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Danish Energy Agency: System Analysis, Energy Efficiency & Global Cooperation

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Note on technology costs for offshore wind farms and the background for updating CAPEX and OPEX in the technology catalogue datasheets

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The winning price in the tenders for the offshore wind farms in Denmark has decreased substantially from 2012 to 2016. The same trend has been seen in e.g. the Netherlands and Great Britain. The reduction in prices is substantially larger than what can be explained by the cost reduction predicted (in the Technology Catalogue). Therefore, the financial data for offshore wind has been updated (June 2017). Changes are made in the sections *"Prediction of costs in 2015"* and in the datasheet.

The update comprises investment costs (CAPEX) and operating & maintenance costs (OPEX), i.e. financial parameters. In terms of data for the more technical parameters such as mill size, full load hours, lifetime and the like existing data are still considered valid.

There are several reasons for the reduction in the winning bids. The costs of the wind turbine technology itself, as well as for installation, operation and maintenance has fallen sharply in recent years. In general, more experience has been gained in this area, making the collaboration between the different players on the market more efficient. Moreover, there are better opportunities for optimizing project plans and the volume of the offshore wind market. In addition, interest rates are low and technological and economic risks are assessed lower by investors, therefore low returns are accepted and competition has been increasing. Expectations for the electricity price after expiry of the grant period and other possible income from e.g. certificates of origin also affect the bid price.

Updated financial data in the Technology Catalogue

On the basis of an analysis of the bid prices, interviews with the sector, etc. it is proposed to change the financial data in the Technology Catalogue as shown in Table 1. Prices in this memorandum are fixed 2015 prices, unless otherwise stated.

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Financial data (2015 prices)							2020		2050	
FID		**2015**	**2017**	**2020**	**2030**	**2050**	**low**	**High**	**low**	**high**
Nominal investment (M€/MW) excl. grid connection	New	2.46	2.05	1.92	1.64	1.39	1.73	2.02	1.11	1.53
	Exist.	2.90		2.60	2.20	1.90				
Total operation and maintenance (k€/MW/year)	New	76.5	66.9	59.9	50.4	42.8	53	62	34	47
	Exist.	96.8		86.3	73.1	63.3				

Table 1: Proposed financial data in the Technology Catalogue.
Note 1: "Exist." is data from the existing catalogue.
Note 2: A farm size of 400-600MW has been assumed. The farm size in the existing catalogue is 400MW.
Note 3. OPEX is shown here as a total, in the existing catalogue OPEX is broken down into fixed costs and costs varying with production. It is assumed that fixed costs account for about 75% of total OPEX.
Note 3. The data in the proposal are shown to three significant figures because they are given as part of an analysis.
Note 4: 2017 is not included in the official Technology Catalogue, but it is shown here as a benchmark, as it is the starting point for the projections.

CAPEX FID (Final Investment Decision) 2015 is Vattenfall's information about Horns Rev 3 (HR3)[1]. OPEX FID 2015 has been derived from an assessment of DONG's information about average OPEX for DONG's existing offshore wind farms, interviews with the sector, and assessments of tenders. OPEX and CAPEX for FID 2017/2018 have primarily been derived on the basis of assessments of [2]the winning bids tendered in Denmark and the Netherlands in 2016, and to be commissioned in 2020. Among other things, FID 2020 is based on an assessment of the Borssele 3+4 (NL) bid.

Between 2015 and 2020, it was decided not to apply the Learning Rate (LR) method[3] because it was assessed that there is less uncertainty in using data derived from the bids. The values for 2030 have been found by applying the LR method on the basis of the figure for 2020 and an assumed LR of 10% on CAPEX and OPEX. Seen over the interval 2015-2030, the change corresponds to an LR of 13.8% for CAPEX and 14% for OPEX. This is higher than the 10% assumed for 2020-2030.

[1] https://corporate.vattenfall.dk/nyheder/pressemeddelelser/horns-rev-3-skal-levere-verdens-billigste-havmollestrom/
[2] The assessment is based on published "project costs" and assessments using internal interest calculations and calculation of a weighted average for the bids. The assessment is described in more detail later in this memorandum.
[3] Described later in this memorandum.

