulting in the conclusion that learning rates were negative. The learning rates of early studies, 2012, see [7] and 2015, see [8] show results between 2% and 12%.

It is proposed to apply, in this study, a conservative learning curve rate of 6% - 8%, the results of the learning curve cost reductions are shown in appendix A and Figure 3.

Based on the cumulative implementation and learning rate coefficients of 6 – 12% the cost reductions with respect to 2020 are listed in Table 14 Learning curve cost reduction based on cumulative European offshore wind energy capacity for learning curve rates between 6 and 12%.

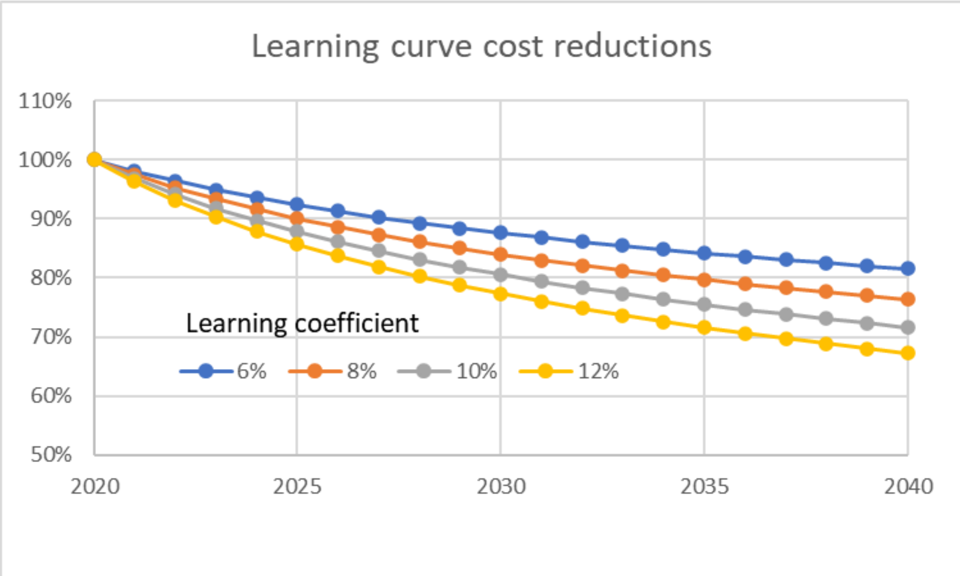

Figure 3 Cost reduction on the basis of learning by doing with learning coefficients between 6 - 12%

Applying the cost reductions due to “Learning by Doing” on the upscaled reference wind turbine/ wind farms the following cost levels can be expected.

		LCoE [€/MWh]		
		2020 (10 MW)	2025 (15 MW)	2030 (20 MW)
LCoE (2020) Learning curve coef.	0%	**55.2**	**48.70**	**42.3**
LCoE (2020) Learning curve coef.	6%	**55.2**	**45.0**	**37.0**
LCoE (2020) Learning curve coef.	8%	**55.2**	**43.8**	**35.5**

3.3 LCoE model used to model the innovations of Phase II

Based on the cost model results an LCoE calculation model has been made to calculate in a straightforward and in a transparent way the effect of incremental innovations. The model can be found in Appendix D.

4 Phase II - Potential cost reductions from incremental innovations and implementations until 2030

Besides the upscaling of turbines, several technical, financial, and organisational innovations can lower the cost price of offshore wind. In Phase II incremental innovations until 2030 that decrease cost and/or increase energy production, thus lowering the LCoE, were investigated. The analysis consisted of three parts:

- Phase II.A - The development of a full list of innovations, using a literature review and input from experts
- Phase II.B - The determination of the most promising innovations from the full list, funnelling down into Top-30
- Phase II.C - Determining the quantitative expected LCoE-impact of eight selected innovations using the LCoE-model developed in Phase I

Note that the innovations mentioned in this chapter sometimes overlap with the ones discussed in the next chapter (‘Disruptive innovations’).

4.1 Phase II.A - The development of a condensed list of innovations

Approach/Methodology

The following methodology was followed to create a condensed longlist:

1 Three initial lists were created, one with technical, one with organizational and one with financial innovations, based on a literature study of two TKI reports.
2 Experts (with backgrounds in several aspects on offshore wind) added additional innovations based on their experience and provided comments to the innovations found in the literature.
3 The resulting list was circulated to within the team and external experts of key players in the international offshore wind industry, and they were asked to add additional innovations and to score the innovations on three different aspects:
    - Expected year of introduction
    - Expected LCoE-impact (1=very low, 5=very high)
    - Expected effort to achieve this LCoE-reduction (1=large effort, 2=small effort)
4 Additional innovations mentioned by the experts were added to the list. Comments and scoring for the circulated innovations were added in additional columns.
5 The resulting input was analysed and roughly twenty innovations suggested by the experts were merged with similar innovations into more overarching concepts.

Sources

Several sources are used to create a condense longlist. An overview of all sources is given below.

The following reports were used as the starting point for the analysis:

- TKI Wind op Zee – Cost reduction options for Offshore wind in the Netherlands FID 2010-2020, [9]
- TKI Wind op Zee - The Netherlands' Long-Term Offshore Wind R&D Agenda, [10]

Eight BLIX experts were involved with the following expertise:

- Contractmanagement
- Energy markets
- Project finance
- General offshore wind project development
- Substructures
- Electrical infrastructure
- Wind farm layout optimization
- Offshore wind construction and interface management

Several experts from nine (external) companies provided input as well:

- Offshore Wind Developers (3x)
- Offshore Installation Contractor (1x)
- Wind Turbine Manufacturer (2x)
- Offshore Wind Development Consultant (2x)
- Offshore Wind Technical Consultant (1)

Results

The input from the experts was used to create a condensed list from the full longlist, which combined similar innovations into one. This resulted in a list with 103 innovations (69 technical, 28 market & supply and 6 finance), which is in its full included in Appendix B.

4.2 Phase II.B - Funnelling down into the most promising innovations based on expert opinions

Approach/Methodology

Based on the condensed list with 103 innovations, together with the scoring by the experts, the innovations are categorized. The following categorization was used:

1. High importance innovations were labelled green. These innovations are expected to have a high chance to materialize soon and/or have a large LCoE-impact.
2. Medium importance innovations were labelled orange.
3. Low importance innovations were labelled red

4. Some innovations, mentioned by the experts, will materialize after 2030 or are disruptive innovations, which makes them hard to price. These innovations were marked purple and were included into the results in the next chapter (which is about these types of innovations). Examples of these kinds of innovations are floating turbines, new types of rotors and standardization.
5. Several innovations were not LCoE-lowering, but will increase the value of the produced energy and therefore revenues, such as:

   a. Offshore energy storage (batteries, flywheel etc). Even though this will lead to a slightly smaller electrical infrastructure and thus lower the Capex, this is largely offset by the Capex of storage. The resulting better energy profile and therefore market price for the produced energy might make this into a positive business case, but this does not show in the LCoE (which only concerns with cost and not value)
   b. Conversion into hydrogen will also lead to higher cost per produced kWh (in this case in the form of hydrogen) since additional Capex and Opex is required for the electrolyser and energy is lost in the conversion. Again, hydrogen might have a higher value per kWh, but this does not show in the LCoE-calculation for offshore wind.

Since these innovations do improve the business case, but not directly affect the LCoE, they are also discussed in the next chapter and labelled purple as well.

Results

The result of the scoring of the innovations is summarized in the table below.

Category	Green (High)	Orange (Medium)	Red (Low)	Purple (Out of scope)	Total
Technology	14	12	31	14	71
Market/Supply chain	11	8	9	0	28
Finance	3	1	0	2	6
Total	28	19	40	16	103

Table 6: Number of high (green), medium (orange) and low-importance innovations (red) in the condensed innovation lists. Out-of-scope innovations are labelled purple.

An important remark several experts made was that some innovations are not necessarily reducing short-term costs (such as floating and some storage components) but they are necessary to keep system costs under control over time.

The paragraphs below provide a more detailed description of the 28 high importance innovations. This description is based on expert opinions and includes the rationale, the expected year of introduction, the LCoE-reduction potential and the amount of effort needed to reach this potential.

Technology

T1 - Turbines - Development of 'dynamic loading-friendly' structural designs, using fatigue-resistant materials and joints			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Small**
Design change from support structures that remain static during operation into a system that functions optimally when in certain dynamic (oscillating) equilibrium. The current design approach may become too costly in the future with bigger turbines. A more integral design of tower and support structure will be required to enable these designs, which can prove to be a barrier for introduction.			

T2 - Turbines - Improvements in blade design & manufacturing			
LCoE-reduction potential	**High**	**LCoE-reduction effort**	**Small**
Innovations in blade design & manufacturing & Automation, such as: • Modular blade designs that facilitate easier installation and lower production cost. Specific attention to joining methods • Automation and robotization of blade manufacturing, lowering CAPEX and increasing manufacturing precision and thus yield (through higher blade quality) while lowering O&M costs • Circular product designs, taking into account end-of-life solutions (to reduce external costs for society in the future)			

T3 - Turbines - High performance composite blade			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Small**
Development of high-performance composites for blades such as: • strong, lightweight, durable composites such as novel thermosetting matrix systems, erosion coatings and multi-scale composites • Composite blades using self-healing polymers			

T4 - Turbines - Integrated design for Wind farm and turbine with attention to wake conditions			
LCoE-reduction potential	**High**	**LCoE-reduction effort**	**High**

Wind farms are currently developed using a single turbine design for the entire wind farm. However, this design does not take into account the different operating conditions throughout the farm; turbine designs typically do not consider any wakes and interactions with other turbines. Especially when wind farms become larger, this approach can lead to sub-optimal yields. Creating an integrated design for turbine, by optimizing the turbine and wind farm in parallel, can lead to a more efficient wind capture and thus increase yields. A major barrier towards introduction is that this approach will require a paradigm shift in turbine design and wind farm development.

T5 - Turbines - Protection of leading edge of blades			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Medium**

The leading edge of blades is prone to erosion, which can reduce yield significantly over the lifetime of the wind farm. Several innovations can be used to protect the blades:

- Development of highly damage-resistant/self-healing and durable coatings
- Development of self-healable coatings or adhesives
- Development of drone based early interventions

T6 - Turbine design - Increased design life up to 40 years			
LCoE-reduction potential	**High**	**LCoE-reduction effort**	**Medium**

Design life in offshore wind has traditionally been related to the subsidy period since operation after expiration of subsidy was considered uneconomical. As a result of more mature technology and lower-subsidy tenders, design life has increased from 25 to 30 years. Further increase of design life can have a significant impact on LCoE due to the longer yield duration. However, a more robust design, especially for support structures suffering from fatigue, is needed, which increases Capex. The net present value of cash flows 30-40 years in the future needs to be big enough to offset these negative aspects to decrease LCoE

T7 - Support structures – Innovations in connecting turbines to substructures			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Low**

Novel approaches to connecting turbines and support structures with lower cost and/or easier installation, enabling alternative installation concepts, such as floating installation. Examples of this technology are slip-joints and wedge bolted connections.

T8 - Support structures - Deep water monopiles			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Medium**
Future wind farms will be further offshore with mostly higher wind speeds (lowering LCoE), but also in deeper waters and requiring longer export cables (increasing LCoE). Monopiles are generally the cheapest substructure but are limited in terms of size and maximum water depth. Development of cost-effective deep-water (40m+) monopiles for large turbines will therefore be an important cost-reducing innovation.			

T9 - Electrical Infrastructure – 133kV Cables			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Low**
Higher voltage array-cables can decrease costs by reducing transmission losses and allowing more energy to be transported per string, thus reducing the amount of strings needed. Even at higher costs per array-cable this can result in an LCoE reduction due to the decreased installation effort and thus total project cable length. Higher voltages will become an LCoE-reducing innovation if the density of a windfarm increases. In this situation, low-capacity array-cables need to be installed in parallel to offload all electricity from a certain location in the wind farm.			

T10 - Transport & Installation - Innovative cable installation concepts			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Medium**
Cable-installation costs can be reduced by using special-purpose vessels year-round, dedicated trenching equipment, and by optimizing cable pull-in and hang-off procedures. An important driver for this innovation is a fast ramp-up of offshore wind development, which give marine contractors confidence to invest into these special-purpose vessels.			

