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The future investment costs of offshore wind: An estimation based on auction results

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Abstract

Offshore wind is one of the renewable energy technologies with the largest potential. However, it still not competitive in costs with other similar technologies, and hence requires public support, which has been mostly done recently through auctions. These auctions have achieved seemingly very large cost reductions in the last years. However, some results may be misleading, because of the large differences between auctions in terms of their design and of the amount of costs explicitly or implicitly assumed by governments. In this paper we estimate the underlying CAPEX behind the most recent auctions' winning bids for a consistent set of assumptions, but accounting for their different designs. Our results show that the cost reductions achieved are indeed real, and larger than shown before. We obtain costs reductions of 50% between 2020 and 2026, and a rather steep learning curve. This general reduction trend is robust to changes in our assumptions. However, our results also show that CAPEX estimates are very sensitive to WACC rates, capacity factors, or market prices (when auction designs rely on a larger market price exposure). On the other hand, wind farm size and distance to shore show low correlation with CAPEX. Finally, we also show that, if the current trend in cost reduction continues beyond 2026, offshore wind might achieve cost competitiveness by 2030. This in turn may point out to a higher share of offshore wind in future energy scenarios.

Highlights:

- Estimating CAPEX from auction bids needs careful adjustment and sensitivity analysis
- Auction-derived CAPEX for offshore wind show a significant decrease in the coming years
- If the current trend persists, offshore wind might become competitive in 2030
- The share of offshore wind in future energy scenarios may be larger than expected.

Keywords: Offshore wind energy costs; learning curves; renewable energy auctions;

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Abbreviations:

CAPEX: Capital expenses
IEA: International Energy Agency
IRENA: International Renewable Energy Agency
LCOE: Levelized cost of electricity/energy
NERA: National Economic Research Associates (a private consultancy firm)
NREL: National Renewable Energy Laboratory
OPEX: Operational expenses
PPAs: Power purchase agreements
PV: Photovoltaics
SDE+: Dutch ministerial regulation promoting clean and sustainable energy
TSO: Transport system operator
UK: United Kingdom
US: United States of America

1 Introduction

One of the renewable energy technologies with the largest potential, according to many forecasts, is offshore wind. Although the existing installed capacity in 2020 was just 32 GW (which may be compared to more than 600 GW for onshore wind), that capacity is expected to increase significantly in the coming years. For example, the IEA World Energy Outlook [1] expects a fifteen-fold increase in its capacity worldwide for 2040, driven in part by the strong policy support in many regions (in particular Europe and China), and in its Sustainable Development scenario assumes that offshore wind may help avoid more than 7 Gt of CO2 emissions in 2040. In fact, in some countries it is already providing significant shares of electricity, larger than solar PV: 16% of the electricity in Denmark[1], or 8% in the UK [2], is already produced by this technology.

Offshore wind presents some advantages compared to other mainstream renewable technologies, such as onshore wind or solar photovoltaics (PV): the variability of its production is lower, hence contributing to a larger extent to security of supply [3]; and its production profile complements very well that of solar PV [3], [4]. However, it is still significantly more expensive than these alternatives, and requires public support to advance along its learning curve and become competitive [5]. This public support should be carefully designed in order to optimize the use of public funds: it should, on the one hand, provide an efficient signal for the innovation and reduction in costs required; and on the other hand, avoid creating excessive rents for developers.

In order to do this, it is essential that policy makers have the right information about the current and future costs of this technology, so that they can fine tune their support policies accordingly [6]. Unfortunately, this information is not always easy to obtain.

Several previous studies have attempted to produce realistic estimations of the cost of offshore wind. For example, [6] calculate LCOE from public documents of actual projects and interviews, whereas [7] introduce a spatial component in these calculations, and [8] add stochastic elements through Monte Carlo simulation. [9] look at CAPEX developments, correcting for factors such as distance to shore and depth, but still based on engineering approaches. The same engineering approach is used by [23], who look at future cost trends for European wind farms, or [25], who focus on economies of scale. Other studies, such as [26]-[29] use representative utility-scale projects to estimate LCOE. However, these estimates are not necessarily realistic, in that they do not account for actual industry or market developments. Auctions, which have become the instrument of choice in many regions to support offshore wind [10]–[17], may help in obtaining this information. In theory, and under the assumption of perfect information, auctions would be revealing the most accurate estimation of industry for future developments [18], hence incorporating additional information compared to previous approaches. This has made some institutions (such as IRENA [19] or NERA [13]) use the winning bids from auctions to build this learning curves, and to derive costs for future scenarios. Unfortunately, the direct translation of bids into costs is not straightforward, as pointed out e.g. by [20].

First, auctions do not take place in perfectly competitive markets: information asymmetry [21], potential market power [22] (be it from on the developers or on the manufacturers side), moral hazard (e.g. when penalties are low [14]), winners' curses, and other market problems may result in bids that do not correctly account for the underlying industry costs [12]. This of course is very difficult to assess.

Second, even if we assume that the problems mentioned above are negligible, winning bids in different auctions are not comparable, due to the differences in the design of auctions, which result in different levels of risk or costs assumed by the participants in the auction. For example, NERA [13] only makes estimations for the UK, which cannot be extrapolated to other regions.

Finally, most of the studies reviewed estimate LCOE, not CAPEX. Although LCOE is a popular choice to compare among technologies, it has many limitations when

used for renewable energy (see e.g [24]). In addition, CAPEX is more useful for assessing technological evolution, and therefore the need for public support. As such, CAPEX is the unit of choice for drawing learning curves. [25] is the only study we have found that follows this approach, although it does not account for the most recent auctions and the corresponding technological development.
In this paper we propose more robust estimates of the future costs, measured as CAPEX of offshore wind. We start from the results of successful auctions, but we introduce several adjustments to correct for the issues pointed at above. We also enlarge the pool of auctions included in the analysis, and we test the sensitivity or results for the major assumptions. Compared to the previous literature, our contributions are:

- The transparent calculation of CAPEX values from winning auction bids, on a site-specific basis;
- The application of this methodology to many different regions, and to the most recent auctions;
- And the evaluation of the sensitivity of CAPEX to several parameters in order to provide more robust results.

This allows us to overcome to some extent the limitations of previous studies, and build a more robust learning curve for offshore wind, which we consider may be very helpful for policy makers in order to design the right support policies.
In section 2, and as a first step towards building the learning curve, we review the past evolution of offshore wind costs, and the potential for cost reductions. Then, in section 3 we describe the methodology followed to adjust the results of auctions. Section 4 presents the results obtained, and Section 5 concludes.

2 Past evolution and potential for cost-reduction

As shown in Figure 1, the offshore wind sector worldwide has experienced a decrease in its costs that ranges between 20% and 5% since 2010, according to the estimations from NREL [26]–[31] and IRENA [19]. IEA’s estimations for 2016 and 2017 [32] are also included in the figure.

