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Offshore wind competitiveness in mature markets without subsidy

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Abstract

Offshore wind energy development has been driven by government support schemes, but recent cost reductions raise the prospect of offshore wind becoming cheaper than conventional generation. Many countries use auctions to provide financial support, but differences in auction design make their results difficult to compare. Here we harmonise the auction results from five countries based on their design features, showing that offshore wind can be considered commercially competitive in mature markets. Between 2015 and 2019, the price paid for offshore wind across northern Europe has fallen by $11.9 \pm 1.6\%$ per year. The bids received in 2019 translate to an average price of $\text{€}51 \pm 3/\text{MWh}$, and substantially different auction designs have received comparably low bids. The level of subsidy implied by auction results depends on future power prices, but projects in Germany and Netherlands are already subsidy-free, and it appears likely that in 2019 the UK has auctioned the world's first negative-subsidy offshore wind farm.

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Main Text

Decarbonising energy systems is a global necessity. Electricity from renewable energy sources (RES) will be crucial for the transformation. Together with photovoltaics and onshore wind, offshore wind energy has become a major contributor of renewable electricity in Europe. With growth rates exceeding 35% p.a. for the last five years¹, global installed capacity reached 28 GW by the end of 2019. Over 127 GW is forecasted by 2040 under the IEA's most conservative scenario² and the European Commission has announced its ambition between 250 GW and 450 GW of offshore wind in 2050 for Europe alone³. Global technical potentials exceed 10,000 GW of capacity and 5,000 TWh annual production in each of Europe, America and Asia^{4,5}.

This historic increase came at a cost. Offshore wind energy was significantly more expensive than conventional generation and even among options for decarbonisation^{6,7}. Recently, the technology has experienced rapid cost reductions, which have been widely discussed in the media and consultancy reports⁸⁻¹⁰, with some speculating that subsidy-free offshore wind was already achieved. As with the rapid cost reductions in solar photovoltaics¹¹ and energy storage¹², the pace of offshore wind cost reductions has proceeded more rapidly than was widely anticipated, in contrast to increasing capital costs during earlier stages of development¹³⁻¹⁶. For example, Wiser et al.¹⁷ used an expert survey in 2016 to forecast cost reductions for wind power, and the prices received in recent auctions have already fallen below the expectations for 2050.

Controversy remains around how close offshore wind power is to economic competitiveness against other decarbonisation options^{18,19}. NREL compared auction results from the Netherlands, United Kingdom and Denmark by adjusting values to account for grid connection, development costs and contract lengths²⁰. A transparent methodology was not provided though, which limits the replicability of results and the ability to update data in this fast-paced industry. The IEA Wind TCP Task 26 has compared country-specific impacts on the levelised cost of electricity (LCOE)²¹, comprehensively covering the costs of offshore wind. Whilst the publications provide valuable background, they do not explain the bids and the pace of the underlying cost reduction. Both issues are addressed in this paper.

Competitiveness can be measured by comparing costs (usually LCOE) to other technologies or to wholesale market prices, as an aggregated measure of competition in the system^{21,22}.

However, actual LCOE data are only available in selected countries because of their commercial value and sensitivity^{23,24} and these can be misrepresentative²⁵, and so costs must be estimated. For offshore wind, estimates of investors' expected LCOE can be derived from auction results, and data on successful bids are often published openly. Although bids should correlate with costs, they cannot be directly translated, as information on expected revenues from wind power projects is unavailable.