T11 - Transport & Installation – Innovative monopile installation concepts			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Medium**
Several alternatives to traditional piling have been developed or are currently under development, such as: • Vibratory-hammering • Blue piling which uses hydropower instead of a batting ram • Suction piling, in which piles are pulled downward under suction • Further research on impact on soil, fatigue of steel, noise impact etc. are needed towards market readiness.			

T12 - Operation & Maintenance - Condition-based monitoring			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Low**
Reduced repair time by condition-based monitoring (improvements in the integration and interpretation of all wind turbine operational data) of turbines, support structures and electric infra, for example: embedding mesh on sensors for continuous monitoring of early damage.			

T13 - Operation & Maintenance - Monitoring and repair using robots and drones			
LCoE-reduction potential	**Low - Medium**	**LCoE-reduction effort**	**Low**
Several innovations fall under this category: • (Small) repairs using remote controlled ROV's and drones, allowing for faster repairs and lower OPEX • Monitoring using autonomous robots			

T14 - Operation & Maintenance – Multi-functional (floating) service islands			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**High**
With increasing distance to shore, installation and OPEX costs increase significantly. Building a multi-functional (floating) service island can decrease these costs significantly. However, a large installed base and outlook to future developments is needed to make these kinds of large investments profitable. Moreover, alternative construction and OPEX concepts directly compete with this approach.			

Market & Supply chain

M1 - Competition - Increased (international) competition in the supply chain			
LCoE-reduction potential	**High**	**LCoE-reduction effort**	**Low**
Increased and/or continued high level of competition in the supply chain can lead to significantly lower prices. Current state of competition is already strong for some components in the offshore supply chain. Moreover, this will require a level playing field on working conditions and environmental record.			

M2 - Competition - Tender for E-infrastructure			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Medium**
Choosing TenneT as the offshore grid operator has been a key aspect of the Dutch offshore wind rollout success. However, other countries (most notable the UK) are having success with a tender for the offshore transmission grid (OFTO-model) as well. Results on comparisons between the two systems are mixed, since both have their merit (OFTO: increased competition, OGO: standardization and lower cost of capital).			

M3 - Contracts and law – Create tender system that favours lowest price/LCoE			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Low**
The current (zero subsidy) tender is a beauty-contest that awards several cost increasing aspects of the bid, such as the use of innovations, minimizing environmental impact and mitigating construction risk. Under the current market, the NPV of the bare project is high enough to justify these additional investments. This hinders achieving a lower LCoE in two (related) ways: 1. The winner of the tender is not necessarily the most efficient and cheapest developer. 2. There is no continuous downward LCoE-pressure on the sector, as there was in the years 2014-2015, which has resulted in significant subsidy-decreases and finally zero-subsidy.			
M4 - Contracts and law – Contract for difference			
LCoE-reduction potential	**High**	**LCoE-reduction effort**	**Medium**
Zero-subsidy tenders leave developers vulnerable to low market-prices, contrary to a subsidy, which will normally pay the difference between the market price and the subsidy applied for. A contract for difference is a similar contract to a subsidy that is not necessarily above the market price. If the market price is above the contract price, the operator will pay a fee to the government and vice-versa. This contract will decrease variations in cashflows and thus de-risk the investment, leading to a lower WACC and therefore LCoE.			

M5 - Contracts and law - Interconnection of wind farm with several bidding zones			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**High**
Interconnection to several bidding zones will increase the ability to sell energy at the highest price and therefore increase income. LCoE impact of this innovation is very limited however, since this will only slightly decrease WACC due to higher expected income (and thus lower risk).			

M6 - Contracts and law - Flexibility to lock in contracts post-tender award instead of pre-award			
LCoE-reduction potential	High	LCoE-reduction effort	Very low

The current (zero subsidy) tender is a beauty-contest that awards offers that mitigate construction risk by locking in contracts for construction pre-tender. Even though this approach does mitigate these risks, it is a relatively expensive way of doing so. Manufacturers providing a quote pre-tender will have a high uncertainty whether their client will win the tender and therefore will not put a lot of effort into preparing a competitive offer (and will add a risk mark-up). This is contrary to a post-tender award, in which a manufacturer will be almost certain that the best offer will lead to an eventual sale. This approach is not an option for all developers, since some consortia include manufacturers as member in the tender process.

M7 - Cooperation - Vertical supply-chain collaboration			
LCoE-reduction potential	Medium	LCoE-reduction effort	Medium

Vertical collaboration in the supply chain can increase synergies, for example:

- early involvement of the fabrication yard in the design
- early involvement T&I crew in design
- increasing supply chain efficiency through digitalization

M8 - Standardization - Standardising and industrialization of supply chain for a certain turbine size			
LCoE-reduction potential	High	LCoE-reduction effort	High

Standardising on for example 15 or 20 MW turbines, e.g., with modular approach. Standardization and industrialisation of supply chain, also in order to facilitate re-use.
The development effort for standardisation would require initiative and collaboration from various players in the offshore wind industry, while the cost reduction potential is promising given that there are many stakeholders in the supply chain that can benefit from these collaborations.

M9 - Wind farm layout - Decrease wind farm density to increase the power curve			
LCoE-reduction potential	Medium	LCoE-reduction effort	Low

Up to a certain level, a sparsely populated wind farm will have a lower LCoE than a dense wind farm due to lower wake effects. Over the last few years, the average power density of the Dutch offshore wind farms has increased from 5MW/km^2 (Borssele) to 8MW/km^2 (HKN) and will further increase to 10MW/km^2. This trend has a negative impact on LCoE but is advantageous from an optimal use of space.

M10 - Wind farm layout - Larger project sizes			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Low**
Larger project sizes can increase economy of scale and thus decrease LCoE. On the other hand, it decreases the amount of developers that are large enough to manage these large projects and their risks. Currently, there is no conclusive evidence that increasing project to above 1GW will lead to a significant decrease in LCoE.			

M11 - Wind farm layout - Improve layout modelling			
LCoE-reduction potential	**High**	**LCoE-reduction effort**	**Medium**
Improved layout modelling can lead to: • Decreased substructure costs by building in shallow water with good soil conditions • Improved yield due to lower wake losses • Decreased E-infra cost by decreasing the array-cable length. These innovations are in line with the innovation ‘Turbine – Integrated design’.			

Finance

F1 – Grid Financing – Lower cost of capital for TenneT			
LCoE-reduction potential	**Low**	**LCoE-reduction effort**	**Medium**
TenneT can optimize its gearing and/or TenneT shareholders require a lower return on their investment. This will lower the WACC and therefore increase LCoE.			

F2 – Grid Financing – Lower operation period for TenneT			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Medium**
Similar to innovation T6, a longer design life for the wind farm will increase the amount of energy that can be produced with a certain investment, which lowers LCoE.			

F3 - New finance providers - New equity providers, such as the government, cooperatives and individuals			
LCoE-reduction potential	**High**	**LCoE-reduction effort**	**Low**
Some new entrants require a lower cost of capital for their investments, such as: • Return on investment for individual savings are at a record low. Individuals and groups of individuals are therefore likely to search for alternatives that provide a relatively safe return. A cash inflow from new sources will increase supply of money and therefore lower the cost of capital and thus LCoE. • The Dutch government actively participates in (offshore) gas exploration and production through EBN, which has a 40% stake in all E&P-investments in the Netherlands. EBN cost of capital is approximately 6%, which is significantly lower than the industry standard of 10%.			

Overview

The table below provides an overview of the 28 high impact innovations in matrix form. The innovations highlighted **bold** will be further analysed quantitatively in the next paragraph.

LCoE reduction potential	LCoE reduction effort: High	LCoE reduction effort: Medium	LCoE reduction effort: Low
High	T4 - Integrated design for Wind farm and turbine with attention to wake conditions M8 - Standardising and industrialization of supply chain for a certain turbine size	**T2 - Improvements in blade design & manufacturing** **T6 - Increased design life up to 40 years** **M11 - Improve layout modelling** **M4 - Contract for difference**	**M1 - Increased (international) competition in the supply chain** **M6 - Flexibility to lock in contracts post-tender instead of pre-award** **F3 - New equity providers (e.g., government, cooperatives, individuals)**
Medium	T14 – Multi-functional (floating) service islands M5 - Interconnection of wind farm with several bidding zones	T5 - Protection of leading edge of blades T8 - Deep water monopiles M2 - Tender for E-infrastructure T10 - Innovative cable installation concepts T11 - Innovative monopile installation concepts M7 - Vertical supply-chain collaboration F2 –Lower operation period for TenneT	T1 - Development of 'vibration-friendly' structural designs, materials and joints T3 - High performance composite blades **T7 - Innovations in connecting turbines to substructures** T9 - 133kV Cables T12 - Condition-based monitoring T13 - Monitoring and repair using robots and drones M3 - Create tender system that favours lowest price/LCoE M9 - Decrease wind farm density M10 - Larger project sizes
Low		F1 – Lower cost of capital for TenneT	

Table 7 Matrix with the highest impact innovations for Phase 2 – Incremental innovations

4.3 Phase II.C - Determining the quantitative expected LCoE-impact of the high-impact quantifiable innovations

Approach/Methodology

The eight innovations with the highest and/or the most quantifiable LCoE-impact were selected. Conversely, using expert judgement, the impact of each of these eight innovations on different parameters (DevEx, Cost of capital, foundation supply costs, wind turbine supply costs, electrical supply costs, installation Capex, Opex and Annual energy production) were determined. Finally, these eight innovations with their altered parameters were analysed with the TNO LCoE-model (which was developed in Phase 1).

Results

The LCoE-reduction potential of the eight innovations with the highest and/or the most quantifiable LCoE-impact in relation to the reference case is shown in the table and figure below. The reference case is the 2030 case of Phase 1, which is a 1GW windfarm at IJmuiden Ver with a DC-connection.

#	Description	Affected parameters	Relative LCoE	Difference
–	Reference IJmuiden Ver	–	100%	–
T2	Improvements in blade design & manufacturing	~8% decrease in O&M costs, ~1.0% increase in yield	96.6%	–3.4%
T6	Increased design life up to 40 years	~10% increase WTG supply costs, ~10% increase foundation supply costs, ~5% increase in substation costs increase O&M by 10 years, increase in yield duration by 10 years	92.4%	–7.6%
T7	Innovations in connecting turbines to substructures	~20% decrease in WTG installation costs, ~5% decrease in O&M costs (equipment and labour)	99.0%	–1.0%
M1	Increased competition	Exact price level impact unknown. Sensitivity assuming 10% lower CAPEX and OPEX for developer.	92.42%	–7.7%
M4	Contract for difference	~1% decrease cost of equity	98.5%	–1.5%
M6	Flexibility to lock in contracts post-tender award instead of pre-award	~3% decrease in WTG supply, transport & installation costs, ~3% decrease in foundation supply, transport & installation costs	98.7%	–1.3%
M11	Improve wind farm layout modelling	~5% decrease in foundation supply costs, ~7% decrease in foundation installation costs, ~1.5% increase in yield	97.7%	–2.3%
F3	New (distributed) equity providers, such as cooperatives, individuals, governments	~1.5% decrease cost of equity	97.8%	–2.2%

Table 8: LCoE-reduction potential for the high-impact innovations in relation to the reference case

The cost reduction model is shown in D, showing the cost factors applied to determine the LCoE reduction.