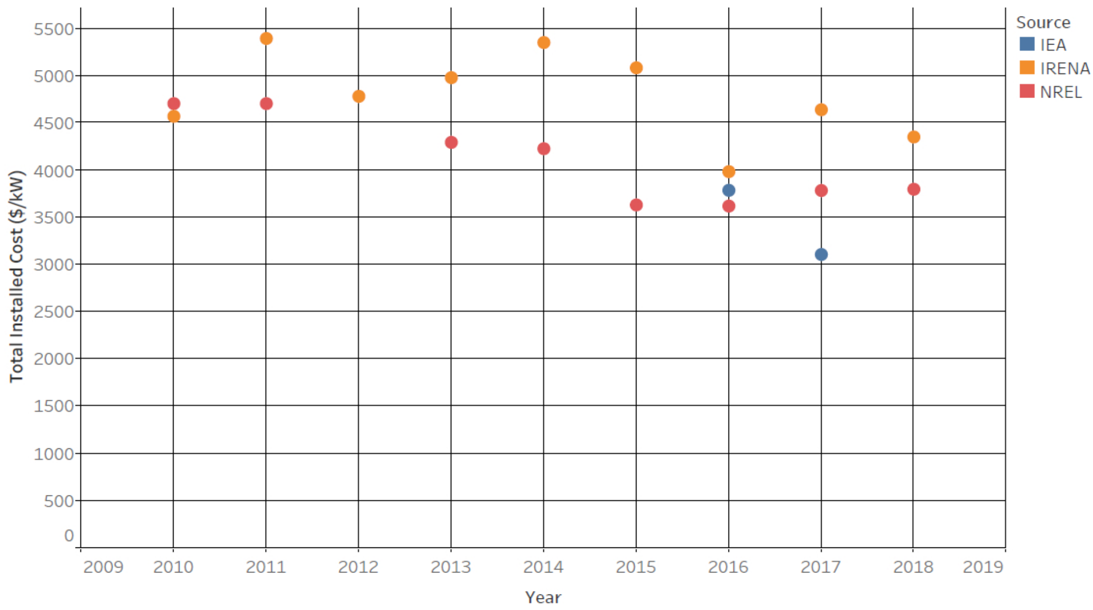

Figure 1: Capital Expenditure (CAPEX) Estimations for Offshore Wind projects between 2010-2018. NREL[26]–[31], IRENA[19] and IEA[32]

Significant year-on-year fluctuations are explained, among other factors, by the relatively low number of offshore wind farms committed every year. Other aspects that can justify this CAPEX variability may be the increase in competition or the volatility of prices of components and raw materials -e.g. steel- [33].

The three sources used: NREL, IRENA and the IEA, take different approaches for their estimations, which explains the differences among the CAPEX values represented.

NREL's estimates [31] are based on the combination of market and simulated data. Market conditions are analyzed in detail for projects in the US, as well as Europe and Asia; whereas modeled data is obtained from the study of a reference offshore wind project, where empirical data is used to obtain prices through scaling and simulation.

In IEA's report [32] " technology and cost assumptions have been compiled based on participants' knowledge of projects being developed and via publicly available data." At the same time "the CAPEX and OPEX estimates are based on country-specific site characteristics, such as water depth, distance from installation port, distance from operation and maintenance (O&M) port, wave climate and foundation type."

In a similar way as the IEA, IRENA's estimations [19] are based on market prices and/or price indicators. However, it does not make a detailed distinction among countries, taking a more holistic approach in comparison to the IEA.

The different methodologies used explain, for instance, the greater year-on-year variability of IRENA's estimated CAPEX with respect to NREL's. This can be explained by the fact that IRENA's estimations are solely based on market data, whereas NREL's models also take into account technology-based parameters.

Taking a closer look at NREL's estimates, Table 1 presents the breakdown of costs corresponding to total CAPEX estimations for NREL [26]–[31] between 2010 and 2018. Only fixed-bottom offshore projects are being considered, since these are those that are currently being developed or expected to be developed in the near-term future.

Table 1: NREL offshore wind cost breakdown estimations (Source: [26]–[31])[2]

	2010 ($/kW)	2011 ($/kW)	2013 ($/kW)	2014 ($/kW)	2015 ($/kW)	2016 ($/kW)	2017 ($/kW)	2018 ($/kW)
Turbine Capital Cost	**1789**	**1789**	**1600**	**1952**	**1466**	**1505**	**1557**	**1301**
Development cost	58	58	149	129	66	66	150	138
E&M	117	117	90	97	73	71	76	70
Substructure & Foundation	1021	1021	730	535	679	639	613	676
Port, staging, logistics, transport	73	73	128	23	24	21	56	58
Electrical Infrastructure	540	540	546	763	396	411	1106	1130
Assembly & Installation	1109	1109	1053	687	893	872	228	338
Lease price				43	36	36		88
Balance of system	**2918**	**2918**	**2696**	**2277**	**2167**	**2116**	**2229**	**2498**
TOTAL	**4707**	**4707**	**4296**	**4229**	**3633**	**3621**	**3786**	**3799**

Remarkably, turbine capital cost, electrical infrastructure and substructure and foundation have an important share in total CAPEX. According to NREL [31], in 2018, turbine costs represented 34% of total CAPEX, electrical infrastructure - including installation- 30%, and substructure and foundation 17% of total costs.

Costs reductions since 2010 have been especially pronounced in engineering and management -40% decrease-, substructure and foundation -34% reduction since 2010- and turbine capital costs -27% reduction-. This decrease in costs can be explained by many factors, related to the higher maturity level reached by the sector [33]–[42].

2 From 2017 onwards, NREL's cost structure criterion changes, including installation of electrical array in the category ''Electrical Infrastructure'', instead of ''Assembly and Installation''.

Regarding the design of the turbines, the two principal components that are expected to be upgraded are the nacelle and rotor. An overall 18% decrease in costs by virtue of increased power rating is expected [33]. Besides, the two principal components of the turbine, nacelle and rotor, are also expected to be upgraded. Improvements in the nacelle include innovative designs for drivetrain and power take-off. New possibilities are being contemplated, such as introducing DC power take-off systems or implementing superconducting or continuously variable transmission drive trains. These technologies have a great potential for improving the efficiency of the turbine and increasing capacity without incrementing the rotor swept area. According to BVG [34], a 6% cost reduction in total expenditures through innovations in the nacelle can be achieved.

Other components of the nacelle that are expected to undergo transformations are generators and gearboxes. For the offshore sector, the substitution of gearboxes for direct drive systems is contemplated as an interesting possibility for cutting down costs, as these components are especially vulnerable to the corrosion and wear inherent to the ocean environment.

As for the rotor, a reduction up to 7% in total costs [33] can be achieved by improved design of blades -in terms of shape and material upgrading- and pitch control systems, which would contribute to a better aerodynamic response of the turbine, while minimizing the weight of the system[3].

Further innovations that are predicted to contribute to a reduction in capital expenditures correspond to the balance of system, which includes all components that do not contribute to the power generation itself but allow the transmission of electricity and installation of the turbines.

For the offshore wind sector, transmission lines and foundations are vital components. In this regard, scaling and the use of installation-specific vessels are key to shorter installation times and improving the cost-effectiveness of the plant [20] [21]. The cost reduction potential through improving the efficiency of existing construction and installation processes would range between 2% [33] and 6% [34]. In addition, a 4% reduction in total costs is expected through improvements to support structure [33].

[3] Some of the cost reductions in the turbine -by virtue of improvements in rotor, pitch control, etc.- might also be common to the onshore sector. However, the main sources used in this document exclusively refer to the offshore wind sector [33]–[35].

Other relevant innovations concerning transmission include the installation of High Voltage Direct Current (HVDC) cables, which would reduce power loss in long transmission lines, therefore making possible the installation of wind farms in the deeper ocean, where the potential for electricity generation is larger. Improved offshore substations, as well as utility-sharing agreements with adjoining farms, are contemplated as interesting measures to drive costs down.