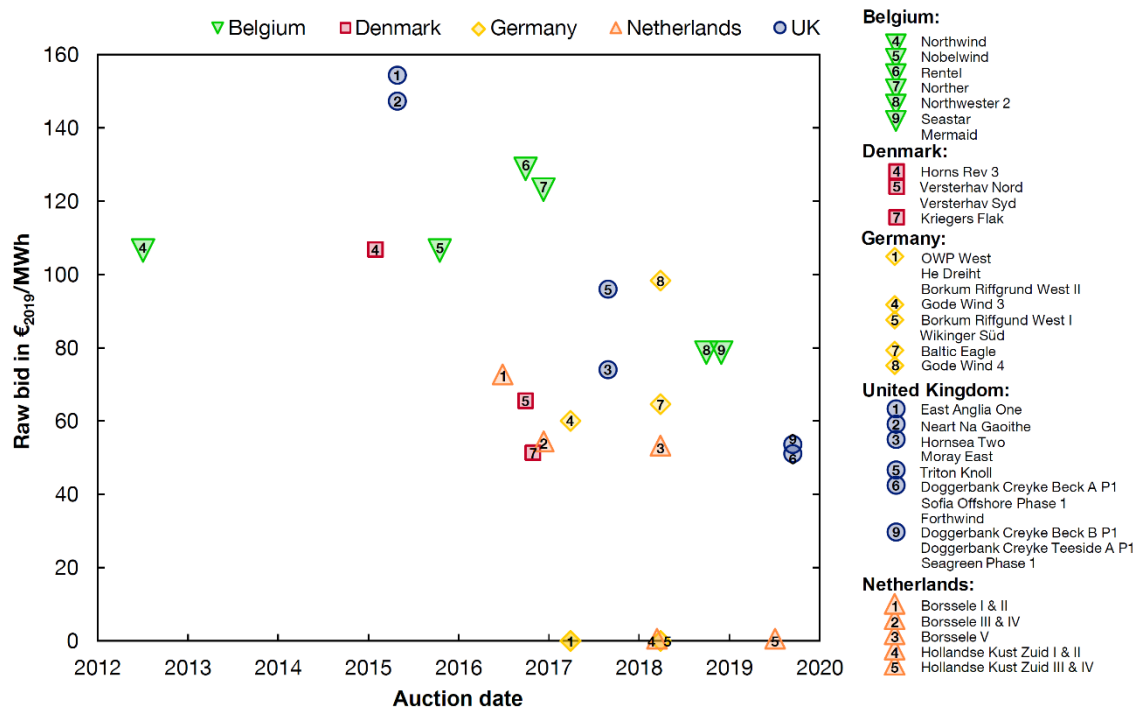
Several important differences exist between auction designs, including the length of support, whether it rises with inflation, optionality in building the project, and whether development costs are included. Most critically, the contracts for differences (CfDs) used for remuneration can be categorised as 1-sided (providing a lower-bound price below which revenues from the wind farm cannot fall) or 2-sided (providing a fixed price with both lower and upper bound). For this reason, a bid of €20 /MWh in Germany may provide more financial revenue to a wind farm developer than a bid of £50 /MWh in the UK.

We harmonise the winning bids from 41 wind farms across auctions in five European countries from 2005 to 2019, accounting for the main features of each auction. Wind farms were selected based solely on their payment allocation scheme, i.e. only wind farms that were auctioned. All offshore wind technologies were considered, as were all countries that had held at least two auction rounds at the time of writing (the minimum required to detect a trend). These five countries represented 77% of global offshore wind capacity, and the only other country to hold more than 1% of global capacity was China, which was not included as it had only auctioned a single offshore wind farm at the time of writing¹. This analysis provides two measures: the expected revenues (in €₂₀₁₉ per MWh) for each wind farm, which we then compare with potential future wholesale market prices to estimate the effective subsidy, and thus the financial competitiveness of each wind farm. We aggregate data on auction settings and results, showing that current offshore wind technologies at good sites in mature markets have implied prices of less than €50 /MWh, which is likely to be subsidy-free or negative-subsidy depending on future power prices.

Offshore wind auctions in Europe

Five countries in Europe have held auctions for offshore wind capacity. In total, 17 auctions have been held, bringing forth over 20 GW of capacity. The evolution of winning bids across these auctions is summarised in Figure 1. This does not reveal a clear trend and is confounded

by several bids of €0 (made into 1-sided CfD auctions) beginning in 2017. While a declining trend can be observed, this reveals as much about the heterogeneity amongst auction designs as it does about the reduction in wind farm costs.