The assessment of accumulated installed capacity for offshore wind in 2050 is so uncertain that it has been decided to estimate the 2050 values for CAPEX and OPEX by assuming that they fall by the same percentage between 2030 and 2050 as between 2020 and 2030 (15%).

The following section describes in more detail how the proposed updated data for the Technology Catalogue was arrived at.

Prediction of costs in 2015 and 2020

In 2015 and 2016, five tenders have been settled for offshore wind farms in Denmark and in the Netherlands, where conditions are considered to be comparable. Data from these five projects has contributed to determine investment costs (CAPEX) and costs of operation and maintenance (OPEX) for the period 2015 to 2020. An overview of wind farms which have been put out to tender in 2015 and 2016 is shown in Table 2.

Project	Country	Farm size [MW]	Year (FID)	Winning
Horns Rev 3 (HR3)	DK	406,7	2015	Vattenfall
Kriegers Flak (KF)	DK	600	2018	Vattenfall
Borssele 1+2 (BS1+2)	NL	Approx. 700	2017	DONG
Borssele 3+4 (BS3+4)	NL	Approx. 700	2020	Shell
Near shore (Vesterhav North and South)	DK	350	2017/2018	Vattenfall

Table 2: Overwiew of the winning bids for offshore wind farm in 2015 og 2016 in Denmark and the Netherlands.

CAPEX

Vattenfall has announced that they expect to invest around 1 billion € in HR3 , which corresponds to approx. 2.46 million € per MW (2015 prices). Furthermore Vattenfall has announced that they expect to invest around 1.1 - 1.3 billion € in KF (2016 prices) corresponding to 1.97 €/MW (2015 prices). No project costs have been published for the remaining offshore farms in Table 2.

Looking at Vattenfall's announcements, CAPEX per. MW has decreased just 15-25% from HR3 (primo 2015) to KF (end 2016), while the bid price per kWh decreased about 50%. Hence, other parameters affecting the bid price for KF must have decreased more than the investment costs. Some explanations could be, for example, lower financial costs and increased competition, scale effect (KF is larger than HR3, advantages of many projects in a short period [IRENA, October 2016], and of projects located nearby, i.e. reduction of costs for ships and other facilities.

Near shore wind farms; Vesterhav north and Vesterhav south, are included in the analysis. However, it is assumed that the ocean depth is the same as for offshore wind turbines (15-25 m), and the two farms can be seen as one 350MW project, as Vattenfall has won both bids and that there will be a synergy with HR3. Hence, the costs of the Vesterhav (north) and Vesterhav (South) are assumed lower than for average near shore wind farm.

OPEX

No OPEX has been announced for the winning bids in 2015 and 2016 (HR3, KF, near shore and Borssele 1-4). Therefore, OPEX (FID 2015) has been determined based on the announced average OPEX for existing offshore wind mills owned by DONG (in 2016), indications from interviews with the industry and analysis of bid prices. The average OPEX for DONG Energy's existing parks is approx. 0.09 million € per. MW per year. Hereafter OPEX for 2015 (FID) has been assumed approx. 10% lower than the average for existing parks.

OPEX and CAPEX

In addition to the above considerations, an assessment of OPEX and CAPEX has been done by calculating internal interest rates and then evaluating the calculated internal return based on the expectation that a significantly lower rate of return is accepted at the end of 2016 than at the beginning of 2015. The calculation includes several other parameters that are subject to considerable uncertainty, for example projection of electricity prices and expected annual electricity production. The entire method is thus subject to great uncertainty, but is considered to be the best approach, taken into account the available information. Table 3 shows data for the mentioned projects