From the financial point of view, capital expenditures can also be cut down thanks to a better knowledge and broader experience in the sector, as well as the utilization of better modeling programs or the implementation of remote monitoring. NREL Smart Management System [35] estimates that up to a 5 % reduction in financing costs can be achieved through lowering long-term risk thanks to improved monitoring and sensing, as well as application of data analysis tools. In a similar vein, improved computational models are expected to lower the cost of capital, as a better characterization of wind resources and geophysical features of the ocean environment represent a key factor to reduce long-term risks [35].

These remote sensing applications are also expected to be one of the main drivers of cost reductions for operational expenditures, as they will allow the implementation of condition-based maintenance and parts replacement, instead of the expensive periodic insurance-required maintenance that is currently predominant in the sector. In addition, the use of specific vessels, that was already mentioned as one important factor for installation capital expenditures, is also an important aspect for the reduction of operational expenditures, especially in combination with economies of scale. Thus, OPEX is forecasted to be cut down by 25 % in the next decade [35].

The combination of all these cost-reduction drivers, from increased turbine capacity to improvements in logistics and specific modelling, will certainly result in a decrease in expenditures of the offshore technology in the next decade. In the following section we try to elicit these reductions from the costs revealed in auctions.

3 Estimating future costs from auctions

As mentioned in the introduction, auction outcomes have been chosen by some institutions as good indicators for evolution of costs over time, as awarded projects become operational gradually, thus providing this information for a relatively long timespan (in our case, from 2020 till 2026). Uncertainty in real costs is not

eliminated, but private operator's investing decisions are supposed to be well-informed -probably counting with better information than public sources-. However, as explained before, extracting robust cost information from auction results is not straightforward.
First, auction strike prices are given in $/MWh, so that capital expenditures are not directly provided. In addition, auctions do not take place in perfectly competitive markets: as mentioned in the introduction, many market failures may happen which will result in the wrong estimation of the underlying industry costs. These aspects will not be addressed in this study.
Finally, even if we assume that the problems mentioned above are negligible, using winning bids in different auctions and comparing them is not straightforward. Even if the general approach is the same, auction designs differ significantly among countries, in terms of the risk assumed by developers, and in terms of the costs assumed by the region organizing the auction. The exposure to risk varies among schemes in which winners are awarded a fixed price, or a premium over electricity market prices; or inflation is accounted for; or if the length of the period covered varies. And this exposure is critical for determining the financial risk of the project, which in turn is essential a technology with high capital costs such as offshore wind [43]. As for the costs assumed, the major difference is in the cost of developing the project (which also entails a significant risk) and in the cost of the offshore transmission grid: some auctioning institutions cover the costs of development and of this grid, whereas others make developers pay for them.
In this paper we propose to extract more robust CAPEX estimations from winning auction bids by following a reverse-engineering process, similar to the one proposed in [25], but based on updated auction results. Our procedure is essentially different from those based on engineering approaches ([7], [6], [22]-[27], [17], [8] or [9]), since we are incorporating industry knowledge and market developments through auctions.
We start from the auction bid in $/MWh, which should be the amount that the investor needs to receive in order to make the offshore wind farm profitable (for a given discount rate), and then we proceed backwards in order to find the underlying CAPEX, introducing in our calculation both explicit and implicit costs. This is done by using the following equation, which is basically a transformation of the classical LCOE one (see e.g. [20]):

$$CapEx = \sum_{t=1}^{n} \frac{E_t * P_t}{(1+r)^t} - \sum_{t=1}^{n} \frac{M_t}{(1+r)^t}$$

Where:

E_t expected energy generation in year t

M_t expected operations and maintenance expenditure in year t

P_t expected price of electricity in year t: if the auction awards a fixed price, this will be equal to strike price during subsidy-years, and equal to wholesale electricity price for the remaining lifetime years. If the auction awards a premium over electricity prices, then during the subsidized period the expected price is the sum of the expected wholesale price and the premium awarded.

r capital cost

t lifetime of the project in years

As may be seen in the equation, CAPEX will depend on expected energy generation (which in turn depends on the installed power and capacity factor), expected price of electricity (determined by the auction price, but also by the electricity market price expectation), operational expenditures, and capital costs (discount rate). This will provide us with a basic CAPEX estimate. Then we adjust that CAPEX based on the characteristics of the auction design (described below): risk factors may cause changes to the capital cost used; costs covered by the auction authority (project development or grid connection) are deducted from the CAPEX. It should be remarked that some cost drivers are implicit: for example, distance to shore or depth are internalized in the auction bid price, and therefore do not need to be modeled explicitly.

All auctions held between 2010 and 2019 have been analyzed following this procedure. Specific policies in this respect are analyzed for the UK, Germany, Denmark, Netherlands, the US and Taiwan. [23-43].

3.1 Specific auction designs

3.1.1 United Kingdom

The UK offers Contracts for Difference (CfD) for winning bidders of the wind farms for a period of 15 years [21], being the subsidy duration not limited by the number of production hours. Unlike all other countries, CfD prices awarded in the UK are

inflation-indexed and ''two-sided'' [44] -which eliminates the possibility of extra revenues in case of high wholesale prices-.
Projects in the UK are not site-specific and capital expenditures for electrical infrastructure and substation are not covered by government or TSO. Thus, offshore wind developers in the UK have to bear the majority of the upfront financial risk involved in site development and grid connection. In contrast, penalties for non-delivery are modest, merely consisting in exclusion from the next auction round [13], [21], [44].

3.1.2 Germany

Both the "Energy at Sea Act" [45] and the "Renewable Energy Act" [46] are regulatory frameworks put in place to support the industry and to push for cost reduction in order to achieve 15 GW by 2030. Offshore wind developers in Germany are offered a sliding ''one-sided'' market premium under the strike price awarded for a period of 20 years, without limit on the number of production hours. The sliding ''one-sided'' market premium acts like a minimum feed-in tariff that the operator will always -at least- perceive [14].
Moreover, the government also covers the site development cost and grid connection cost from the offshore substation to shore (not including the substation) [13].
In addition to these incentives, penalties are also low [47], consisting in the reimbursement of 30 % of a €100/kW bid bond [13], [16].

3.1.3 Denmark

In Denmark, auction winning bidders don't undertake the costs derived from development, grid connection and electrical infrastructure (including substation cost), as these expenditures are provided by the TSO [13].
Corporate PPAs offered are based on contracts for differences and correspond to a fixed price per kWh generated[4]. The guaranteed price is limited to 50,000 hours in full load operation. At regular load factors, this approximately corresponds to 11-12 years of operation, depending on site-specific characteristics [48].
Compliance rules for offshore wind auctions in Denmark are remarkably strict. Delays up to one year are penalized with reductions in contract remuneration (delays up to 5 months would correspond to 1% decrease in remuneration, 9

[4] PPAs in Denmark are ''sleeved'', which means that the energy produced in the offshore wind farm is directly consumed by the corporation, being both the wind farm and the corporation in the same grid system [96].

months delay to 2% decrease, and one-year delay to 3%). Besides, a reimbursement of DKK 400 million (USD 60 million) is to be made if the project is not fully operational within one year of the PPA signature [49].

In case the bid winner drops out within the first six months, the second winner has to assume the contract and take on the project within the same deadlines, thus incurring in higher risk of no-compliance [49], [50].