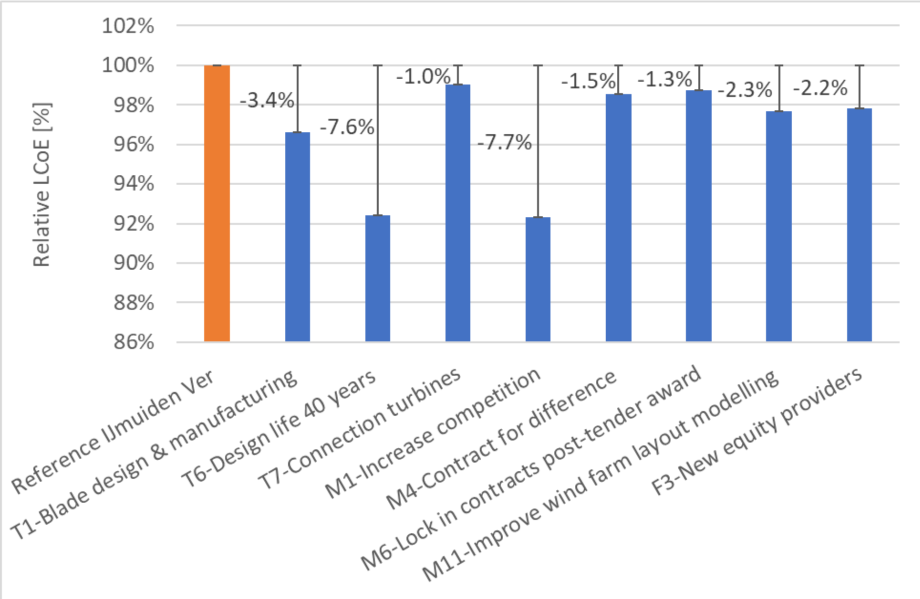

Figure 4 Relative LCoE of eight high-impact quantifiable innovations compared to reference IJmuiden Ver

The following conclusions can be drawn from the results:

- From the technical innovations, increasing the design life of the wind farm by ten years up to 40 years is the most promising innovation with largest cost reducing impact, lowering the LCoE with –7.6%. The reason for this large impact is the fact that with relatively low costs increases (=< 10%) the total generated yield increases by 40%. However, this upside is highly dependent on the assumed WACC with diminishing returns at increased WACC.
- Improvements in the blade design & manufacturing also cause a significant reduction on the LCoE of –3.4% compared to the reference IJmuiden Ver, as a result of lower maintenance costs and yield increase.
- Innovations in connecting the turbines to substructures, such as floating installation of slip-joints and wedge bolted connections, have a small reducing impact on the LCoE of the wind farm of –1.0%. The required effort to achieve this LCoE-reduction is also low, however.
- From the market and supply chain innovations, increased competition in the supply chain is the most promising. This innovation has the largest cost reducing impact, lowering the LCoE with –7.7%. The result is based on the assumption of a 10% lower CAPEX and OPEX for the developer. The exact price level impact is unknown, but nevertheless the LCoE impact is expected to be large (–3.0% or more).
- Improving the wind farm layout modelling, by considering the wind and soil conditions variations over the site, was also considered promising and therefore analysed with the LCoE model, causing a reduction in LCoE of –2.3%.
- A contract for difference and the option to lock in contracts with supplier's post-tender award instead of pre-tender both have a reducing impact on the LCoE, estimated at approximately –1.5%.
- New (distributed) equity providers, such as cooperatives, individuals, governments, which require a 1.5% lower cost of capital for their investment that current equity providers can cause a significant decrease in LCoE of –2.2%.

5 Phase III - Potential cost reductions of disruptive or emerging innovations with an expected implementation after 2030

Several European wide studies predict an increase in average electricity prices for the intermediate and further future. It is however uncertain whether the revenues of offshore wind farms will increase equally with this trend of time averaged in electricity price increases. Due to the energy transition the share of wind energy will increase in the electricity network leading to a surplus of electricity when the wind is blowing hard in a certain region. That will have a negative effect on the electricity prices resulting in a lower revenue for offshore wind farms. Other foreseeable effects on the LCoE of offshore wind farms are higher transmission cost due to the fact that most wind farms will be built further from shore, the near shore sites have almost been exhausted already.

In order to improve the business case of offshore wind farms of the future, the following steps will need consideration from wind farm developers:

- Reducing Capex, especially for the sites far from the coast
- Reducing the profile effect on the prices of renewable energy, especially of wind energy (increasing the capture prices)
- Reducing operating cost
- Increasing project lifetime
- Participating in ancillary services market
- Increasing the demand for renewable electricity

To make an inventory of potentially cost reducing technologies beyond 2030, three workshops were conducted with TNO, BLIX and external experts from various disciplines of offshore wind energy were present. The aim of the workshops was to facilitate brainstorming sessions where different ideas would be put forth, discussed and evaluated by those participating. Each workshop had a group size of ~10 experts, and the themes of the workshops were:

1. New wind turbine (WT) concepts (e.g., floating WTs, high altitude WTs, vertical axis WTs etc.)
2. System integration related concepts (e.g., innovations in the electrical system, layout, storage and grid integration)
3. Wind farm (WF) related concepts (e.g., wind farm operation and wind farm control)

5.1 Workshops to identify potentially disruptive innovations

5.1.1 Evaluation criteria (qualitative)

During the workshops, several ideas were generated which were then grouped together in various topics. Each topic was then evaluated on a number of criteria with scores between 1 and 5. Higher scores tend toward the idea being favourable/ beneficial. The values are averaged without applying weighting. The evaluation criteria used were:

- Development risk: [1-high risk; 5-low risk]
- Development effort: [1-high effort; 5-low effort]

- Potential cost reduction: [1-low cost reduction potential; 5-high cost reduction potential]
- Scalability: [1-low scalability; 5-high scalability]
- Environmental impact: [1-high environmental impact; 5-low environmental impact]
- Employment generation: [1-low employment generation; 5-high employment generation]
- Social acceptance: [1-low social acceptance; 5-high social acceptance]

5.1.2 New wind turbine concepts

The number of expert attendees in this workshop was six. The ideas generated in the workshop on new wind turbine concepts were grouped into the topics listed below.

Table 16 in Appendix E shows the full list of the ideas from this workshop.

- Optimised WT designs: downwind rotors, traditional wind horizontal axis replaced by a ring (e.g., MegaWindForce [12]) etc.
- Different rotor concepts: floating vertical axis WTs, typhoon resistant WTs with cylinders instead of blades etc.
- Smart monitoring and standardisation: floating vessels with WT assembly on board, shared components across WT brands etc.
- High altitude wind: kites and other non-fixed energy generation systems etc.

Hydrogen and P2X WTs: hydrogen production from electrolyser integrated within the wind turbine etc.

Table 9 shows the average scores from participants evaluating the above topics across the criteria listed in Section 5.1.

Topic		Dev.risk	Dev.effort	Cost red.	Scalaility	Env. impact	Employability	Social accept.	Overall
1	**Optimised WT designs**	4.0	3.6	3.2	4.2	2.8	3.0	4.0	3.5
2	Different rotor concepts	3.0	2.4	2.6	3.8	2.8	3.0	3.2	3.0
3	**Smart monitoring and standardisation**	4.0	3.6	3.0	4.4	3.2	3.2	4.5	3.7
4	High altitude wind	1.8	2.6	3.2	2.8	2.4	3.2	2.4	2.6
5	**Hydrogen and P2X WTs**	4.0	3.4	3.4	4.4	4.2	4.2	4.2	**4.0**

Table 9 Evaluation results of topics in workshop related to new wind turbine concepts

Topics related to hydrogen production within WTs were evaluated as the most promising in several criteria. High altitude wind was evaluated with high development risk, whereas optimised WT designs and smart monitoring related topics were rated high in terms of scalability and social acceptance.

5.1.3 System integration related concepts

The number of expert attendees in this workshop was nine. The ideas generated in the workshop on system integration related concepts were grouped into the topics listed below.

Table 17 in Appendix E shows the full list of the ideas from this workshop.

- Integration of renewables: floating solar and offshore wind integration, increase export cable capacity factor etc.
- EU grid integration: offshore grid development and integration to EU markets, export cable interconnector to multiple countries etc.
- Intra array cable developments: reuse intra array cables for second project, decrease costs and losses with high voltage infield cables etc.
- Integrated markets: real time renewable certificates for consumers, improving liquidity and transparency of intraday markets etc.
- Export system developments: use of new technology like HVDC VSC cables, increase design life of export cables etc.
- Extending the value chain: increasing CO2 prices, decouple specific offshore wind portfolio from grid to increase revenue from other markets etc.
- Innovative transport: umbilical infield transport for fresh water, hydrogen, electricity in the integrated energy system etc.
- Energy islands: hydrogen production on a central island, offshore island for power collection and O&M base etc.

Table 10 shows the average scores from participants evaluating the above topics across the criteria listed in Section 5.1.

Topic		Dev.risk	Dev.effort	Cost red.	Scalaility	Env. impact	Employability	Social accept.	Overall
6	**Integration of renewables**	3.3	2.8	3.1	4.3	3.8	3.6	4.1	**3.6**
7	EU grid integration	2.2	2.3	3.1	3.6	3.4	3.2	3.9	3.1
8	Intra array cable developments	3.6	3.4	3.0	4.0	3.4	2.9	3.6	3.4
9	**Integrated markets**	3.3	3.0	3.2	4.0	4.2	3.2	3.7	3.5
10	Export system developments	3.7	3.4	3.4	4.2	3.7	2.8	3.6	3.5

11	Extending value chain	3.6	2.3	3.1	4.2	4.1	3.3	4.2	3.5
12	Innovative transport	2.5	2.7	2.6	3.3	3.4	3.4	3.2	3.0
13	Energy islands	2.0	2.2	2.9	3.4	2.5	3.8	3.0	2.8

Table 10 Evaluation results of topics in workshop related to system integration related concepts

Topics related to integration of renewables were evaluated as the most promising overall. Other ideas in this topic included removing data exchange barriers between different energy systems and sustainable zero CO_2 hybrid systems with integrated WTs and electrolysers for hydrogen production, which was also covered as a popular topic in Section 5.1.2. The scores of topics in this workshop were much closer than in the previous one. Energy islands and EU grid integration topics were evaluated with comparatively high development risks and development efforts, while array cable, export system developments and integrated markets were rated high in terms of scalability and social acceptance.

5.1.4 Wind farm operation and control related concepts

The number of expert attendees in this workshop was six. The ideas generated in the workshop on new wind farm concepts, specifically on wind farm operation and controls, were grouped into the topics listed below.

in Appendix E shows the full list of the ideas from this workshop.

- Wind farm cluster wake control: position control of floating wind farms to reduce wake losses, cooperative control of wind farm clusters etc.
- WT loads control and lifetime extension: condition-based WT maintenance, integrated models for weather, degradation, production etc so that (uncertain) effects of decisions on net income can be calculated.
- Curtailment strategies: WF curtailment based on load monitoring, WF overplanting to spread preventive maintenance campaigns year-round etc.
- Optimizing for max. value under uncertainty: advanced optimization of hybrid RES for best value of energy in the presence of uncertainty in resource and energy market prices, self-learning farm control to optimise net income etc.
- Lidar assisted control: active wake control combined with accurate wake measurements with a LiDAR etc.
- Robust WT design: self-healing turbines, balancing cost with survivability, more wear resistant materials, robotised turbines with self-disassembly and replacement etc.
- Improved vessel and access system design: More effective or safe personnel transfer in harsh weather, semi-submersible crew vessel, fast installation and overhaul vessel capable of installing a complete WT etc.
- Automated and smart logistics: automated spare part delivery using drones, in-farm delivery and inspection robots, remote presence for inspection and manipulation of WTs
- Self-diagnosing turbines: turbines and farms automatically requesting maintenance etc.
- Shared logistics: automated auction for sharing scarce resources (vessels, technicians, spares) between wind farms, shared maintenance components between WFs etc.
- Influencing boundary layer: energise the boundary layer, vertical active wake control to steer wakes over other turbines etc.

Table 11 shows the average scores from participants evaluating the above topics across the criteria listed in Section 5.1.