	Horns rev 3	Near shore	Borssele 1+2	Krigers flak	Borssele 3+4
Internal interest rate relative to the period 2015-2016	High	Middle	Middle	Low	low
Farm size (MW)	406.7	350	700	600	700
Expected wind turbine size (MW) [4]	8.3	8-10	6-10	8-10	8
Distance from coast (km)	30	4-7	31	15-25.5	15-37
Sea depth (m)	11-19	10-25	14-38	15-30	40
Feed in tariff (€/MWh)	103.4	62.8	71.7	49.1	53.7
Estimated grant period (year)	11.2	11.1	15.0	11.2	14.7
Commission Year	2020	2020	2020	2021	2023
Production in the commission year [5]	25%	25%	25%	10%	50%
FID year (assumed)	2015	2017	2017	2018	2020
Expected electricity price projection[6]	EUBF14 minus10 %		EUBF14	EUBF14 minus 10 %	EUBF14
Time for publication of winning bid	Feb. 2015	Sept. 2016	July 2016	Nov. 2016	Dec. 2016
Winner of the project	Vattenfall		DONG	Vattenfall	Shell
CAPEX (M€/MW) +/- 0,5	2.46	2.07	2.09	1.81-2.13	1.92
OPEX (M€/MW/år) +/- 0,02	0.077	0.064	0.071	0.062	0.059

Table 3: Data for Danish and Dutch projects for which tenders were submitted in 2015 and 2016 (2015 prices).
Note 1: Data with red print are own assessments.
Note 2: OPEX is stated as a total costs, which covers an assumption of 75% fixed costs and 25% that vary with production.
Note 3: In the assessment, it has been assumed that costs of nearshore wind farms are approx. 10% lower than for offshore wind farms. Moreover, it has been taken into account that the costs for near shore wind farm, as reflected in the bids, include payment for grid connection. CAPEX for near shore wind mills, however, is excl. grid connection.

[4] http://www.4coffshore.com/windfarms/vesterhav-nord-denmark-dk55.html
[5] Production in the first year in percentage of full production, - not all the turbines are in service January 1 in the first year of production.
[6] "EUBF14" is an electricity price projection used by the Danish Energy Agency, at the time of the tender. After 2024, the average spot market price for electricity is expected to be 28.7 øre/kWh. For "EUBF minus 10%" the electricity price is 10% lower. EUBF minus 10% is assumed for Danish offshore wind farms because the wind-weighted electricity price in Denmark is expected to be lower than average. "EUBF14" is used for Dutch parks because there is an expectation of a slightly higher electricity price in the Netherlands.

Method to project CAPEX (excluding grid connection) and OPEX

Changes in costs up to 2050 have been projected as in the current Technology Catalogue, in part with outset in recognized experts and sources, and partly by applying the LR method for CAPEX and OPEX up to 2030. CAPEX and OPEX for 2050 have been estimated by assuming that they will fall by the same percentage between 2030 and 2050 as between 2020 and 2030, as the projections of development of offshore wind up to 2050 are considered too uncertain to serve as the basis for estimating the changes in costs.

The LR method is a projection model[7] that assumes that the costs of a technology fall at a fixed percentage (LR) every time the installed capacity doubles. However, there is a tendency for LR to fall when technologies become mature[8]. The same article refers to a study that predicts an LR for offshore wind of 10% up to 2030 and 5% thereafter. The article also refers to a second study that expects an LR of between 8% and 19%. The LR method is a projection method often used when more detailed knowledge is not available. However, in reality there are many parameters that do not reconcile with this method, such as national and global competition, tender specifications, quantum leaps in technology and site-specific conditions. Therefore, in reality, actual developments will not follow this smooth curve. When the figures for the future are being estimated, it is important to ensure as large a data basis as possible in order to avoid the risk that the point of departure is a one-off extreme value. It would be too uncertain to make projections based on a single project such as Anholt or Kriegers Flak.

The projection from 2020 to 2030 uses the expected accumulated offshore wind capacity in Europe, as shown in Table 4, together with an assumed LR for both CAPEX and OPEX of 10% for the change from 2020 to 2030.

Accumulated capacity, GW		
2015	**2020**	**2030**
10.0	23.5	66.5

Table 4: Expected accumulated offshore wind capacity in Europe [EWEA 2016]. Note 1: Predictions for 2030 are associated with great uncertainty, and they were estimated before bid prices in 2016 were known. An updated projection taking account of the lower prices could show a larger rate of development. See also Annex 1.

The percentage drop from 2020 to 2030 will be approx. 15%, and the fall in costs from 2030 to 2050 is also assumed to be 15%. Seen over the entire period from 2015 to 2030, LR is 13.8% for CAPEX and 14% for OPEX.