3.1.4 The Netherlands

Following the example of Germany, under the SDE+ act, the Dutch government provides support in form of a sliding ''one-sided'' market premium, so that developers perceive -at least- the amount corresponding to the strike price [44], [50]. As in Denmark, the subsidy is limited to the number of hours at full-load operation, corresponding to 11-12 years in average [48].

Government support also includes grid connection, including substation, and site development cost, which results in lower upfront expenditures and financial risks. In return, penalties for non-compliance within the realization time limit (5 years) are hard, consisting in the loss of support rights and exclusion from SDE+ for a three-year period [12].

According to the IEA [51], offshore wind farms in the Netherlands have experienced a small reduction in costs through greater capacity of its farms. Besides, the close proximity of the farms to shore, with an average distance of 20 km, further contributes to the reduction of the upfront capital expenditures.

3.1.5 United States

Support for offshore wind projects in the US is provided for 20 years, under the form of corporate PPAs[5] [7].. Tax incentives (production tax credit and investment tax credit), which may differ from one state to another, are also put in place to encourage investors [37].

Despite these incentives, offshore wind developers bear a significant risk, as projects are not site-specific and grid connection costs are not covered by government or TSO. Winning bidders are merely awarded the right to explore a specific area, which might not result in a feasible project [15].

[5] PPAs in the US are ''synthetic'', which means that energy generated is not directly consumed by the corporation, as the wind farm and the corporation usually don't belong to the same power system. This way, ''*it is a contract for difference/financial hedge, rather than two back to back contracts for sale of power''* [74]

The principal incentive mechanism for offshore wind in the US is the production tax credit, which is an inflation-indexed credit, aimed to incentivize developing technologies until they reach higher maturity levels. The credit received is not constant, decreasing by 2% annually, so that investors receive a stronger financing support at the early stages of the project [32].

Another important supporting mechanism is the investment tax credit, which is awarded to renewable projects and consists of a 30% tax credit on capital expenditures. The support decreases by 6% each year [51].

3.1.6 Taiwan

Similarly to the US, offshore wind developers in Taiwan must bear capital expenditures derived from site development, grid connection and transmission [51]. Besides, prior to the development of projects, environmental impact assessments and preparation permits need to be acquired. Auction winners are offered 20-year PPAs [53], whose non-compliance derives in high penalties.

A summary of the most important aspects about the different countries' regulatory regime for offshore wind auctions is shown in Table 2.

Table 2: Summary of regulatory frames for offshore wind auction-holding countries (Source: The authors, based on [12]–[16], [44], [47], [48], [50], [51], [53]–[62])

Country	Subsidy period	Grid connection covered	Site dev cost	Inflation indexed	Type of payment	Penalties
US	20	No	No	No	feed-in tariff PPA	Severe
UK	15	No	No	Yes	two-sided CfD	Light
Germany	20	Yes	Yes	No	one-way CfD (feed-in premium)	Light
Netherlands	11.5	Yes+substation	Yes	No	one-way CfD (feed-in premium)	Severe
Denmark	11.5	Yes+substation	Yes	No	one-way CfD (feed-in premium)	Severe
Taiwan	20	No	No	No	feed-in tariff	Severe

3.2 Capital cost adjustment

After having analyzed the most important aspects of offshore wind regulatory framework for each auction-holding country, several assumptions are made in order to consider the effect of these factors in the exposure to risk. On this purpose, the capital cost for each country is analyzed in detail, as it is one of the most important factors in the equation used for estimating the CAPEX. IEA's nominal WACC (weighted average cost of capital) estimations are taken as a starting point for our analysis [32].

For WACC's estimates, inflation is assumed to take a constant value of 1.8% [32]. This factor will have especial relevance in countries where prices are restated based on inflation, such as the UK.
Another important factor is the market risk premium, as it is an essential element of the Capital Asset Pricing Model used to calculate the WACC [54]. The market risk premium varies with project conditions, type of remuneration, support regime, etc. thus affecting the resulting WACC value. Several assumptions have therefore been made to account for the most relevant risk-related factors that are specific to offshore wind projects.
NERA's procedure for WACC adjustment [13] has been used as a reference. In NERA's report, percentage points are added/subtracted to the WACC value to account for differences in rules, prices and support regimes between the UK and the Netherlands. Although the estimations considered in this document are different, the approach taken is similar to NERA's.
First, the uncertainty linked to the absence of predetermined site specification in the US, the UK and Taiwan, and the subsequent higher upfront financial risks, is accounted for by adding one percentage point to the WACC.
In addition, a reduction of the WACC by one percentage point is assumed for countries with lenient compliance rules. This is the case of Germany and the UK, where the non-stringent penalties may lead investors to take more risks and bid more aggressively.
The resulting WACC values, along with the initial values taken from IEA and our adjustments are presented in Table 3.
Table 3: WACC estimations for offshore wind auctions (Source: The authors, based on [13], [26])

	WACC IEA	Inflation indexed	Site development	Penalties	Final WACC
US	9.2%		+1%		10.2%
UK	6.6%	-1.80%	+1%	-1%	4.8%
Germany	6.0%			-1%	5.0%
Netherlands	6.7%				6.7%
Denmark	7.2%				7.2%
Taiwan	6.0%		+1%		7.0%

WACC estimations for the US are noticeably high in comparison to other countries. This can be explained by the less-supporting regulatory regime, along with the lack of experience in the sector [32].

In contrast, the weighted average cost of capital is remarkably low for Germany and the UK, thanks to the strong supporting schemes and the benefits of clustering and longer experience in the implementation of offshore projects [32].
In the case of Taiwan, as no country-specific WACC estimations were available, Japan's WACC value has been utilized as the best approximation, by virtue of the geographical proximity and conjunctural similarity of both countries.

3.3 Other parameters

The following parameters are considered constant for all projects: a lifetime of 20 years [21], [50], [64], capacity factor of 40% [65], an OpEx of 59,9K€/MW/year (according to Danish Ministry [66], for offshore wind projects built in 2020). Changes in these values can depend on site-specific factors: wind speed, distance to shore, water depth, etc. [17], [18], [23], which are not the focus of this study (but which will be analyzed briefly later). Besides, an average wholesale electricity price of $60/MWh is considered to account for generation revenues when the subsidy period has expired (this estimate is based on current prices[67] and the expectations for the coming years[68]).
NREL's cost estimations for site development and electrical infrastructure are utilized to adjust the final values for countries where these expenditures are subsidized. We assume 138$/kW for site development cost and $1130/kW for electrical infrastructure [31]. Substation costs are estimated to be 4.4% of the total capital expenditures, according to Catapult [69].

4 Results

On the basis of the parameters presented above, Table 4 gathers all the relevant parameters for each offshore project, including the auction strike price, the year when the auction was hold, the expected year of commission, the capacity in MW and the distance to shore [44-72], as well as the final CAPEX estimation in $/kW.

Table 4: Estimation of CAPEX from offshore wind auctions (Source: The authors, based on [14], [15], [17], [18], [21], [23], [25], [27], [31], [50], [62], [64], [65], [69]–[95])[6].