Topic		Dev.risk	Dev.effort	Cost red.	Scalaility	Env. impact	Employability	Social accept.	Overall
14	WF cluster wake control	3.4	3.2	2.6	3.9	3.4	2.4	3.4	3.2
15	WT loads control and lifetime extension	4.1	3.4	2.6	4.2	3.6	2.6	3.7	3.4
16	Curtailment strategies	4.0	3.5	3.1	3.3	3.8	2.6	3.6	3.4
17	Optimise for max. value under uncertainty	3.4	3.0	2.8	3.4	3.4	3.1	3.4	3.4
18	LiDAR assisted control	3.3	3.2	2.3	3.3	3.2	2.8	3.7	3.1
19	**Robust WT design**	2.3	1.8	2.6	2.8	3.6	3.4	3.5	2.9
20	Improved vessel and access system design	3.3	3.0	2.3	2.7	3.8	3.0	3.3	3.1
21	Automated logistics	2.4	2.3	2.8	3.8	3.8	3.2	3.4	3.1
22	**Self-diagnosing turbines**	3.7	2.3	3.0	4.7	3.7	3.0	4.0	**3.5**
23	**Shared logistics**	3.5	3.3	3.0	3.3	4.0	3.3	3.7	**3.5**
24	Influencing boundary layer	3.0	2.9	2.2	3.3	3.4	2.8	3.3	3.0

Table 11 Evaluation results of topics in workshop related to wind farm operations and control related concepts

Topics related to self-diagnosing turbines and shared logistics were evaluated as the most promising overall. Other ideas in these topics include on-turbine diagnostics (fault architecture, known failure modes, edge computing) to reduce time from failure to diagnosis, sharing of warehouse stock between projects and having general O&M companies like those involved in O&M onshore. Curtailment strategy and wind turbine loads control and lifetime extension related topics were also relatively promising overall.

5.2 Qualitative analysis of innovations

The innovations resulting from the workshops above have been combined to end up with six innovations that are discussed in this section, see list below
These six most promising innovations are described and assessed in a qualitative way. These innovations are of a nature that they cannot be modelled in the developed LcoE model of Phase I due to the fact that the model is created for wind turbines of the present technology. The concepts evaluated are completely different or the innovation is much more complex, and the interactions cannot be modelled in this LcoE model.

The six innovations identified are (within brackets the innovations that it originated from tables in section 5.1):

1. Robust, self-diagnosing and healing wind turbines (based on # 19, 22 & 3)
2. Alternative wind turbine concepts (based on # 2 – 4)
3. Turbine load control/Lifetime extension (based on # 15, 3)
4. Smart wind energy (based on # 14, 15, 18, 22, 23, 3)
5. Optimised wind turbine including smart turbine design (based on # 1, 3)
6. Wind energy and P2X e.g., Hydrogen (base on # 5, 6 & 9)

These innovations will be discussed in more detail and evaluated in a qualitative way to looking at the assessment criteria also applied during the workshops. In the tables a qualitatively estimated reduction of LcoE is assumed to be low when the LcoE reduction is ≤3%, when the LcoE reduction is assumed to be between 3 –10% as medium and an LcoE reduction of more than 10% qualified as high.

Some of the innovations in the tables 9 – 11, even though they have high potential in cost reductions, are not integrated in the above list due to the fact that these are isolated innovations, or more related to developments of renewable energy markets. These innovations are not part of a connected, coherent cluster of innovations in offshore wind technology.
We expect that these clusters offer the best perspective to realize the cost reduction potential.

5.2.1 Robust, self-diagnosing and self-healing wind turbines

Robust, self-diagnosing and self-healing wind turbines			
LCoE-reduction potential	**Medium**	**LCoE-reduction effort**	**Medium**

This innovation is aimed at decreasing the O&M cost while maintaining or even improving the availability of the wind turbines. The innovation requires two significant developments, the self-diagnosing monitoring system and the healing material development. Both developments are still at a low TRL level where the monitoring system might be already at TRL 4–5 the self-diagnosing algorithm development is still at level 3–4. The self-healing material development is for general purpose application also still at a relatively low TRL level. Self-healing materials are applied in automotive and aero-space technology for specific parts where it is still not possible to apply those in load carrying components.

A robust turbine would have alternative back-up systems in case major components (like wind turbine transformers) fail, to ensure higher availability and lower maintenance requirements. Instead of replacing wind turbine blades damaged by erosion or impact, using self-healing composites that are triggered remotely can help save maintenance costs. Studies have also looked into automatic diagnosis of high-speed shaft bearings, using vibration-based diagnosis methods, among others [11] [12]. Wind turbines in the future will use edge computing, which refers to facilitating data processing near the source of data generation. This will allow wind farm operators to diagnose faults much quicker and consequently reduce time from failure to repair. The potential for LCoE reduction via O&M savings can be reduced because of investment costs of back-up systems, self-healing composites and fault diagnostic systems. The effort required for these systems is deemed medium, as there is already ongoing research from companies and institutes in this field.

5.2.2 Emerging wind turbine concepts

Emerging wind turbine concepts			
LCoE-reduction potential	**Medium to High**	**LCoE-reduction effort**	**High**

Several non-standard concepts, where the standard concept is defined as a horizontal axis -3 bladed upwind rotor wind turbine, are still developed by many parties. Main reason for these alternative developments is the promise they have, to reduce substantially the cost of wind energy.

A complete list of alternative concepts under development is not available, however, to mention a few, several floating concepts for (deep) water, where next to the standard wind turbine concepts also several vertical axis wind turbines with different rotor configurations are under development.
Multi-rotor systems, around for more than 30 year, are being investigated for onshore as well for (floating) offshore. The 2 bladed down-wind rotor wind turbine, a concept, around for more than 30 years, is still under development by a few parties. A more recent development, although also already 20 years under investigation, the high altitude or airborne wind (HAAW) needs to be mentioned [13]. Several HAAW concepts have proven technology although mostly at relatively small scale from a few kW to a few 100 kW's. The different types under developments are e.g., the flying kite concept of e.g., Ampyx, where the generator is on the ground level or flying planes (kites) with the generator is onboard of the flight vehicle, e.g., Makani. A third concept is a rotating loop with many kites, like the Laddermill which was a development in 2005 -2010 by Dutch prof. and astronaut Wubbo Ockels.

In a recent paper by S. Watson et.al. [14] many of the alternative concepts are reviewed and no clear winning technology has been selected. The main conclusion was that more fundamental research is required to overcome the presently limited knowledge. Specifically, for high altitude wind, the need for better or more high-performance materials and more knowledge of the complex wind inflows is identified as knowledge gaps requiring more public and private funding.

The promise that some of the concepts under development have, are still present. Upscaling from small prototypes to commercial size multi-MW size are challenges not easily solved.

During the development of these new concepts the standard concept wind turbine is also evolving and is showing substantial cost reductions making it not easy to introduce a new concept in a commercial environment where risk is usually being avoided.

The floating wind concept will certainly be applied and might even reach a higher market share than bottom mounted wind energy between 2030 and 2040. Main reason for that is the scarcity of shallow water sites and also due to the fact that the cost for the floating structure is decreasing in the newly developed floater concepts.

5.2.3 Turbine load control/ Lifetime extension

Turbine load control/Lifetime extension			
LCoE-reduction potential	Medium	LCoE-reduction effort	Low

A new way of controlling wind turbines in a wind farm could be with the objective to reduce (fatigue) loads and extend the lifetime of wind turbine. One can think of reducing the power of individual machines when the (fatigue) lifetime consumption is higher per unit of time or per unit of electricity (MWh) supplied. This would require integrated models for weather, degradation, production, etc. so that the (uncertain) effect of decisions on an objective like net income can be calculated. Another objective could be to control the energy production on the basis of the value of the energy. Load monitoring can be applied to reduce model uncertainties on the fatigue load, which can result in better estimates of the remaining fatigue capacity, asserting the availability of additional fatigue life. Current research looks at the value of load monitoring based on a Bayesian decision analysis [15] and the application of structural health monitoring data to underpin a long-term wind farm lifetime extension strategy [16]. Given the state of current research on this topic, adapting it in the real world is seen to require low effort, while the application of the technology is expected to show somewhat significant benefits in reducing LCoE.

5.2.4 Smart wind energy/ Industry 4.0

Smart wind energy / Industry 4.0			
LCoE-reduction potential	High	LCoE-reduction effort	High

Under this title the innovations dealing with digitalisation and Internet of Things (IoT), that reshapes the manufacturing and also the operational environment completely. In general, it relates to the transformation of the industry to industry 4.0 application of technology. Within this development several innovations can be mentioned, like completely or substantially increasing the automation process in manufacturing components, in logistics and/or even complete assemblies of wind turbines. Next to the manufacturing and installation also the operational processes will alter due to this development. Planned inspection and maintenance can be performed remotely with robots to a large extend reducing the offshore work, which is expensive, substantially.

A report from McKinsey [17] shows cost improvements of 25 to 55 % of the operating cost in the harbour, largely due to port automation and the application of Port 4.0. In terms of infrastructure developments, large capital investments are expected for automated systems providing connections between warehouses on quayside and O&M vessels, particularly on the software front, as data standardisation is seen as a potential challenge.

5.2.5 Optimised wind turbine including smart turbine design

Optimised wind turbine including smart turbine design			
LCoE-reduction potential	High	LCoE-reduction effort	Medium to High

This innovation is related towards optimising wind turbines rotor and / or drive train concepts. One can think of super conducting direct drive generators that are much smaller and lower weight than present direct drive generators. Other drive train concepts could involve hydraulic gearboxes with high efficiencies and nearly no maintenance requirements. New rotor blades could be developed with smart control options whether by applying flaps or synthetic jets to control the flow around the rotor blade in such a way that the fatigue loading is reduced, making blades substantially lighter. Initial studies have shown substantial reduction of fatigue loading of rotor blades and tower leading to cheaper rotor blades and towers however the initial cost estimate of the cost of the smart devices reduced the total benefit to a large extent. Challenges are to make these innovative systems as reliable or robust as the present technology systems are and at a substantial lower cost.

Optimising the wind turbine for floating concepts and optimising the floating support system could lead to substantial cost reductions for the floating wind energy concept. At the moment the floating system apply wind turbines that are originally design for bottom mounted application however innovations like e.g., a composite tower which could lead to large weight reductions of the top structure and weight reductions in the drive train, whether due to innovative gearbox designs or super conducting generators could lead to substantial lower weight of the top structure and subsequently lower cost for the floating structure.

5.2.6 Wind energy and P2X (hydrogen)

Wind energy and P2X e.g., Hydrogen			
LCoE-reduction potential	-	LCoE-reduction effort	-

Even though the Power to X is not a wind turbine innovation this innovation has been discussed in all workshops and several interviews. To enable the roll out of offshore wind accordingly to the EU road map, especially looking to 2030 and beyond, require that the energy produced can be supplied to a specific market. Due to inherently lower capacity factor of renewable energy production methods the installed capacity needs to be substantially larger than the average or peak electricity demand. This however leads to the situation that on many moments the electricity production is much higher than the electricity demand. Without creating a new market for this surplus of electricity that is generated when the wind speeds are high there is no other option than to switch off wind turbine / farms. Switching assets off has a very large influence on the LCoE, the Annual Energy Production (AEP) is the only parameter in the denominator of the LCoE equation and has consequently the largest influence on the LCoE.

Power 2 X, where X is e.g. (green) hydrogen, (green) ammonia, or synthetic fuels, will create a substantial demand for green electricity. This additional demand, especially if the demand can be flexible is an excellent way to improve the market value of wind generated electricity at a level equal to or higher than the LCoE of offshore wind. It will however be required to initially stimulate the market to enable this option due the fact that the green hydrogen, ammonia or synthetic fuels will be still too expensive compared to conventional production of these chemicals.

6 Conclusions

The results of phase I and phase II show that there are a substantial number of reasons to assume that the reduction of LCoE for offshore wind farms will continue. Upscaling present technology wind farms to a 15 MW 250 m rotor diameter wind turbine applied in a 1 GW wind farm will reduce the LCoE by approximately 12% and increasing the wind turbine size to a 20 MW 290 m rotor diameter applied in a 2 GW wind farm will lead to an additional 12% cost reduction.

Learning curve effects based on the increase in installation in Europe alone are also investigated. It is shown that learning curve or “learning by doing” will lead to substantial cost reductions even assuming a relatively low learning curve coefficient of 6% the LCoE will reduce by 2025 by 8% which will increase to 12% by 2030.

The upscaling and learning curve cost reductions effect can probably be accumulated to a large extend.

Incremental innovations, from phase II, have shown many options where reductions are in the order of a few percent. The maximum technical reduction analysed was the innovation identified as Operation design (T12), leading to a LCoE reduction of 7.6%. The market innovation M1, increasing the competition in the supply chain from wind turbines to support structure and grid connection components can even lead to a slightly higher LCoE reduction of 7.7%.
Some of the innovations could be applied in parallel leading to higher LCoE reduction, however due to interactions or correlations between the innovations it is presumably not straight forward multiplication of the benefits.