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Figure 1: Raw bids received by auctions for new offshore wind capacity in five European countries over the past eight years. Points show the date that auctions were announced, and are converted from local currency to €₂₀₁₉.

70 All auctions for offshore wind in Europe are designed so that the wind farm operator receives a guaranteed price for a certain predefined period. This so-called strike price or bid price closes the gap between the market reference price (i.e. wholesale electricity prices) and a guaranteed price. However, the exact arrangements of the payments differ between countries, and the specific design of the support scheme gives rise to significant differences in the bids received, and so must be accounted for when comparing bids across different schemes. Clarification on auction design features and their influence can be found in ²⁶⁻²⁹.

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Several differences in implementation exist. (1) The choice of remuneration mechanism, specifically the allocation of market upside. One-sided CfDs usually pay when wholesale prices are below bid prices but do not demand money if wholesale prices are above bid prices. With two-sided CfDs, investors must compensate for wholesale price revenues above bid prices.

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Further explanation can be found in Supplementary Note 1. (2) Defining the support duration based on a fixed time period (years) or by the total support volume (TWh). (3) Accounting for indexation, which defines whether the guaranteed price is adjusted for inflation, choice of inflation index and base year for indexation. (4) Choice of market reference price used as the basis for comparison to the guaranteed price (e.g. hourly, daily, monthly average). (5) Floors of market price below which no support is being paid out (e.g. at negative market prices for several consecutive hours). (6) The allocation of land lease costs, (7) grid connection costs and (8) site development costs. (9) The option to capture alternative revenue streams (e.g. ancillary services), and (10) penalties for non-fulfilment of the contract, which could mean bids are conceived as options to build, not necessarily reflecting realistic cost estimates in all cases.

The auction schemes vary considerably across the five countries we consider, as summarised in Table 1. All auctions provide remuneration based on produced energy (i.e. per kWh), but other design aspects are not comparable between auction schemes. Further details are given in Supplementary Data and Supplementary Table 1. An overview of each country's auction design and their differences is given in Supplementary Note 2.

Table 1: Main characteristics of the auction systems for offshore wind capacity in five European countries. Full details about each wind farm in these auctions are provided in Supplementary Data and Supplementary Table 1. Two bids from German wind farms were undisclosed³⁵ and thus not further analysed. Denmark implements a new auction design for each round and support length is based on energy production. For more information on the auction design of each country refer to Supplementary Note 2.

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Country	Wind capacity [GW] (total / offshore) ³⁶	Date of auctions	Capacity awarded (all rounds) [GW]	Wind farms awarded	Average bid (Capacity-weighted)	Minimum bid	Sided	Duration (years)	Grid costs in bid	Site costs in bid	Inflation adjustment
Denmark	5.7 / 1.3	2005–16	2.2	7	€84 (DKK625)	€50 (DKK372)	2	12	×	✓	×
UK	21.0 / 8.2	2015–19	9.8	11	€65 (£57)	€46 (£40)	2	15	✓	✓	✓
Netherlands	4.5 / 1.1	2016–19	3.0	5	€32	€0	1	15	×	× ^a	×
Germany	59.3 / 6.4	2017–18	2.7	10	€19	€0	1	20	×	✓	×
Belgium	3.4 / 1.2	n/a ^b	2.3	10	€104	€79	1	16 ^c	× ^d	×	×

^a Land lease paid for by the wind farm in the latest tender round ^c 16-20 years, with 16 years for latest wind farms