Country	Project	Strike Price ($/MWh)	Year Auctioned	Capacity (MW)	Year to be commissioned	Distance to shore (km)	CapEx ($/kW)
US	Vine Yard Wind 1	98	2018	800	2022	24	2338
US	Mayflower wind	82	2018	804	2025	35	1859
UK	East Anglia 1	120	2015	714	2020	43	4055
UK	Neart Na Gaoithe	114	2015	448	2023	20	3851
UK	Moray East	73	2017	950	2022	22	2331
UK	Hornsea 2	73	2017	1386	2022	89	2328
UK	Triton Knoll	95	2017	857	2022	33	3140
UK	Seagreen Phase 1	50	2019	454	2024	27	1839
UK	Sophia Phase 1	48	2019	1400	2026	195	1839
UK	Forthwind	48	2019	12	2023	2	1839
UK	Doggerbank Creike Beck B P1	50	2019	1200	2024	130	1839
UK	Doggerbank Creyke Beck A P1	48	2019	1200	2025	130	1839
UK	Doggerbank Teeside A P1	48	2019	1200	2025	200	1839
Germany	Gode Wind 3	74	2017	110	2023	95	3679
Germany	Bokrum Riffg W 2	0	2017	450	2024	45	3069
Germany	OWP West	0	2017	240	2024	40	3069
Germany	He Dreiht	0	2017	900	2025	48	3069
Germany	Borkum Riffg W1	0	2018	420	2024	19	3069
Germany	Gode Wind 4	107	2018	132	2023	75	5109
Germany	Kaskasi II	0	2018	325	2022	28	3069
Germany	Arcadis Ost 1	0	2018	247	2021	23	3069
Germany	Wikinger Süd	0	2018	10	2022	45	3069
Germany	Baltic Eagle	69	2018	476	2023	30	3462
Netherlands	Borssele 1 & 2	83	2016	752	2020	22	3555
Netherlands	Borssele 3 & 4	59	2016	732	2021	30	2930
Netherlands	Hollandse Kust Zuid 1 & 2	0	2017	1500	2022	15	2930
Netherlands	Hollandse Kust Zuid 3 & 4	0	2019	769	2023	9	2930
Denmark	Anholt	155	2010	400	2013		5421
Denmark	Horns Rev 3	112	2015	407	2020		4262
Denmark	Kriegers Flak	54	2016	600	2021	40	2876
Denmark	Vesterhav Syd & Nord	69	2016	344	2020	50	3124
Taiwan	Greater Shangua (NW and SW)	84	2018	920	2025		2435
Taiwan	Hai Long II	73	2018	232	2025		2016
Taiwan	Hai Long III	83	2018	512	2025		2388

[6] Strike prices for US wind farms do not correspond to actual strike prices. For the Vineyard Wind project NREL estimations [97] are taken to account for ''*the complete set of expected revenue sources and tax benefits available to the Vineyard Wind LLC project''*. The Mayflower wind project strike price has been assumed to benefit from similar supporting mechanisms, so that a similar correcting factor for its strike price has been applied.

These results would allow us to make a forecast on the cost evolution for the next decade, taking the CAPEX estimation to be the cost of each offshore project in the year it is expected to become operational. According to our study, offshore wind costs would drop from $3803/kW to $1839/kW between 2020 and 2026, although this may also reflect differences between regions which we will address in the Discussion section.

4.1 Sensitivity to relevant parameters

The results presented depend of course on many assumptions, so we have tested how robust they are to changes in some of these. Contrary to other approaches [8], we have followed a classic sensitivity analysis, instead of a stochastic procedure or Monte Carlo analysis. The reason for this is there is not enough information to build probability functions for most of the parameters assumed, for the time horizon considered. For example, we cannot estimate a probability function that describes the evolution of capacity factors, or electricity prices, or changes in support policies, in the coming years. The uncertainty in these parameters is Knightian, not probabilistic, which makes the stochastic approach less useful.
In the following table we present the percentage changes in the original CAPEX for each wind farm analyzed, when different parameters change. Parameter changes have been simulated in both directions (increase and decrease), although in most cases the change is symmetric. We only include both changes when results differ.

Table 5: Sensitivity of CAPEX to changes in parameters (Source: The authors)

Project	-1% WACC	+1% WACC	+10% Capacity Factor	-20% OPEX	-20% Electricity Market Price	+20% Electricity Price	20% Lifetime	+20% Lifetime
Vine Yard Wind 1	7%	-6%	31%	5%	0%	0%	-4%	3%
Mayflower wind	7%	-6%	32%	6%	0%	0%	-5%	4%
East Anglia 1	8%	-7%	30%	4%	-2%	2%	-6%	5%
Neart Na Gaoithe	8%	-7%	30%	4%	-2%	2%	-6%	5%
Moray East	9%	-8%	34%	7%	-4%	4%	-11%	9%
Hornsea 2	9%	-8%	34%	7%	-4%	4%	-11%	9%
Triton Knoll	8%	-7%	32%	5%	-3%	3%	-8%	6%
Seagreen Phase 1	9%	-8%	36%	9%	-24%	29%	-13%	11%
Sophia Phase 1	9%	-8%	36%	9%	-29%	29%	-13%	11%
Forthwind	9%	-8%	36%	9%	-29%	29%	-13%	11%
Doggerbank Creike Beck B P1	9%	-8%	36%	9%	-24%	29%	-13%	11%
Doggerbank Creyke Beck A P1	9%	-8%	36%	9%	-29%	29%	-13%	11%
Doggerbank Teeside A P1	9%	-8%	36%	9%	-29%	29%	-13%	11%
Gode Wind 3	6%	-5%	22%	4%	0%	0%	-6%	5%
Bokrum Riffg W 2	5%	-5%	21%	5%	-17%	17%	-8%	6%
OWP West	5%	-5%	21%	5%	-17%	17%	-8%	6%
He Dreiht	5%	-5%	21%	5%	-17%	17%	-8%	6%
Borkum Riffg W1	5%	-5%	21%	5%	-17%	17%	-8%	6%
Gode Wind 4	7%	-6%	23%	3%	0%	0%	-5%	4%
Kaskasi II	-	-	-	-	-	-	-	-
Arcadis Ost 1	-	-	-	-	-	-	-	-
Wikinger Süd	5%	-5%	21%	5%	-17%	17%	-8%	6%
Baltic Eagle	6%	-5%	22%	5%	0%	4%	-7%	6%
Borssele 1 & 2	5%	-4%	20%	4%	-3%	3%	-5%	4%
Borssele 3 & 4	4%	-4%	19%	5%	-5%	15%	-6%	4%
Hollandse Kust Zuid 1 & 2	4%	-4%	19%	5%	-15%	15%	-6%	4%
Hollandse Kust Zuid 3 & 4	4%	-4%	19%	5%	-15%	15%	-6%	4%
Anholt	5%	-4%	22%	3%	-2%	2%	-3%	2%
Horns Rev 3	5%	-4%	21%	3%	-3%	3%	-4%	3%
Kriegers Flak	4%	-4%	19%	5%	-9%	15%	-5%	4%
Vesterhav Syd & Nord	4%	-4%	19%	4%	-4%	6%	-5%	4%
Greater Shangua (NW and SW)	8%	-7%	32%	6%	0%	0%	-7%	5%
Hai Long II	8%	-7%	34%	7%	0%	0%	-8%	6%
Hai Long III	8%	-7%	32%	6%	0%	0%	-7%	5%

As may be seen, the CAPEX is very sensitive to changes in WACC and capacity factors. Also, results can be very sensitive to electricity market prices, but only for those auction designs in which revenues are more exposed to market prices (as in some in the UK). Operation and maintenance costs, or lifetime assumptions, are not that critical.