		LCoE reduction effort		
		High	Medium	Low
LCoE reduction potential	High	T4 - Integrated design for Wind farm and turbine with attention to wake conditions M8 - Standardising and industrialization of supply chain for a certain turbine size	**T2 - Improvements in blade design & manufacturing** **T6 - Increased design life up to 40 years** **M11 - Improve layout modelling** **M4 - Contract for difference**	**M1 - Increased (international) competition in the supply chain** **M6 - Flexibility to lock in contracts post-tender instead of pre-award** **F3 - New equity providers (e.g., government, cooperatives, individuals)**
	Medium	T14 – Multi-functional (floating) service islands M5 - Interconnection of wind farm with several bidding zones	T5 - Protection of leading edge of blades T8 - Deep water monopiles M2 - Tender for E-infrastructure T10 - Innovative cable installation concepts T11 - Innovative monopile installation concepts M7 - Vertical supply-chain collaboration F2 –Lower operation period for TenneT	T1 - Development of 'vibration-friendly' structural designs, materials and joints T3 - High performance composite blades **T7 - Innovations in connecting turbines to substructures** T9 - 133kV Cables T12 - Condition-based monitoring T13 - Monitoring and repair using robots and drones M3 - Create tender system that favours lowest price/LCoE M9 - Decrease wind farm density M10 - Larger project sizes
	Low		F1 – Lower cost of capital for TenneT	

Table 12 The results of the incremental innovations positioned in an impact – effort table

Several of the new emerging innovations from phase III have a promise of to be able to reduce the cost of energy substantial as can be seen in Table 13.

LCoE reduction potential	LCoE reduction effort: High (1-2.5)	LCoE reduction effort: Medium (2.5-3.2)	LCoE reduction effort: Low (3.2-5)
High (3-4)	7. EU grid integration 11. Extending value chain 21. Automated logistics 23. Shared logistics	1. Optimised WT designs 6. Integration of renewables 9. Integrated markets	8. Intra array cable developments 10: Export system developments 16: Curtailment strategies
Medium (2.5-3)	2. Different rotor concepts 4. High altitude wind 13. Energy islands	3. Smart monitoring and standardisation 5. Hydrogen and P2X WTs 12. Innovative transport 17. Optimise for max. value under uncertainty 19. Robust WT design 22. Self-diagnosing turbines	14. WF cluster wake control 15. WT loads control and lifetime extension
Low (2-2.5)		20. Improved vessel and access system design 24 Influencing boundary layer	18. LiDAR assisted control

Table 13 The results of the emerging innovations positioned in an impact – effort table.

Many of the innovations however also have already a long history which means that the effort of implementing the effort must be substantial.

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A Recent studies on innovations and potential effect on the LCoE

In the recent past, since 2012, several reports have been published showing that the required cost reductions to fulfil the roadmap are achievable before 2020. Even though actual cost reductions have been much higher and faster implemented than the first studies it is important to know which improvements were identified in the past.

2012 - *Offshore wind cost reductions Pathways Technology work stream* [18] from

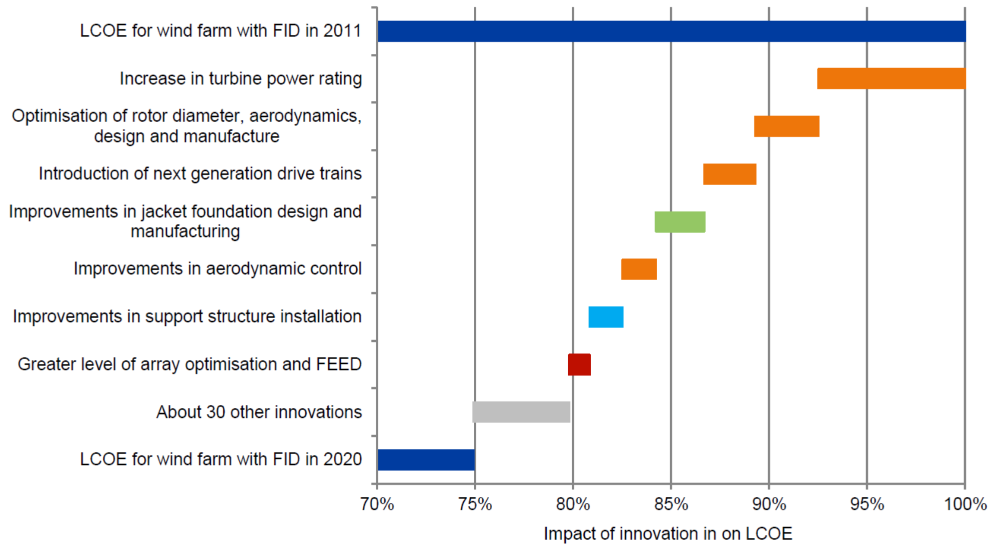


Figure 5 Anticipated impact of technology innovations for a wind farm using 6MW-Class turbines with FID in 2020, compared with a wind farm with 4MW-Class turbines with FID in 2011, from [18]

In [18] largest cost reductions are expected to come from increase in nominal power of the wind turbine and improvement of the rotor aerodynamic modelling. The estimated growth in turbine size is actually limited, growing from MW 4 (2011) to 6 (2020). The total cost reduction is estimated between 25 and 30%.

2012 – *Offshore Wind Cost reduction; Pathways Study,* [19]. This report concludes that a cost reduction of 40% is achievable in 2020 and it is expected that the technology innovations through changes in product or component design and manufacturing will continue to deliver cost reductions also after 2020. The largest cost reduction here is also due to new turbine designs. The other innovations are likewise as the other study although the total cost reduction is approximately 10% higher than reported in [18] which is all due to New Turbines.

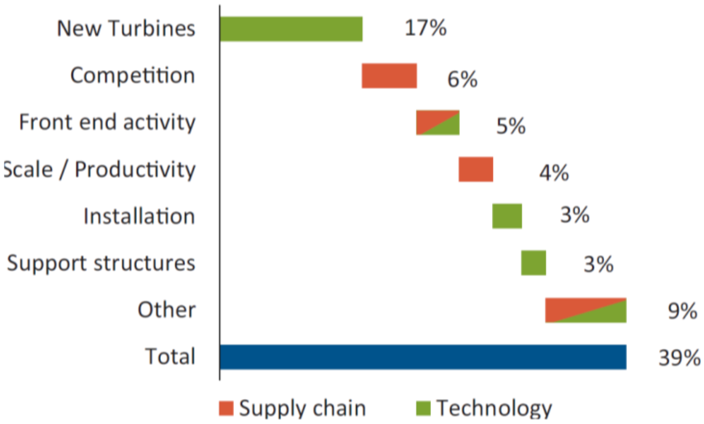


Figure 6 Offshore wind power cost reduction opportunities from technology and supply chain, [19]

2014 – *Future renewable energy cost: Offshore wind; How technology innovations is anticipated to reduce the cost of energy from European Offshore wind farms*, [20]. This report is updated in 2016, with a lot more details, [21]

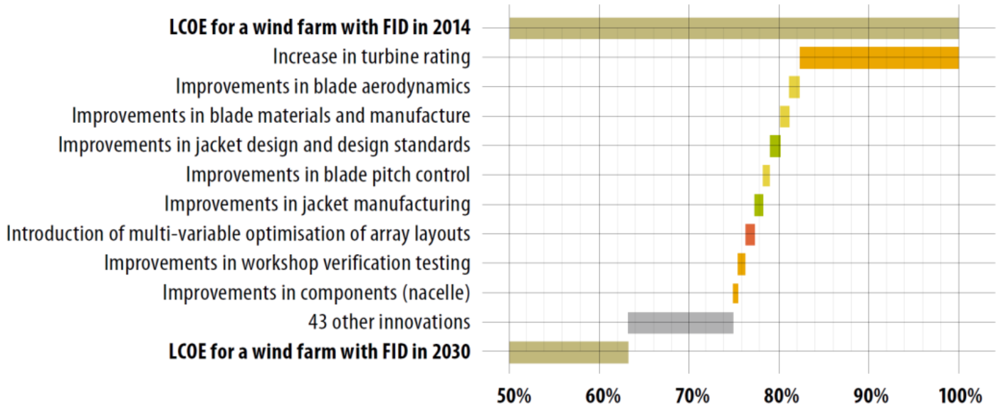


Figure 7 Anticipated impact of technology innovations for a wind farm using 10 MW-Size Turbines with FID in 2030 compared to a wind farm with 4 MW-Size Turbines with a FID in 2014, from [21]

The cost reduction in this report is estimated to occur between 2014 and 2030, so 10 years later than the previous reports. The largest cost reduction is again the nominal rating of the wind turbine with many innovations nearly 50, that lead to a total cost reduction, including the turbine rating, of nearly 40 to 50%

2015 – *Approaches to cost reduction in offshore wind*; a report for the committee on climate change [22]. This report concludes that next to technology innovation also tender/ auction innovation can lead to substantial cost reductions. For this a one sided or two-sided Contract for Difference (CfD) is an example. The lower cost of capital (Weighted Average Cost of Capital or WACC) is also identified as a substantial contribution to reducing the cost of energy.

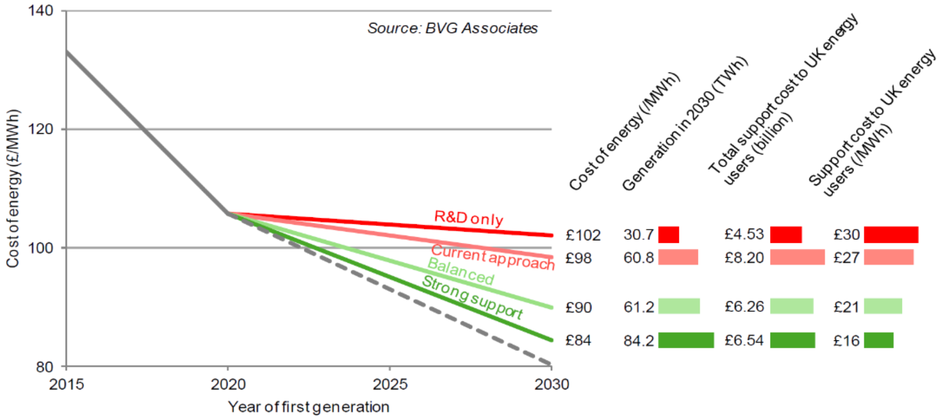


Figure 8 Summary of scenario analysis. Dashed grey line represents "Upper bound" scenario. All generation and support costs are for offshore wind projects built under the CfD regime between 2021 and the end of 2030. Values are in 2012 terms, from [22]

2015 TKI Wind op Zee, Cost reduction options for Offshore wind in the Netherlands FID 2010 - 2020, [9]. The cost reduction potential shown in this report are summarised in the categories Technology, Market and Supply Chain and Finance. The highest cost reduction is due to technical innovations where the increase in nominal power again shows the highest cost reduction potential.

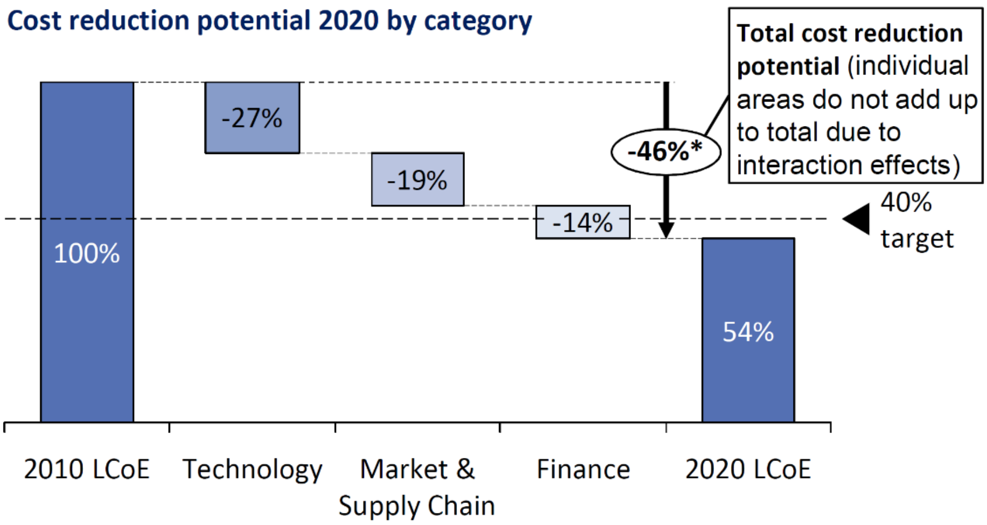


Figure 9 Cost reduction potential grouped in three categories, from [9]

The technology cost reductions reported are mainly due to improved rotor blade design and production and the application of XL monopiles.
2016 - *Offshore Wind Cost Reduction, Recent and future trends in the UK and Europe*, [23], showing the how the cost gap is closed between UK round 3 cost level, £ 110/MWh) and the cost level for the Borsselel I, II, which was estimated at £ 40/MWh.