[7] See more about the LR method and use in the Technology Catalogs in "Technology Data for Energy Plants Updated chapters, August 2016", Energinet.dk and Danish Energy Agency 2016.
[8] A review of learning rates for electricity supply technologies, E.S. Rubin et al. / Energy Policy 86 (2015) 198–218

All the estimates for CAPEX and OPEX mentioned in the memorandum are shown in Figures 1 and 2.

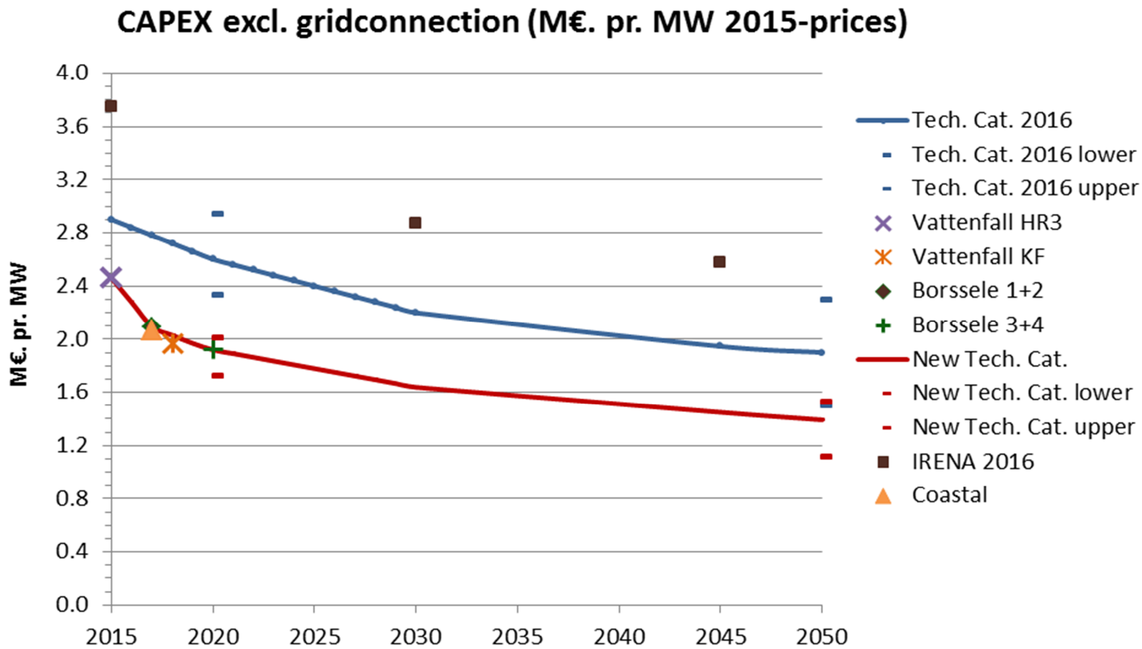


Figure 1: CAPEX excl. grid connection (FID year)