^b Renewable obligation certificate scheme mirroring NL auction results

^d Financial cap on total investment

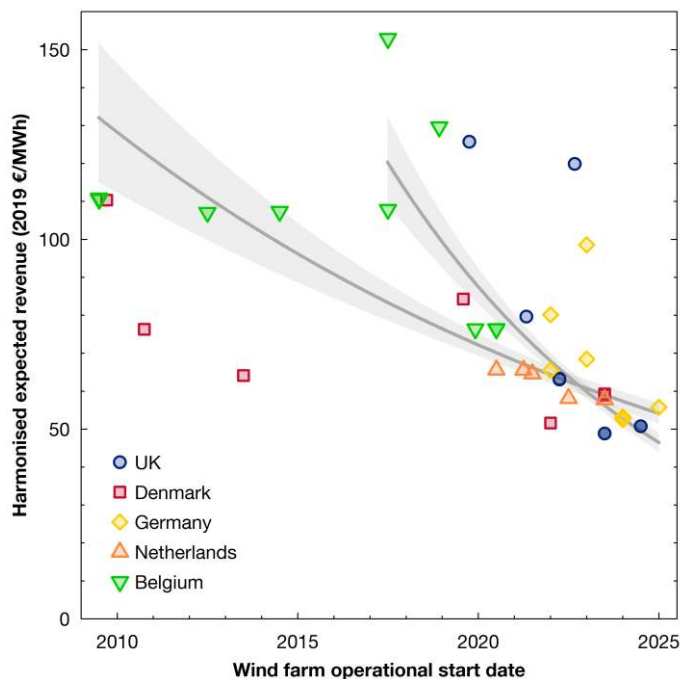
Harmonisation of expected revenues

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The significant differences we identify in auction and product design across countries directly influence the costs and/or revenues of projects, and thus influence the bids received. The winning bids in European auctions for offshore wind were harmonised using a monthly cash-flow analysis, accounting for the most significant factors identified in the previous chapter (see Methods). We define the ‘harmonised expected revenue’ as the discounted average revenue per MWh of electricity generated over the lifetime of the project. This gives the equivalent bid

110 that would be offered into a support scheme with a 2-sided CfD with 25-year support duration,
indexation to inflation, and site development costs paid by investors.

The harmonised expected revenue incorporates all the money a wind farm can expect to earn
over its lifetime, including revenues for later in the project's lifetime when support has run out.
It is therefore complementary to the widely-used LCOE metric, referring to revenue rather than
115 cost. It could therefore be a proxy to LCOE in perfectly competitive markets. The details for
each wind farm that were used to harmonise expected revenue, including key dates and
technical specification, are given in Supplementary Data and Supplementary Data 1.



120 *Figure 2: Harmonised expected revenues for each offshore wind farm auctioned in Europe. Each
symbol shows the planned start date of operation against the harmonised expected revenue. Lines
show the lognormal regression of expected revenue against time across all countries, covering all
bids and the most recent bids (since 2015). Shaded areas depict ± 1 standard deviation on each
regression. Wholesale electricity prices are assumed to remain constant in real terms when deriving
revenue beyond the end of the support duration. Other price scenarios are shown in
125 *Supplementary Figures 1 & 2.**

Comparing the harmonised expected revenues in Figure 2 with the raw bids reveals substantial
differences: The raw bids range €0-150 /MWh, whereas expected revenues are €50-150 /MWh,
with wind farms due after 2020 converging towards a range of €50-70 /MWh. From this

130 analysis we cannot identify one country that consistently creates lower bids than others,
despite varying site conditions, auction criteria and level of competition. A capacity-weighted
logarithmic regression through all auction results yields a reduction in the harmonised revenue
requirement of 5.8% per year, with a standard error of the regression of $\pm 1.1\%$. When
135 considering the more recent auctions, with a start date from 2015 onwards, this rate increases
to $11.9 \pm 1.6\%$ per year. Results for individual countries are presented in Supplementary Table 2
and Supplementary Figure 2. A logarithmic fit was chosen to ensure that regression results
cannot fall below zero. The increased rate of cost reduction indicates that auctions may have
helped to improve efficiency in the offshore wind industry.

Large differences between auction date, final investment decision (FID) and planned
140 commencement of operation can be noted. For some zero bids in Germany, more than five
years lie between the auction result and commencement of operation, whereas several wind
farms in the UK made FID on the day of winning the auction or shortly after. This gives German
wind farm developers more time for turbine costs to decrease and lets the bids appear more
in line with each other.