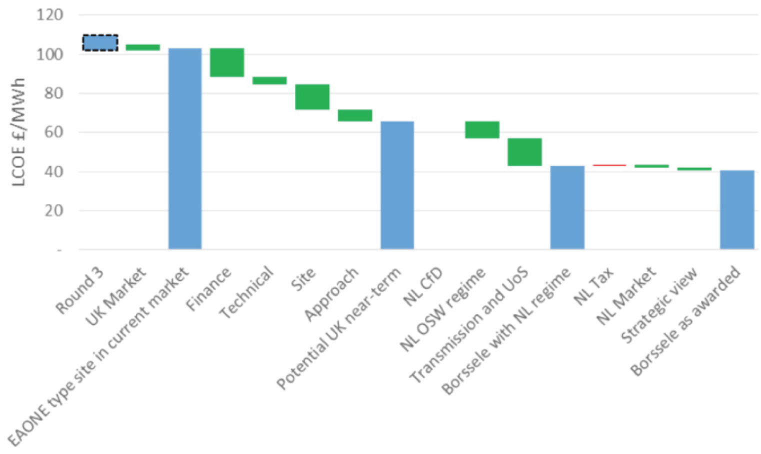


Figure 10 Round 3 (UK) to Borssele LCoE (UK Pounds/MWh) bridge, from [23]

2018 – *Ports and services for offshore wind in 2030; A vision of the future including their role in LCoE reduction*, [24]. This report lists a few direct and indirect savings originated from ports. The indirect savings from ports are mainly due to improved vessels that can be employed due to port innovations. The total savings related to port innovations on LCoE are estimated to be 5.3% between 2017 and 2030, see [24].

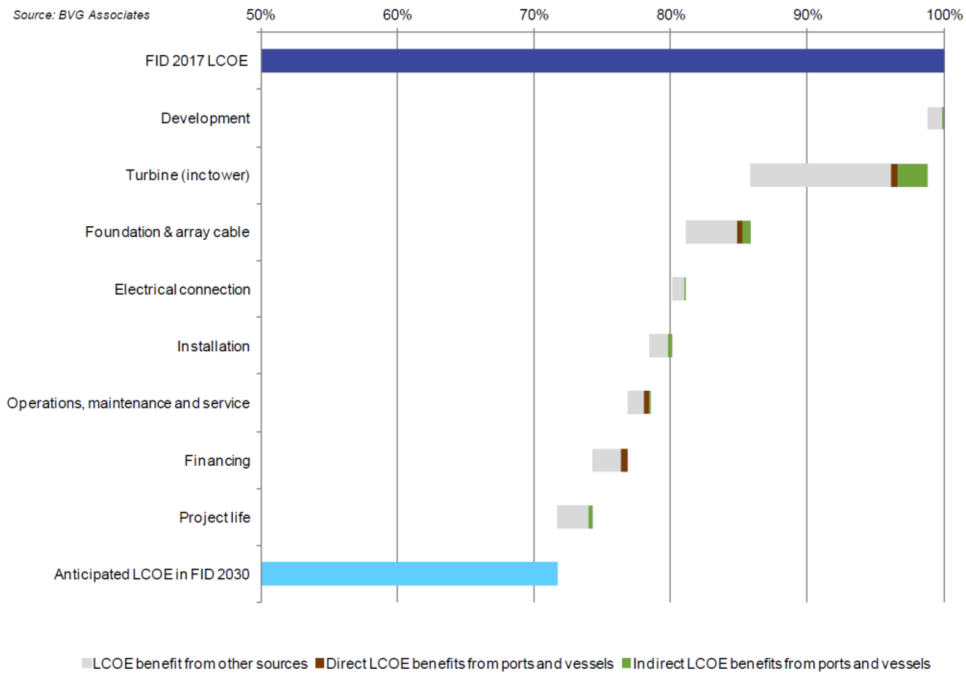


Figure 11 LCOE change between FID 2017 and FID 2030 at a typical reference site showing effect of port and vessel developments, from [24]

2019 – *Guide to an offshore wind farm; updated and extended*, BVG associates for The Crown Estate and ORE – Catapult, [25]. This document describes the Capex and Opex of all main cost components for an Offshore Wind Farm.

2020 *Evaluating the role of unit size in learning by doing of energy technologies*, [26]. In this article it is discussed whether it is preferable to applying smaller units instead of going for the largest unit available. Due to the larger number of smaller units required to reach the same targeted installed power the learning curve effects might be more advantages than the cost reduction that is anticipated to due to increasing the unit size.

2020 Opportunities for and challenges to further reductions in the specific power rating of wind turbines installed in the US, [27]. The main conclusion from this research is that lowering the specific power of the rotor (RPD) has a good potential to reduce the LCoE and increase the revenue of the wind farm project. Although the title indicates turbines installed in the US, the conclusions are not solely valid for the US. The analysis seems to be for onshore wind turbines but could be equally interesting for offshore wind energy. The cost increases due to upscaling the rotor is mainly an increased cost for the rotor and support structure. The cost ratio of the rotor cost as part of the total Capex of an offshore wind farm is lower than that for an onshore wind farm, for the support structure cost as ratio of the total Capex for offshore wind farm might be not much different.

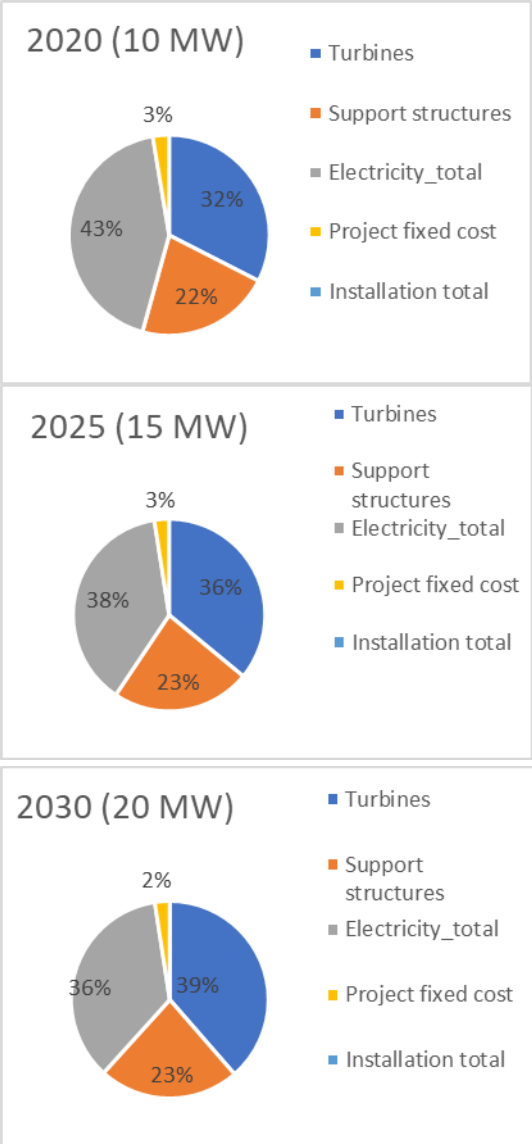
B Cost and performance of reference and upscaled wind turbines 2020, 2025 and 2030

		2020 (10 MW)	2025 (15 MW)	2030 (20 MW)
# of wind turbines		75	67	100
Pnom of wind farm		750	1005	2000
Distance to shore		70	70	70
Distance to grid		100	100	100
year		2020	2025	2030
Single turbine total	**[M€]**	**7.41**	**13.05**	**19.02**
Turbine electric	[M€]	0.62	0.84	1.04
Turbine gearbox	[M€]	1.47	2.86	4.42
Turbine generator	[M€]	0.21	0.27	0.32
Turbine hub	[M€]	0.10	0.20	0.29
Turbine main shaft	[M€]	0.52	1.05	1.57
Turbine miscellaneous	[M€]	0.51	0.71	0.91
Turbine nacelle	[M€]	1.06	2.05	3.05
Turbine rotor	[M€]	2.64	4.74	7.02
Turbine Transformers	[M€]	0.28	0.34	0.40
Support structure	**[M€]**	**4.97**	**8.50**	**11.38**
Turbine Tower	[M€]	1.73	3.93	5.51
Monopile transition	[M€]	0.75	1.10	1.41
Monopile	[M€]	2.49	3.48	4.45
Electricity total	**[M€]**	**735.97**	**926.83**	**1766.74**
Array infield cables	[M€]	62.30	73.80	108.30
Offshore sub station	[M€]	466.67	625.33	1244.44
Export cable	[M€]	207.00	227.70	414.00
Project fixed cost		**45.00**	**60.30**	**120.00**
		45.00	60.30	120.00

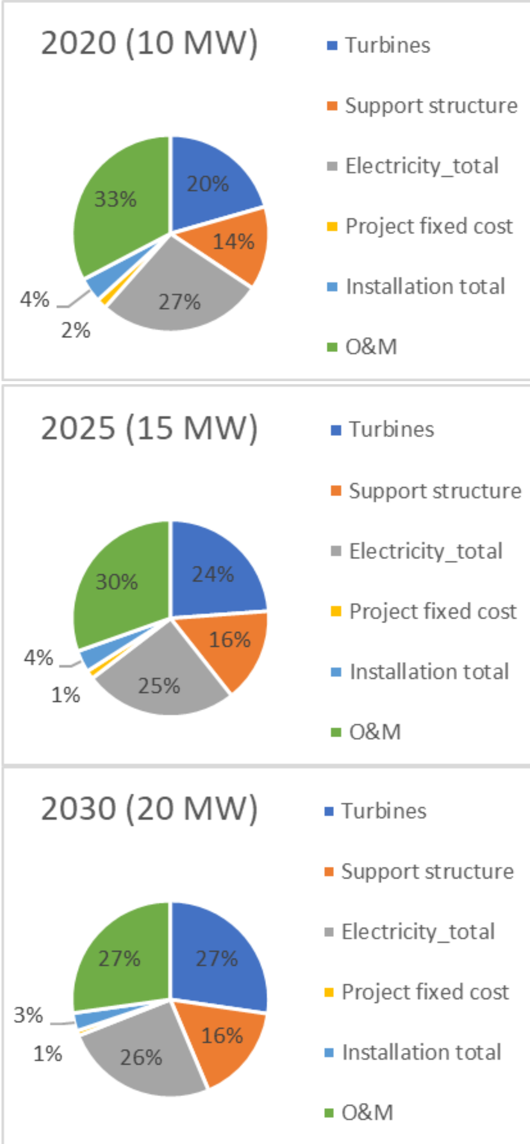
Installation total	**[M€]**	**110.31**	**131.39**	**205.75**
Installation vessel	[M€]	86.30	105.57	167.37
Installation equipment	[M€]	1.39	1.35	1.75
installation harbour	[M€]	2.18	2.15	3.28
Installation labour	[M€]	20.43	22.32	33.35
Total Capex	**[M€]**	**1819.8**	**2563.0**	**5132.4**

O&M	**[M€]**	**63.90**	**70.59**	**107.96**
O&M equipment	[M€]	23.16	22.41	26.00
O&M fixed	[M€]	18.75	25.13	50.00
O&M labour	[M€]	11.20	11.00	12.00
O&M material	[M€]	10.79	12.05	19.96
Yield				
Capacity factor	[-]	**0.539**	**0.543**	**0.541**
farm efficiency	[-]	0.913	0.875	0.860
Availability (yield)	[-]	0.974	0.974	0.976
Stand alone yield in wind regime	[MWh]	3.9834E+6	5.6080E+6	11.2829E+6

Cost distribution in share of Capex



Cost Distribution as share of LCoE



			Learning curve rate	
Year	6%	8%	10%	12%
2020	100%	100%	100%	100%
2021	98.1%	97.5%	96.9%	96.3%
2022	96.4%	95.3%	94.2%	93.1%
2023	94.9%	93.3%	91.8%	90.3%
2024	93.6%	91.6%	89.7%	87.9%
2025	92.4%	90.0%	87.8%	85.7%
2026	91.3%	88.6%	86.1%	83.7%
2027	90.2%	87.3%	84.5%	81.9%
2028	89.3%	86.1%	83.1%	80.2%
2029	88.4%	85.0%	81.8%	78.7%
2030	87.6%	84.0%	80.5%	77.3%
2031	86.8%	83.0%	79.4%	76.0%
2032	86.1%	82.1%	78.3%	74.8%
2033	85.4%	81.2%	77.3%	73.6%
2034	84.8%	80.4%	76.4%	72.6%
2035	84.2%	79.7%	75.5%	71.6%
2036	83.6%	78.9%	74.6%	70.6%
2037	83.1%	78.3%	73.8%	69.7%
2038	82.5%	77.6%	73.0%	68.8%
2039	82.0%	77.0%	72.3%	68.0%
2040	81.5%	76.4%	71.6%	67.2%

Table 14 Learning curve cost reduction based on cumulative European offshore wind energy capacity for learning curve rates between 6 and 12%.