As mentioned earlier, size and distance to shore are implicit in the auction bid, and not explicit factors in our model. Therefore, we cannot test how sensitive are CAPEX figures to these elements. What we can do, however, is to assess the extent to our CAPEX figures (which in turn depend on auction bids) depend on size and distance to shore. This is done in Figure 2, which represents the relationship between CAPEX and wind farm capacity, which seems to be downward, as expected: Economies of scale and optimization of resources should play a part in the cost of large offshore wind farms [25]. However, the correlation is not very strong: trying to fit a linear relationship results in a rather low R^2 of 0.18.

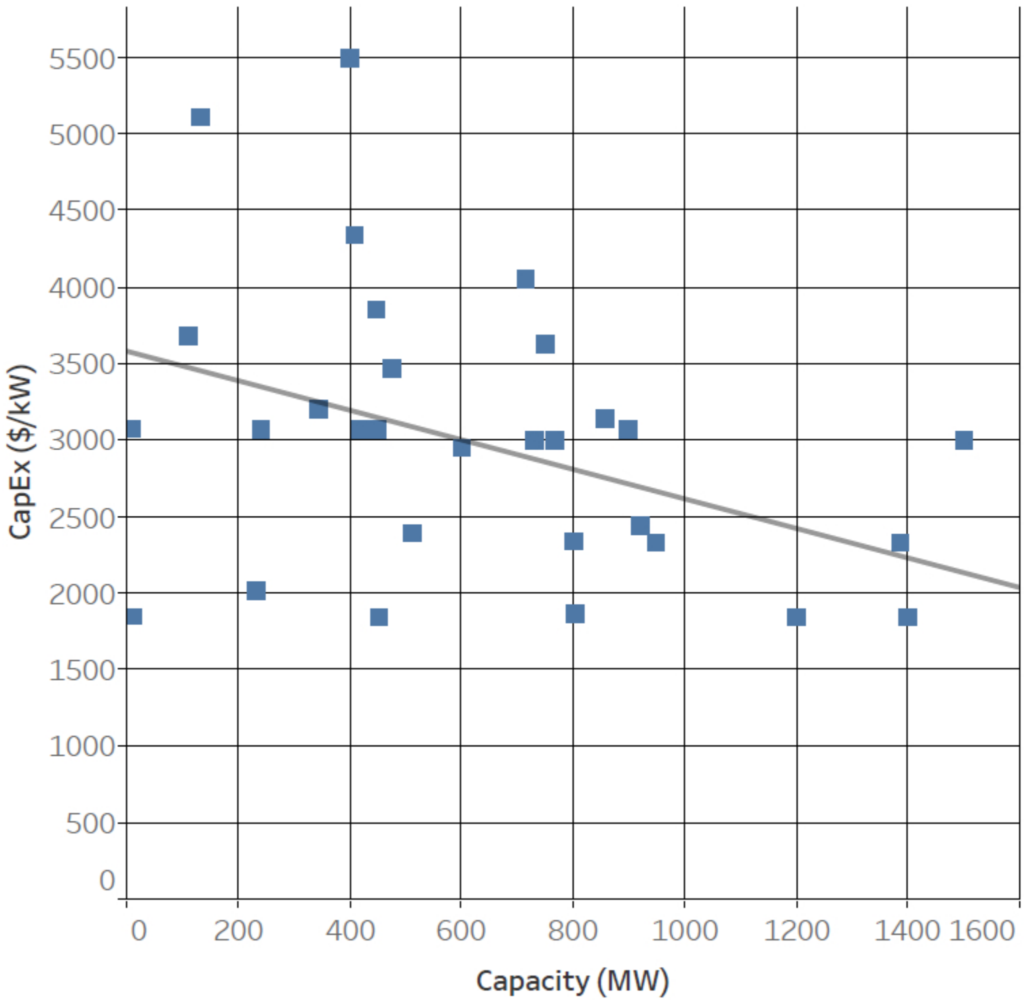

Figure 2: Capital Expenditures compared to capacity for offshore wind projects

An explanation of this low correlation may be that other, more important factors are at play, such as the WACC or capacity factor pointed earlier. Indeed, if we look at most of UK's offshore wind projects, we find that they generally present the lowest costs and are -with the exception of the Forthwind project, which could be considered more as a pilot farm rather than a regular project- big-sized farms. But this may be also a result of the large experience that the UK has on offshore wind. The country is the one featuring the largest installed capacity. Thus, investors may be benefiting from this experience, as well as from the benefits of clustering and competition in an already established sector.

A similar analysis may be done for distance to shore. In this case, the R^2 of the correlation is even lower, 0.11. This runs against the usual understanding (see e.g. [9] or [17]), but has been observed also by other authors [18], who found that water depth, and not distance to shore (which may be uncorrelated), is the real cost driver for these type of wind farms. Unfortunately, we did not have information in our sample about water depth, so we cannot say anything about this potentially relevant cost driver.

4.2 Building an expected learning curve

The gain from experience in building wind farms can be further confirmed by the observation of the learning curve for auctioned offshore wind projects -Figure 3a and 3b-. We built two learning curves: one in which we assume that all the future capacity will arrive through auctions, and another one, probably more realistic, in which we assume that an equivalent capacity will be built using other support systems.

The learning curves are built following the conventional model: we correlate cumulative installed capacity for offshore wind with CAPEX. We see that, in both curves, the best fit is a line, with a very good correlation. The R^2 is 0.91 for 4a and 0.88 for 4b. The learning rate lies between 10 and 15%.