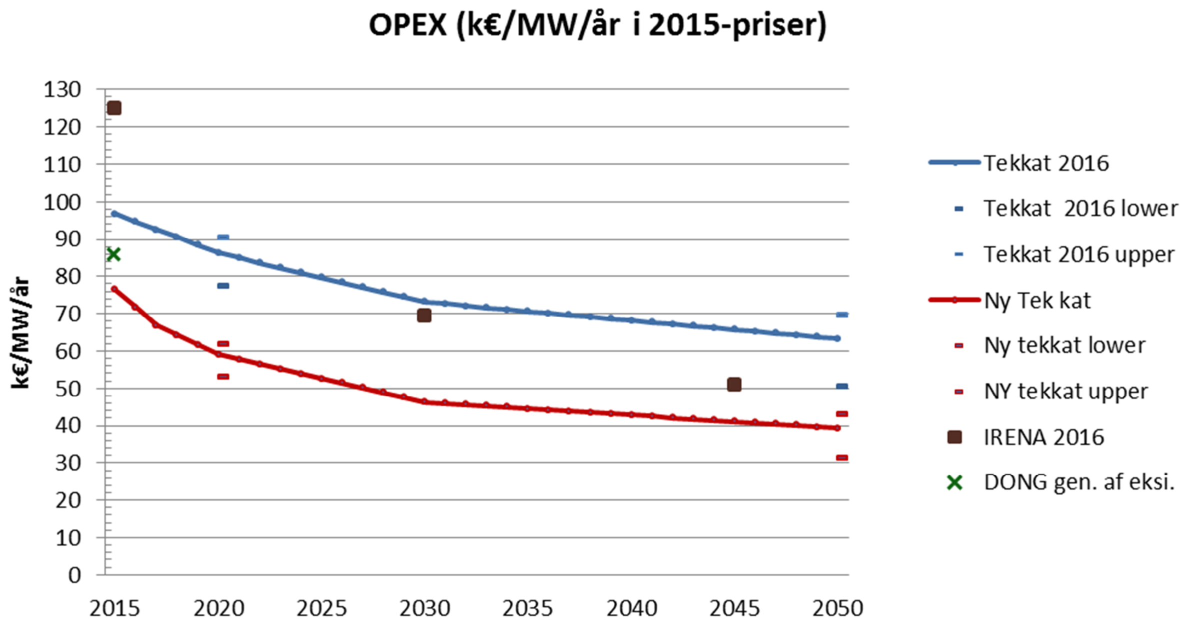


Figure 2: OPEX total annual with annual production equal to expected full load hours (FID year).
Note 1: DONG's existing wind farms are shown for 2015, but in reality they were earlier as they are existing wind farms. Therefore, the projection in the Technology Catalogue is lower in 2015.

The costs proposed as updated values in the Technology Catalogue 2017 are listed in Tables 5 and 6.

Investment costs excl. grid connection, M€/MW in 2015 prices	**FID 2015**	**FID 2020**	**FID 2030**	**FID 2050**
Current Technology Catalogue	2.9	2.6	2.2	1.9
New Technology Catalogue March 2017	2.46	1.92	1.64	1.4
IRENA (2016), Innovation Outlook: Offshore Wind for comparison	3.7		2.9	2.6 (2045)

Table 5: CAPEX excl. costs of grid connection.

Total* annual operating and maintenance costs, k€/MW/year in 2015 prices	**FID 2015**	**FID 2017**	**FID 2020**	**FID 2030**	**FID 2050**
Current Technology Catalogue	96.8		86.3	73.1	63.3
New Technology Catalogue March 2017	76.5	66.9	59.1	50.4	42.8
IRENA (2016), Innovation Outlook: Offshore Wind for comparison	125			69	51 (2045)

Table 6: OPEX.
*In the Technology Catalogue, total operating and maintenance costs are divided into a fixed cost of 75% of the total annual costs and a cost which varies with production and constitutes 25% of the total annual costs.

International expectations for CAPEX and OPEX are also listed in Tables 4 and 5. Data is from the IRENA "Innovation Outlook: Offshore Wind"[9]. The report was published in 2016 and the Horns Rev 3 and Borssele 1+2 bids have been included in the observations in the report.

The table shows that, internationally, CAPEX and OPEX are expected to be considerably higher than for the Danish bid. The international assessments of CAPEX are around 50% higher than CAPEX for the updated Technology Catalogue. Furthermore, IRENA's assessments of OPEX are 20-40% higher than the updated data in the Technology Catalogue. The comparison with the IRENA data confirms that no one predicted rapid drops[10], but most of all the comparison indicates that offshore wind power is most highly developed in (northwest) Europe[11] and this is considered relatively mature technology with relatively low investment risk, while in 2015 offshore wind was still generally considered as technology under development. According to the industry, in the UK LCOE fell faster than expected, so that the industry's 2020 target had already been met in 2016. The two most

[9] IRENA (2016), Innovation Outlook: Offshore Wind, International Renewable Energy Agency, Abu Dhabi
[10] IEA(2016) Forecasting wind energy costs & cost drivers, https://emp.lbl.gov/sites/all/files/lbnl-1005717.pdf
[11] In 2015, there was 12.6GW offshore in operation, of which 11.2GW was in Europe.

important reasons were improvements in turbine technology and lower capital costs [report from Catapult[12]]

Prediction of Grid connection costs for the period 2015 to 2050

The assessment of costs of grid connection is based on information from Energinet about the costs of connecting the latest four projects (HR2, Rødsand 2, Anholt and HR3) with emphasis on the latest projects. Based on this, it is estimated that grid connection costs are approx. 0.4 M€ / MW for offshore wind farms with transformer station located on offshore platform, farm size 400-600MW and located about 30 km from the coast. Moreover, it is assumed that the grid connection costs are approx. 0.3 M€ / MW for near shore wind farms that are connected to onshore transformer stations, farm size 50-200 MW, and located 4-10 km from the coast. Distribution of costs are shown in Table 7.