C Condensed list of innovations from BLIX literature study and interviews

Technical innovations

Category	Subcategory	Description
Turbines	Turbine design	Alternative designs for turbine topology
Turbines	Turbine design	Optimal dynamic equilibrium for support structures
Turbines	Blade design	Improvements in blade design & manufacturing & Automation, such as: Modular blade designs that facilitate easier installation, lower production cost. Specific attention to joining methods
Turbines	Blade materials	Development of strong, lightweight, durable and/or recyclable composites for blades with a high damage tolerance
Turbines	Integration	Wind farm and turbine integrated design, wrt wake conditions
Turbines	Blade materials	Self-healing and healable materials (mostly in turbine blades)
Support structures	Design	Optimised foundation design by efficient critical failure state foundation design by improved modelling (with decreased safety margins) - risk based.
Support structures	Connection to turbine	New approaches to connecting turbines to substructures, e.g., slip joint, wedge bolted connections and double slip joint, which makes floating installation of WTGs possible
Transport & Installation	Cables	Reduced inter array cable installation costs (by using special-purpose vessels year-round, dedicated trenching equipment, optimise cable pull-in and hang-off procedures by limiting the required personnel transfers or dry testing)
Operation & Maintenance	Monitoring	Reduced repair time by condition-based monitoring (improvements in the integration and interpretation of all wind turbine operational data) of turbines, support structures and electric infra, for example: embedding mesh on sensors for continuous monitoring of early damage
Turbines	Operation design	Increased design life up to 40 years
Operation & Maintenance	Monitoring	Monitoring and repair of assets using autonomous/remote controlled robots, subsea or drone technology
Electrical infrastructure	IA Cables	133kV cables
Electrical infrastructure	GCS	Monitoring and control leading to increasing uptime and reduced losses l in the DC-transmission system
Electrical infrastructure	Export cable	HV export cable innovations: higher voltages etc.
Operation & Maintenance	Operation design	Multi functional (floating) service islands
Support structures	Corrosion & Fatigue	Improved knowledge on corrosion and fatigue to increase coating lifetime approval
Support structures	Corrosion & Fatigue	Development of long-lasting coatings (25+ years) or improved evaluation of current available coating systems.
Support structures	Monopile	Deep water monopiles

Support structures	Waves&Scour	Improved soil-structure interaction approaches, such as alternative concepts for Scour protection and improved design using in-depth modelling
Transport & Installation	Monopile	Vibro-hammering instead of pile driving, blue piling concept, suction piles (impact on soil, fatigue of steel, noise impact, etc.).
Transport & Installation	Substructures	decommissioning strategies
Turbines	Blade design	Protection of leading edge of blades
Turbines	Turbine design	Turbine size: increasing rated power
Support structures	Floating	Application of floating (instead of jackets)
Support structures	Floating	Reduced floating installation costs (by ….)
Support structures	Floating	Collapsible wind turbine structures (entire structure) for floating concepts
Turbines	Turbine design	Repower/ project extension/ component re-use options
Turbines	Blade desgin	Improvements in blade pitch controls and inflow wind measurements, adding active controls such as flaps on the blades, improved blade aerodynamics
Turbines	Blade materials	Circular design and recycling methods for fiber-reinforced polymers in composite blades
Turbines	Generator	Drive train concepts (superconducting generator, mid-speed generators)
Turbines	Materials	Availability of materials
Support structures	Floating	Development and Lessons Learned on floating
Support structures	Floating	Shallow water floating solutions
Support structures	Design	Optimised secondary steel design
Support structures	Design	Active and passive dampers for support structures
Transport & Installation	Monopile	Using Heavy Lift vessels on Dynamic Positioning to increase the weather windows and therefore reduce monopile installation costs
Transport & Installation	Jacket	Reduced jacket installation costs (by improvements in operational limits, use of special-purpose vessels)
Transport & Installation	Vessels	Dedicated installation vessels WTG
Transport & Installation	Vessels	Dedicated installation vessels FOU
Operation & Maintenance	Maintenance	Component exchange without jack-up's or large cranes
Transport & Installation	Turbine	Reduce bolting efforts in installation & O&M, for example by using quick connection technologies as alternative to bolts
Transport & Installation	?	Robotisation in installation and maintenance
Operation & Maintenance	Maintenance	Increase the number of working days (by turbine transfer improvements raising the operational limits up to around 2.5m significant wave height)

Operation & Maintenance	Operation design	Zero breakdown: design for very low maintenance.
Electrical infrastructure	Interfaces	Reduction of interfaces between TenneT & developer
Electrical infrastructure	Technology	Grid harmonics mitigation and resonance damping
Storage & Conversion	Storage	Innovative offshore energy storage (flywheel, supercap, pumped hydro)
Storage & Conversion	Hydrogen	Combining wind energy generation with electrolysis to gas or other molecules into an integrated design
Storage & Conversion	Hydrogen	Meshed hybrid (AC-DC-H2) offshore infrastructures
Electrical infrastructure	IA Cables	Dynamics of cables around foundation structure
Electrical infrastructure	Substations	Cheap Offshore Substations with little redundancy, like OTM & OSP
Operation & Maintenance	Maintenance	Walk-to-work concept in O&M
Operation & Maintenance	Monitoring	Equipment for inspection of corrosion
Operation & Maintenance	Monitoring	Automatic interpretation of autonomous inspection results, e.g., analysis of images
Operation & Maintenance	Monitoring	Fast inspection & Repairs (drone technology)
Support structures	Connection to turbine	Flange calculation methods
Support structures	Corrosion & Fatigue	Improved reliability of Impressed Cathodic Corrosion Protection
Support structures	Corrosion & Fatigue	Temporary power supply to ICCP system before hot commissioning.
Support structures	Corrosion & Fatigue	Manufacturing of steels with improved fatigue performance and corrosion resistance
Support structures	Corrosion & Fatigue	Corrosion/fatigue behaviour in freshwater conditions
Support structures	Design	Machine Learning (using monitoring data) for better understanding of structure behaviour and improvement of design
Support structures	Design	Design methodology for optimisation of structure design (equipped with monitoring systems)
Support structures	Design	Removal of boat landings/marine access
Support structures	Jacket	Robot/automated welding of complex structures e.g., jackets
Support structures	Jacket	Automated Non-Destructive Testing of welds including automated reporting (during fabrication process).
Support structures	Jacket	Improvement of welding techniques for increased fatigue performance: smoother weld geometry and reduced residual stresses
Support structures	Jacket	3D printing for improvement of welds

Support structures	Jacket	3D printing for manufacturing of jacket nodes
Support structures	Waves&Scour	Wave run up loads
Support structures	Waves&Scour	Ice loading on support structures

Market & Supply chain innovations

Category	Description
Competition	Increased (international) competition in the supply chain
Competition	Increase competition by developers, for example by removing entry barriers
Competition	Tender for E-infrastructure enables possibility for vertical integration
Competition	Support 3rd party O&M activities on the WTG's (create competition)
Contracts and law	Improved contract forms that lower risk
Contracts and law	Better legal framework and market model (improved E-act)
Contracts and law	Change tendering system from zero subsidy tender with a (costly) beauty contest into a system where the expenses for the environmental aspects are used to lower LCoE.
Contracts and law	Contract for difference instead of (zero)subsidy tenders decreases expected costs due to lower downside risk
Contracts and law	State taking over extreme risks of developers (extreme weather, innovative design, epidemics)
Contracts and law	Interconnection of wind farm with several bidding zones
Cooperation	Vertical collaboration in the supply chain can increase synergies, e.g., early involvement fabrication yard in design, early involvement T&I crew in design, increasing supply chain efficiency through digitalization
Cooperation	Horizontal cooperation in the supply chain (for example sharing of vessels, Combined O&M between BoP & WTG's, Combined O&M between projects)
Standardization	Standardising on for example 15 or 20 MW turbines, e.g., with modular approach. Standardization and industrialization of supply chain, also in order to facilitate re-use.
Standardization	Grid redundancy through modularity, e.g., standard 2GW HVDC substation
Integration	Cable pooling, integration of floating solar panels into offshore wind farms
Integration	Integration in the Hydrogen supply chain
Integration	Combined Hydrogen / Offshore wind tenders
Integration	Role of offshore infrastructure in cost reduction (offshore port facilities; conversion/storage; pipelines vs cables etc)
Operation	Sweating of assets
Operation	More experience and learning by doing
Operation	Reduced construction time
Wind farm layout	Decrease wind farm density to increase the power curve
Wind farm layout	Larger project sizes >1 GW
Wind farm layout	Better location determination considering spatial planning, wind conditions etc
Wind farm layout	Wind farm design and operation for large clusters
Wind farm layout	Improve layout modelling
Contracts and law	Thorough analysis and implementation of pre-competitive actions from which the entire sector might profit from (marine ecology, energy infrastructure, O&M infrastructure, harbour facilities)
Integration	Seaweed farming in the park, nurseries for oysters
Contracts and law	Flexibility to lock in contracts post-tender award instead of pre-award (currently required to mitigate construction risks)

Financial innovations

Category	Description
Lower perceived risk by incumbents	Declined cost of equity due to more experience, more mature technology, better legal framework and therefore lower perceived risk by developers, investors and other equity providers
Lower perceived risk by incumbents	Declined cost of debt due to more experience, more mature technology, better legal framework and therefore lower perceived risk by developers, investors and other equity providers
Grid financing	Lower WACC for grid TenneT due to lower interest rates, required rate of return by shareholders and changes in gearing
Grid financing	Longer operation period TenneT in line with longer operation period wind farm
New finance providers	Entrance of new (distributed) equity providers, such as the government (e.g., through EBN) cooperatives, individuals, governments
New finance providers	Entrance of new (distributed) debt providers, such as the government (e.g., through EBN) cooperatives, individuals, governments

D LCoE model to valuate incremental innovations

To evaluate innovations in a quantitative manner a model, in excel, has been created in which the predicted effects of innovations can be modelled. The model is based on the cost calculation made in Phase I, upscaling present technology.

The cost distribution in model is based on the cost, Capex and Opex distribution as reported in Appendix B.

CAPEX	
Single turbine Total	**[M€]**
turbine_electric	[M€]
turbine_gearbox	[M€]
turbine_generator	[M€]
turbine_hub	[M€]
turbine_main_shaft	[M€]
turbine_miscellaneous	[M€]
turbine_nacelle	[M€]
turbine_rotor	[M€]
Turbine Transformers	[M€]
Support structure	
Turbine Tower	[M€]
Monopile transition	[M€]
Monopile	[M€]
Electricity total	
Array infield cables	[M€]
Offshore sub station	[M€]
Export cable	[M€]
Project fixed cost	**[M€]**

Installation total	[M€]
Installation vessel	[M€]
Installation equipment	[M€]
installation harbour	[M€]
Installation labour	[M€]
Total Capex	**[M€]**
OPEX	**[M€]**
O&M	**[m€]**
O&M equipment	[M€]
O&M fixed	[M€]
O&M labour	[M€]
O&M material	[M€]
Yield	**[GWh]**
Nett capacity factor	[-]
farm efficiency	[-]
Availability (yield)	[-]
Standalone yield in wind regime	[GWh]

For each incremental innovation from Phase II, that is evaluated it will be needed to provide an indication of the effect on one or more parameters in the Capex/ Opex and or Yield components in the section of the LCoE model.