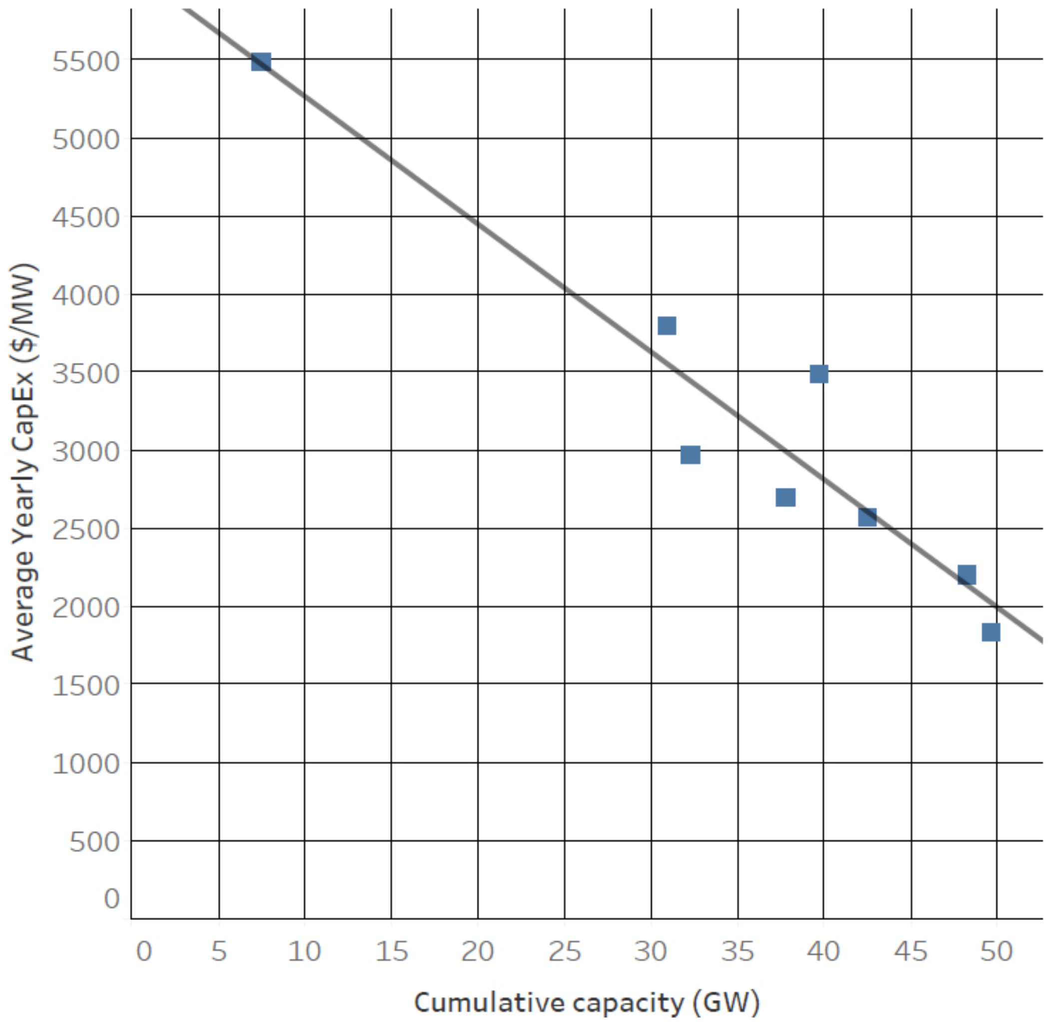

Figure 3a: Learning curve for auctioned offshore wind projects expected to be commissioned between 2013-2026, assuming that all future capacity will be auctioned (Source: The Authors)

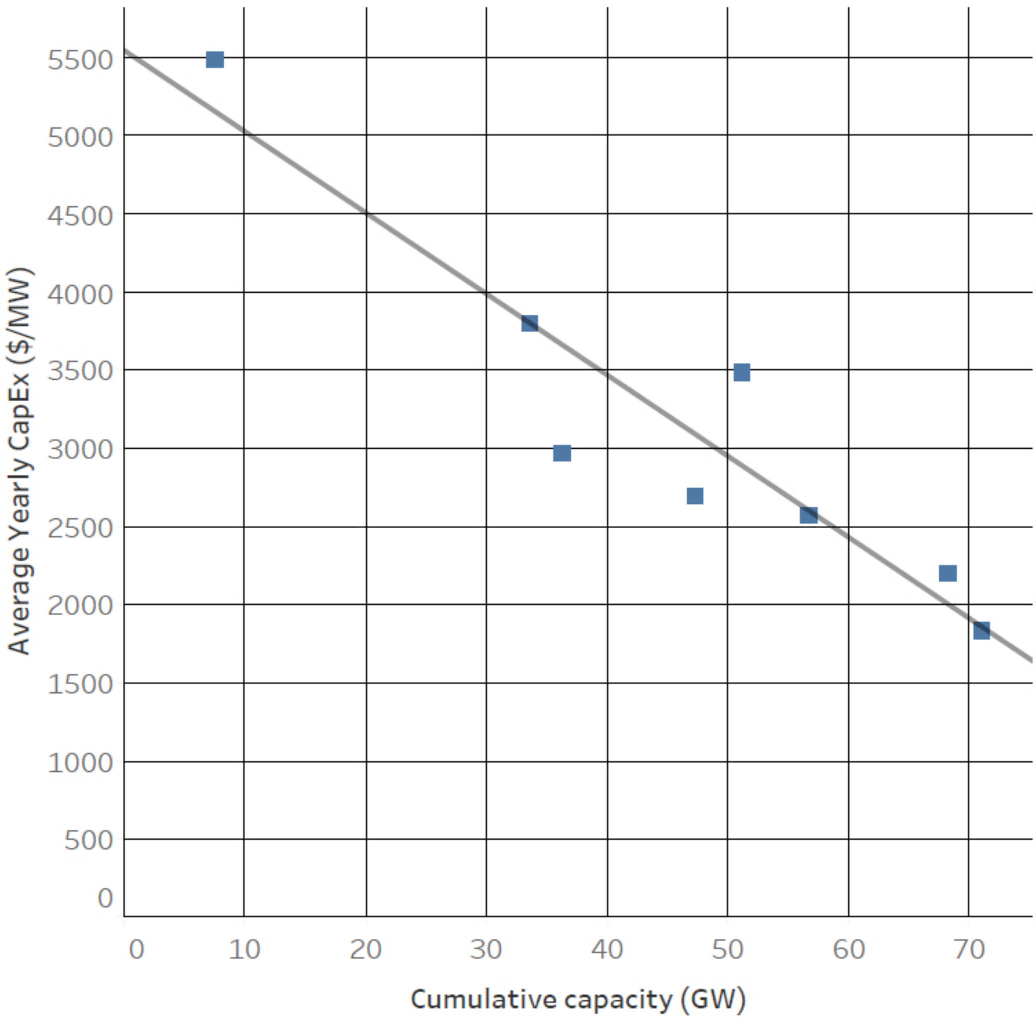

Figure 3b: Learning curve for auctioned offshore wind projects expected to be commissioned between 2013-2026, assuming that only half of future capacity will be auctioned (Source: The Authors)

5 Discussion

As mentioned in the introduction, our methodology is different from many other studies, in that it tries to estimate CAPEX (and not LCOE) based on auction results (not on engineering or representative project analysis). In addition, most of the studies found (cited earlier) look at historic costs, rather than trying to forecast. Therefore, we can only compare it with a limited set of studies.

In Figure 4 our cost evolution forecast is shown along with IRENA's [19] and NREL's [26]–[31] cost estimations. This representation allows for a global picture of the cost evolution -future and past-, and at the same time it facilitates the comparison among the different sources.

For auction-based CAPEX there is only one data point before 2020, as there was only one project committed before that year -Anholt offshore wind farm came into operation in Denmark in 2013 [50]. Therefore, the estimations of cost evolution from auctions before 2020 may not be accurate.

IRENA's cost estimations are based on market analysis up to 2018, whereas its forecast for the following years are based on auction results. As previously commented, NREL assessment is based on the study of a theoretical reference offshore wind project.