Grid connection costs (FID 2015, 2015 prices)		Offshore wind turbines	Near shore wind turbines
Total costs [13]	M€/MW	0.4	0.28
Offshore platform	M€/MW	0.16	0
Project management and environmental assessment	M€/MW	0.03	0.04
Transformer station onshore	M€//MW	0.07	0.10
Sea cable total costs	M€/MW	0.08	0.04
Land cable total costs	M€/MW	0.07	0.10
Sea cable costs per km	€/km/MW	2680	4030
Land cable costs per km	€/km/MW	1340	2010
Sea cable length	Km	30	10
Land cable length	Km	50	50

Table 7: Network connection costs for offshore wind farms of 400-600MW and near shore wind farms of 50-200MW

Prediction of costs of grid connection in the future has been calculated by assuming that the costs drop by 1% per year until 2020, by 0.75% per year between 2020 and 2030 and by 0.5% per year after 2030. The learning rate method is not used because some parts of the grid connection technology are considered mature while other parts are not, consequently different parts will be at different stages on the learning curve and consequently it is also difficult to assess the accumulation of "capacity put into operation".

[12] Cost Reduction Monitoring Framework 2016, Offshore Wind Programme Board, Catapult 2016
[13] Energinet.dk marts 2017

Levelized Cost of generating Electricity (LCOE)

The costs of generating electricity are often calculated as the Levelized Cost of generating Electricity (LCOE). This is a widespread comparison parameter for projecting energy-production technologies.

Figure 3 below shows projections from various sources. The LCOE is calculated in the sources using data from the current Technology Catalogue 2016, the new Technology Catalogue 2017 and IRENA's report, as well as MAKE's data for the LCOE, and Wind Europe's new industry measurements. A WACC (interest rate) of 4.5% is used in the calculation for the current Technology Catalogue, the updated draft Technology Catalogue and the IRENA data. The interest rate (WACC) has great significance for the LCOE, and therefore the LCOE is also shown calculated with the WACCs recommended by IRENA of 9% in 2015, 7.5% in 2030 and 6.8% in 2045. MAKE's projection is taken directly, and the interest rate applied is unknown, although it is likely to be 4-5%. All the LCOEs shown include costs of grid connection.