In Table 15 the LCoE model is shown where on the left the reference cases are shown. The column on the right starting with B1 Blade materials contains the factors of cost difference to the reference base case, in this case the 15 MW 2025 case.

		Upscaling present technology											
		2020 (10 MW)	2025 (15 MW)	2030 (20 MW)									
# of wind turbines		75	67	100									
Pnom of wind farm		750	1005	2000	Innovation	T1 blade	T7 Connection	T6 Operation	M1 Competition	M11 Integration	M4 Lower	M6 Flexibility to	F3 New finance
Distance to shore		70	70	70	Reference to base case	2025 (15 MW)	2025 (15 MW)	2025 (15 MW)	2025 (15 MW)	2025 (15 MW)	2025 (15 MW)	2025 (15 MW)	2025 (15 MW)
Distance to grid		100	100	100									
year		2020	2025	2030	Year of full cost reduction potent	2025	2025	2025	2025	2025	2025	2025	2025
WACC	[%]	3.80	3.88	3.88		1.000	1.000	1.000	1.000	1.000	0.948	1.000	0.923
Depreciation period	[years]	20	25	30		1.000	1.000	1.400	1.000	1.000	1.000	1.000	1.000
Single turbine Total	[M€]	**7.41**	**13.05**	**19.02**									
turbine_electric	[M€]	0.62	0.84	1.04		1.000	1.000	1.100	0.900	1.000	1.000	0.970	1.000
turbine_gearbox	[M€]	1.47	2.86	4.42		1.000	1.000	1.100	0.900	1.000	1.000	0.970	1.000
turbine_generator	[M€]	0.21	0.27	0.32		1.000	1.000	1.100	0.900	1.000	1.000	0.970	1.000
turbine_hub	[M€]	0.10	0.20	0.29		1.000	1.000	1.100	0.900	1.000	1.000	0.970	1.000
turbine_main_shaft	[M€]	0.52	1.05	1.57		1.000	1.000	1.100	0.900	1.000	1.000	0.970	1.000
turbine_miscellaneous	[M€]	0.51	0.71	0.91		1.000	1.000	1.100	0.900	1.000	1.000	0.970	1.000
turbine_nacelle	[M€]	1.06	2.05	3.05		1.000	1.000	1.100	0.900	1.000	1.000	0.970	1.000
turbine_rotor	[M€]	2.64	4.74	7.02		1.000	1.000	1.100	0.900	1.000	1.000	0.970	1.000
Turbine Transformers	[M€]	0.28	0.34	0.40		1.000	1.000	1.100	0.900	1.000	1.000	0.970	1.000
Support structure		**4.97**	**8.50**	**11.38**									
Turbine Tower	[M€]	1.729	3.933	5.511		1.000	1.000	1.100	0.900	1.000	1.000	0.970	1.000
Monopile transition	[M€]	0.752	1.096	1.415		1.000	1.000	1.100	0.900	0.900	1.000	0.970	1.000
Monopile	[M€]	2.486	3.475	4.452		1.000	1.000	1.100	0.900	0.900	1.000	0.970	1.000
Electricity_total		**735.97**	**926.83**	**1766.74**									
Array infield cables	[M€]	62.30	73.80	108.30		1.000	1.000	1.000	0.900	0.980	1.000	1.000	1.000
Offshore sub station	[M€]	466.67	625.33	1244.44		1.000	1.000	1.050	1.000	1.000	1.000	1.000	1.000
Export cable	[M€]	207.00	227.70	414.00		1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Project fixed cost		**45.00**	**60.30**	**120.00**									
		45.00	60.30	120.00		1.000	1.000	1.000	0.900	1.000	1.000	1.000	1.000
Installation total		**110.31**	**131.39**	**205.75**									
Installation vessel	[M€]	86.30	105.57	167.37		1.000	0.920	1.000	0.900	1.000	1.000	0.976	1.000
Installation equipment	[M€]	1.39	1.35	1.75		1.000	0.920	1.000	0.900	1.000	1.000	0.976	1.000
installation harbour	[M€]	2.18	2.15	3.28		1.000	1.000	1.000	0.900	1.000	1.000	1.000	1.000
Installation labour	[M€]	20.43	22.32	33.35		1.000	0.920	1.000	0.900	1.000	1.000	0.976	1.000
Total Capex		**1819.8**	**2563.0**	**5132.4**									
O&M		**63.90**	**70.59**	**107.96**									
O&M equipment	[M€]	23.16	22.41	26.00		0.920	0.950	1.000	0.900	1.000	1.000	1.000	1.000
O&M fixed	[M€]	18.75	25.13	50.00		0.920	1.000	1.000	0.900	1.000	1.000	1.000	1.000
O&M labour	[M€]	11.20	11.00	12.00		0.920	0.950	1.000	0.900	1.000	1.000	1.000	1.000
O&M material	[M€]	10.79	12.05	19.96		0.920	1.000	1.000	0.900	1.000	1.000	1.000	1.000
Yield													
Nett capacity factor	[-]	**0.539**	**0.543**	**0.541**									
farm efficiency	[-]	0.913	0.875	0.860		1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Availability (yield)	[-]	0.974	0.974	0.976		1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Stand alone yield in wind regime	[MWh]	3.9834E+6	5.6080E+6	11.2829E+6		1.010	1.000	1.000	1.000	1.015	1.000	1.000	1.000
						T1 blade material	T7 Connection Tu	T6 Operation des	M1 Competition	M11 Integration	M4 Lower downs	M6 Flexibility to	F3 New finance p
$\frac{\frac{Capex}{a}+Opex}{AEY}$ **LCoE 2020 [€/MWh]**		**55.20**	**48.68**	**42.28**	Relative LCoE [%]	47.03	48.19	44.99	44.94	47.54	47.96	48.06	47.61
Relative Reduction		100.0%	88.2%	76.6%	100%	**96.61%**	**99.00%**	**92.42%**	**92.32%**	**97.66%**	**98.53%**	**98.74%**	**97.80%**

Table 15 LCoE calculation in the innovation column cost components and assumed effect on cost and/or performance parameters.

E Full list of ideas from TNO organised workshops

Topic	Idea
Optimised WT designs	Down-wind rotor with two/three low weight flexible blades
	Ring type generators (needed when rpm becomes so low, while further upscaling of rotor diameter, that regular DD generators, even with gearbox) are not feasible anymore.
	Apply (combination of) leading edge protection, self-healing materials, mesh of sensors for early failure monitoring
Different rotor concepts	High Power density rotors
	Replace current direct drive generators + gear transmission with large ring generators in the future
	Typhoon resistant VAWT with cylinders instead of blades
	Smart rotor techniques, enabling increase in rotor dimensions without high rotor loads
Smart monitoring and standardisation	Size of rotor decreasing RPM, common DD generators are too fast
	Heavily robotised installation and maintenance
	Floating vessel with nacelle and turbine assembly onboard
	Sharing components across brands, like yaw/pitch drives etc.
High altitude wind	Now DD generators +gear transmission (Hybrid?), future large ring generators
Hydrogen and P2X WTs	Hydrogen production from electrolyser integrated within the wind turbine etc

Table 16 List of ideas from workshop on new wind turbine concepts

Topic	Idea
Integration of renewables	Floating solar and offshore wind integrated structures
	Develop complete supply chain from perspective of business model, energy system, design etc.
	Flexible/hybrid industrial processes
	Increasing capacity factor for the export cable (combine with solar PV)
	Sustainable hybrid systems (zero CO_2 hybrid systems)
	Remove data exchange/ communication barriers between systems
EU grid integration	Coordinated offshore grid development and operation to open up foreign markets
	EU wide hydrogen consumption (by industrial processes) plan
	Integrate infrastructure multi point configurations
	Interconnector function by two export cables from offshore wind farms to two countries
Intra array cable developments	Allow higher percentage of dynamic rating of electricity collection and transmission system
	Offshore overhead lines for medium distance transport
	Using asynchronous AC or low frequency AC infield cables
	Decrease costs and losses with high voltage infield cables (133kV)
	Increase intra array voltage (132kV) to combine more WTs per string, leading to less losses and lesser kms of cables
	Reuse electrical infield cables for second projects
Integrated markets	Real time renewables certificates and targets for consumers
	Variable consumer prices and tariffs that create incentives to increase consumption at times with high renewables
	Improve liquidity and transparency of intraday markets
Export system developments	Use the HVDV-VSC technology for the support system
	Increase design life of export cables
Extending value chain	Create a closed value chain from wind into higher hydrocarbons
	Decoupling specific OW portfolio from the grid to increase revenue in other H2 markets
	Where possible, try to create local energy demand to reduce transportation
Innovative transport	Umbilical infield transport for fresh water, hydrogen, electricity in the integrated energy system etc
Energy islands	hydrogen production on a central island, offshore island for power collection and O&M base etc.

Table 17 List of ideas from workshop on system integration turbine concepts

Topic	Idea
Wind farm cluster wake control	many OWF in the future, impacting each other's production, cooperative control of clusters could increase yield
	Position control of floating wind farms to reduce wake losses (e.g., through yaw misalignment)
	Improved yield predictability using remote sensing devises around wind farms, combined with novel wind cluster wake models
	Improved site assessment through novel wind farm cluster wake models
	wind farm cluster control - optimizing airflow across wind farm borders
WT loads control and lifetime extension	Wind turbine diagnoses by comparing measured and simulated time series of power production
	Condition-based WT control: lower O&M costs, longer lifetime
	Integrate models for weather, degradation, production, etc. so that the (uncertain) effect of decisions on net income can be calculated.
Curtailment strategies	Loads-based WF curtailment through loads monitoring: lower O&M costs, longer lifetime
	Overplanting WFs: spreading PM campaigns year-round rather than in only summer
Optimise for max. value under uncertainty	Advanced optimization of hybrid RES for best value of energy in the presence of uncertainty in resource and energy market price
	Self-learning farm control to optimise net income (balance degradation and repair costs with production/price and reduce variability)
	Pay as you go wind turbines: only run if cost < revenue
	Hydrogen (or P2X) hub, OWFs using a 'low' voltage business case: connection to central hub, where energy from several farms is combined
	Optimising O&M effort, balancing additional cost to the additional revenue
	Use turbine foundation for storage / data centres / other energy use
Lidar assisted control	LiDAR-assisted AWC: feedforward control expected to improve power gain due to very slow yaw dynamics)
	LIDAR assisted market operation: curtailment for max value.
	AWC combined with accurate wake measurements (LiDAR)
Robust WT design	Multiple pitching hinges per blade
	alternative back-up systems in case major components fail
	Self-healing turbines (balance cost with survivability). 3D printing of spares
	Robotised turbines with self-disassembly and replacement
Improved vessel and access system designs	More effective/safe personnel transfer in harsher weather conditions
	Semi-submersible crew vessel; minimally wave affected vessel that 'floats' under the wave level
Automated/Smart logistics (industry 4.0)	Automated spare part delivery (using ASV's / drones)
	Remote presence for inspection and manipulation of turbines

	Robotic maintenance
Self-diagnosing turbines	On-turbine diagnosis (fault architecture, known failure modes, edge computing) to reduce time from failure to diagnosis
Shared logistics	Automated auction for sharing scarce resources (vessels, technicians, spares) between wind farms Shared maintenance components between wind farms
Influencing boundary layer	Energise the boundary layer: use wind turbines or other objects to energise the atmospheric boundary layer/mixing Shear based curtailment/operation Vertical AWC (tilt angle adjustment to steer wakes over other wind turbines)
Standardising components	Standardising components. like e.g., aircraft engines can be shared between aeroplanes. E.g., pitch actuators yaw drives etc
Movable floating wind farm	operation as floating wind farm hub/city

Table 18 List of ideas from workshop on wind farm operation and control related concepts

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