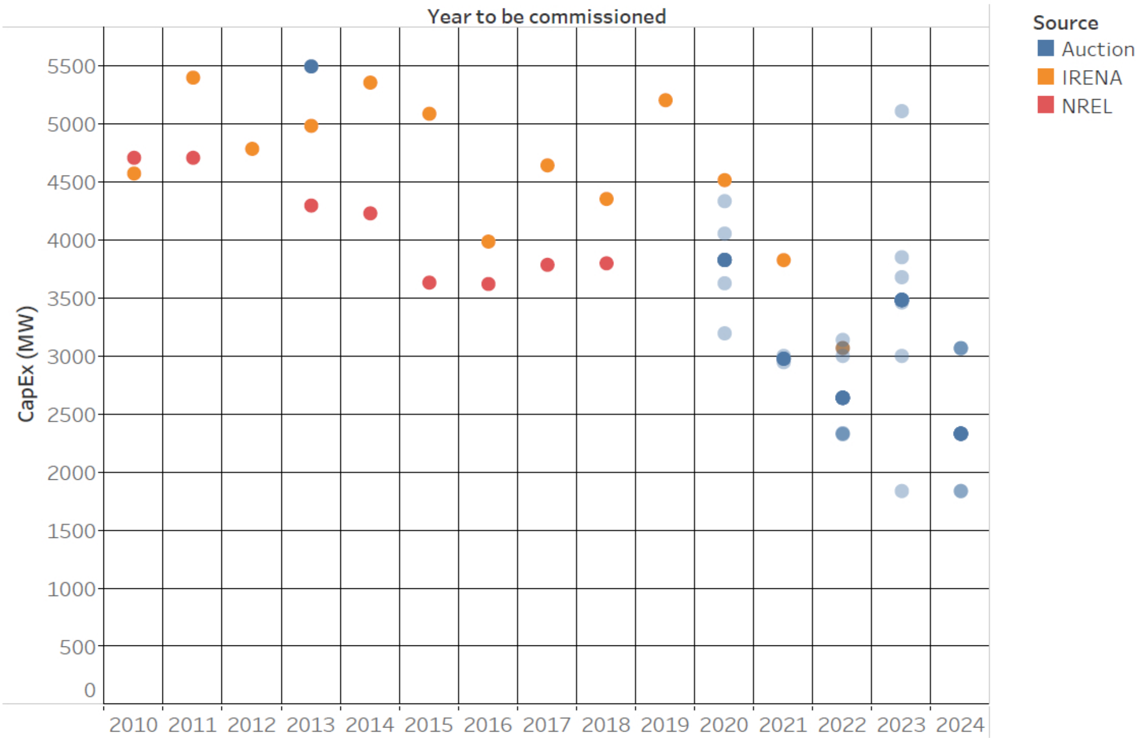

Figure 4: Offshore wind cost forecast-NREL, IRENA, own elaboration

The estimation of past costs shows significant variations year to year, which can be explained by the fact that market prices are at the basis of these estimations. On the other hand, NREL's are more stable, which may be explained by their technology-based approach, which makes it much less dependent on the volatility of market prices.

It may be observed that our estimations are placed consistently below IRENA's for 2020-2022: IRENA forecasts a cost reduction of 40% between 2019 and 2022, whereas our estimations are that CAPEX will be reduced by 50%.

The dispersion of the different data points shown in the figure for future costs is quite reduced (with more variation for 2023), especially within regions where water depth and weather conditions are similar: for example, CAPEX in the Baltic region is rather stable for the different projects of the same vintage. Confirming some earlier estimations, distance to shore or wind farm size are not able to explain both similar values within regions, or different values between regions. The UK shows lower CAPEX values in general, what may reflect to some extent the larger experience with offshore wind in this country. However, the US and Taiwan also feature low CAPEX values.

Of course, another explanation for this range of variation among countries would be differences larger (or smaller) than expected in the underlying parameters. Our sensitivity analysis show that our estimates are very sensitive to the choice of WACC or capacity factors. In the case of the UK, results are also sensitive to market prices, given the larger exposure to these of the projects developed there. According to the sensitivity analysis, deviations of 20% of the expected market prices could explain the difference in CAPEX. If UK operators expect higher prices in the UK than in the rest of the European power market, then CAPEX values would get closer to the European ones (that is, in the higher end of the range estimated).

In spite of these uncertainties, average values show a pretty consistent and robust downward trend. Learning rates range between 10-15% depending on the assumptions. This is higher than the learning rate of onshore wind (e.g. [98]), which makes sense given the lower maturity of offshore compared to onshore. This reduction trend is supported by the technological foresight studies, which point to a significant potential for improvement of power ratings and turbine efficiencies (which in turn would result in higher capacity factors). The growing number of operating projects should also result in more confidence by investors and hence lower WACCs required.

Of course, this does not mean that the cost reduction will not flatten afterwards. However, if we assumed that the reduction trend continued along this line, we would be able to determine the amount of offshore wind that needs to be supported until it arrives to cost competitiveness.

Without any type of subsidy, and including all development and grid costs, the expected LCOE for the period analyzed in the curve would be around 108 $/MWh[7], lower than the range identified in [5], but still higher than the LCOE expected for solar PV or onshore wind (30-40 $/MWh, according to IRENA).

Assuming that cost competitiveness would occur when costs go below the expected 60 $/MWh market price, that would mean that CAPEX should go below 1,000

[7] Assuming a market rate of 15% WACC and 40% capacity factor.

€/MW. This in turn would require an installed capacity of more than 62 GW under the first scenario (all capacity built is auctioned) or 87 GW under the second scenario. That would require supporting an additional 15-20 GW more beyond 2026. Even assuming that the 5 GW annual capacity added in the last years remains stable, that would mean that offshore wind could be competitive with market prices already in 2030.
However, the competitiveness of offshore wind with other more mature technologies in the electricity market will depend not only on costs, but also on other characteristics, such as its correlation with demand or its flexibility, particularly in 100%-renewable systems. Assessing the role that offshore wind may play in these markets would require more comprehensive models, able to take into account the interactions between generation technologies and demand. This is clearly out of the scope of this paper, although we do believe that our study contributes to a better modeling, by developing robust CAPEX estimators that can be then introduced into these more comprehensive models so that the right investment strategies for a fully decarbonized future may be determined.

6 Conclusions

Understanding correctly the evolution of costs of not-yet-competitive technologies is essential for policy makers, so that they may be able to adjust the level of public support and not waste public resources, and also be able to forecast better future energy scenarios and the contribution of these technologies. Offshore wind is one of these technologies, expected to contribute significantly to future energy scenarios, but which still needs public support in order to achieve cost-competitiveness.
The reduction in costs of offshore wind in the last years has been striking, with auctions in different countries showing very significant reductions in the prices bid. However, the translation of these price bids into CAPEX may be difficult, since they may be hiding differences in auction design, or in costs explicitly or implicitly paid by the government. In this paper we have tried to estimate the evolution of costs from the results of the auctions carried out until now, adjusting for design differences and country specificities. The major conclusions that can be extracted from the study (which are further elaborated below) are:

- Auctions show a significant reduction in the CAPEX of offshore wind projects;

- The main parameters that affect CAPEX estimates are the WACC, capacity factors, and expected market prices; Water depth (but not distance to shore) may also be an important driver;
- If the current trend in cost reduction continues, offshore wind could become competitive by 2030.
- Improvements in capacity factors, through increased power ratings and higher efficiency of the turbines, are indeed the drivers of further cost reductions pointed out by industry.

Our results show that the cost reductions achieved are indeed real, and larger than shown before (e.g. by IRENA). We obtain costs reductions of 50% between 2020 and 2026, and a rather steep learning curve. This general reduction trend is robust to changes in our assumptions. However, our results also show that CAPEX estimates are very sensitive to WACC rates, capacity factors, or market prices (when auction designs rely on a larger market price exposure). On the other hand, wind farm size and distance to shore show low correlation with CAPEX.

Setting our results within the framework of a learning curve is also quite interesting, in that they point out that, if the current trend in cost reduction continues beyond 2026, offshore wind might achieve cost competitiveness by 2030. This in turn may point out to a higher share of offshore wind in future energy scenarios. Their lower variability, high compatibility with solar PV, and, if our estimations are correct, competitive costs, may make offshore wind play a larger role in the decarbonization of the energy sector in Europe and other regions.

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