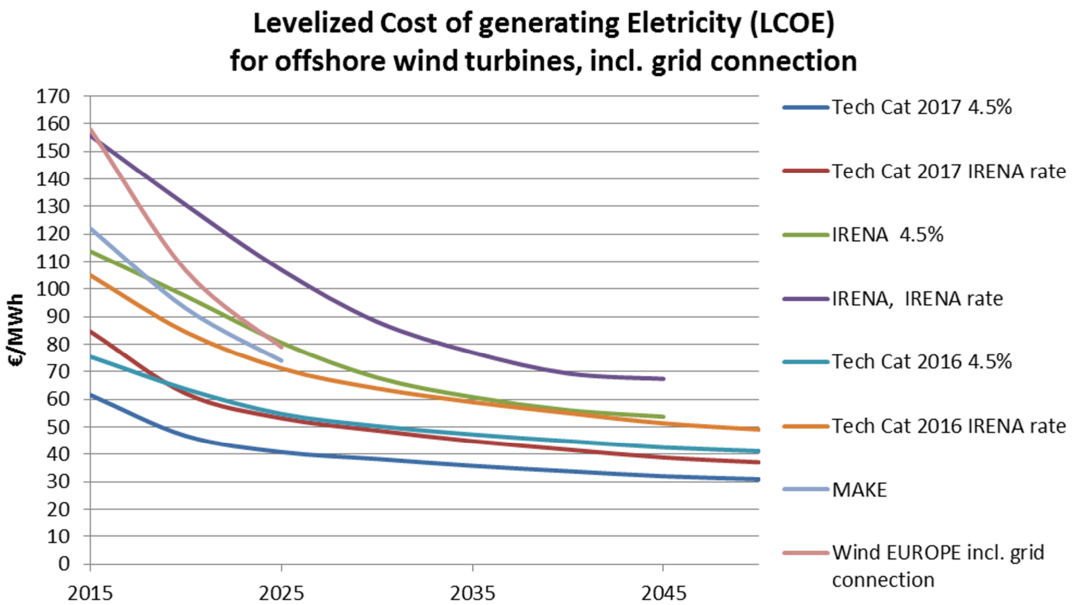


Figure 3: Own calculations of the LCOEs for the Technology Catalogue and IRENA data applying different interest rates (WACC).
Note 1: It has been assessed that MAKE and Wind Europe have applied an interest rate of 4-5% when calculating the LCOEs.

Comparison of the different LCOEs in Figure 3 shows that the LCOE for offshore wind in Denmark is lower than the general level internationally. Some of the parameters such as better sites and tender specifications will still give a lower LCOE in Denmark, while global competition will even out the differences between Denmark and the "rest of the world". In the future, it is likely that the LCOE will still to be lower in Denmark than internationally, but that the difference will be less, including in percentage terms. This means that a larger drop in LCOE is expected internationally than in Denmark, and therefore a higher LR is expected internationally than in Denmark.

Table 8 shows the LR for the LCOE calculated for Technology Catalogue data. LRs from other sources are shown for comparison. The Table shows that the LR in the updated Technology Catalogue is at par with the other estimates of the LR, although the basis for the LCOE (2015) calculated from Technology Catalogue data is considerably lower than the other LCOEs.

Source	**LR**
Technology Catalogue 2016 (2015-2030), WACC is 4.5%	13%
New Technology Catalogue 2017 (2015-2030), WACC is 4.5%	17%
Industry report (2015-2028)	20%
Danish Wind Industry Association (DWIA)/DONG Energy	18%
MAKE(2015-2025)	18-19%

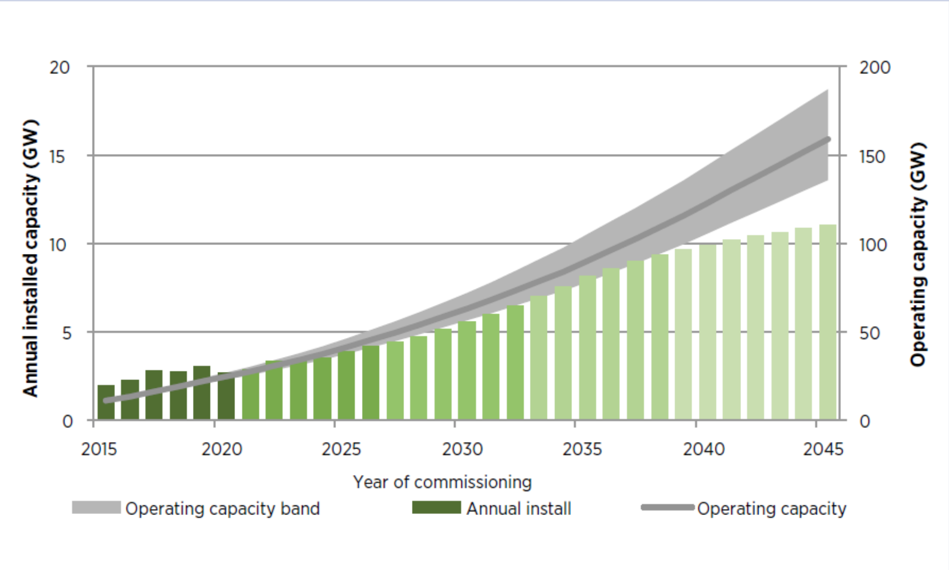
Table 8: Assessments of learning rates for LCOE for the updated Technology Catalogue and including the presentations by the Danish Wind Industry Association (DWIA) at a meeting with the Danish Energy Agency, October 2016

Annex 1.

	2014			2020 Target (Central scenario)			Low 2030 scenario			Central 2030 scenario			High 2030 scenario		
	Onshore	Offshore	Total	Onshore	Offshore	Total	Onshore	Offshore	Total	Onshore	Offshore	Total	Onshore	Offshore	Total
Austria	2,095	-	2,095	3,400	-	3,400	5,000	-	5,000	5,800	-	5,800	6,650	-	6,650
Belgium	1,247	713	1,959	3,000	1,500	4,500	2,650	2,200	4,850	3,300	3,000	6,300	4,000	3,800	7,800
Bulgaria	690	-	690	1,500	-	1,500	1,000	-	1,000	1,220	-	1,220	1,440	-	1,440
Croatia	347	-	347	600	-	600	1,600	-	1,600	1,800	-	1,800	2,000	-	2,000
Cyprus	147	-	147	300	-	300	447	-	447	483	-	483	581	-	581
Czech Republic	282	-	281	1,000	-	1,000	1,040	-	1,040	2,200	-	2,200	4,320	-	4,320
Denmark	3,603	1,271	4,845	3,700	2,800	6,500	3,300	2,650	5,950	4,600	3,530	8,130	6,000	5,320	11,320
Estonia	303	-	303	700	-	700	365	-	365	433	750	1,183	500	1,500	2,000
Finland	607	26	627	2,500	26	2,526	5,000	26	5,026	8,500	26	8,526	12,000	26	12,026
France	9,285	-	9,285	18,500	1,500	20,000	19,000	6,000	25,000	26,250	9,000	35,250	28,000	15,000	43,000
Germany	38,369	1,049	39,165	45,000	6,500	51,500	60,000	15,000	75,000	62,500	17,500	80,000	65,000	22,500	87,500
Greece	1,980	-	1,980	4,500	-	4,500	8,000	-	8,000	9,000	-	9,000	12,000	500	12,500
Hungary	329	-	329	600	-	600	925	-	925	973	-	973	1,051	-	1,051
Ireland	2,246	25	2,272	4,000	25	4,025	5,500	25	5,525	6,892	800	7,692	8,390	1,200	9,590
Italy	8,665	-	8,663	12,000	-	12,000	10,768	-	10,768	13,600	-	13,600	16,768	500	17,268
Latvia	62	-	62	200	-	200	234	-	234	308	-	308	430	-	430
Lithuania	279	-	279	600	-	600	878	-	878	1,110	-	1,110	1,200	1,000	2,200
Luxembourg	58	-	58	100	-	100	123	-	123	141	-	141	169	-	169
Malta	-	-	-	30	-	30	30	-	30	49	-	49	80	-	80
Netherlands	2,565	247	2,805	4,000	1,400	5,400	5,872	6,000	11,872	6,067	6,500	12,567	6,391	7,000	13,391
Poland	3,834	-	3,834	10,000	-	10,000	7,900	500	8,400	11,800	1,350	13,150	13,500	2,200	15,700
Portugal	4,913	2	4,915	5,700	25	5,725	5,924	27	5,951	6,373	27	6,400	7,012	27	7,039
Romania	2,954	-	2,954	3,200	-	3,200	4,500	-	4,500	5,000	-	5,000	6,000	-	6,000
Slovakia	3	-	3	300	-	300	300	-	300	331	-	331	486	-	486
Slovenia	3	-	3	30	-	30	33	-	33	49	-	49	75	-	75
Spain	22,982	5	22,987	26,000	5	26,005	35,000	5	35,005	44,500	5	44,505	52,000	500	52,500
Sweden	5,220	212	5,425	6,000	212	6,212	8,600	202	8,802	13,300	1,000	14,300	18,000	2,000	20,000
UK	7,953	4,494	12,440	11,500	9,500	21,000	12,300	12,000	24,300	17,000	23,000	40,000	20,000	35,000	55,000
Total	121,021	8,044	128,744	168,960	23,493	192,453	206,291	44,635	250,926	253,578	66,488	320,066	294,043	98,073	392,116

EWEA projection of installed capacity. The central scenario (2020 and 2030) is used in the Technology Catalogue.

Figure 40: Annual installed and operating capacity of offshore wind in Europe, 2016-2045



IRENA (2016), Innovation Outlook: Offshore Wind, International Renewable Energy Agency, Abu Dhabi*