145 Figure 2 shows that harmonised expected revenues for several projects have fallen below
 $\text{€}50/\text{MWh}$. This locates offshore wind towards the lower end of estimated LCOE for fossil
generators²². Such comparison must be caveated though, as these revenues will only reflect
costs in perfectly competitive markets, and cost comparisons between variable renewables and
dispatchable fossil-fuelled generators are subject to ongoing debate around integration
150 costs³⁰⁻³².

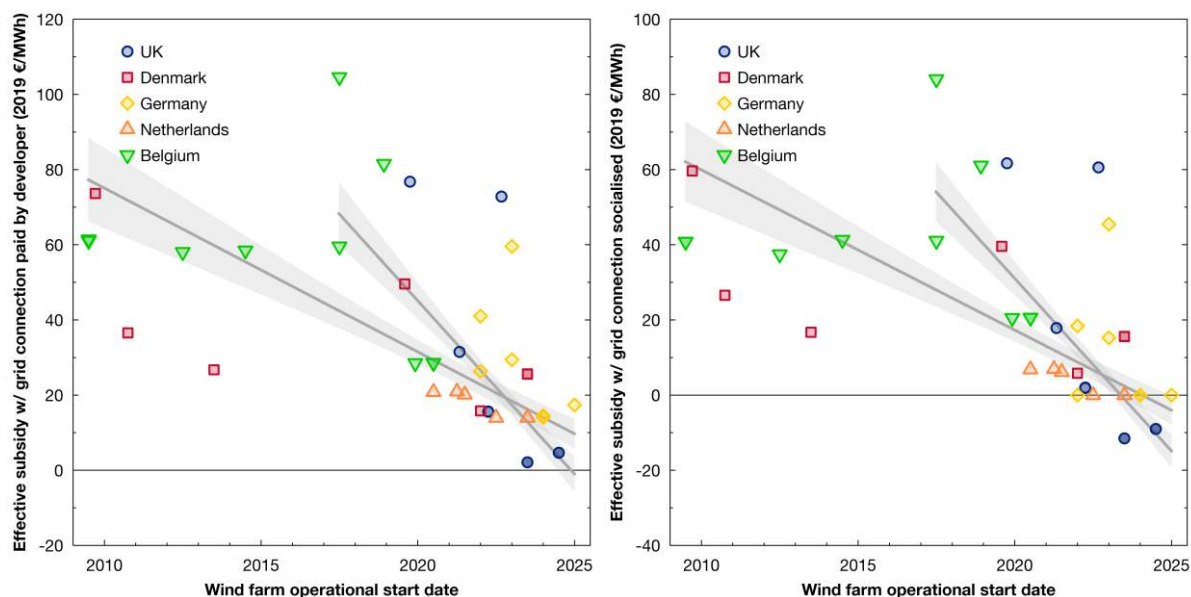
The harmonised expected revenue of most projects depends on the future development of
wholesale prices. First, wholesale prices are directly received by projects under 1-sided CfDs
provided they are above the bid. Second, with an assumed technical lifetime of 25 years, all
projects are expected to sell their output on the wholesale market after their auction
155 remuneration expires. Medium- to long-term wholesale prices are therefore of particular
importance to these results, but at the same time, they are highly uncertain. This is not only
an academic exercise but an issue that the bidding companies must deal with, and one that
the energy industry is, in general, familiar with. Estimates can be made using electricity market
models to quantify the future energy system, but these depend on numerous uncertain
160 assumptions, such as the future CO₂ allowance price. The fact that we find similar revenues for

wind farms across several countries in the future would, however, indicate that several bidders have arrived at comparable outlooks on the future power prices.

The results in Supplementary Figure 2 consider the sensitivity of these results to the future trajectory of wholesale power prices. We explore this uncertainty by presenting a range of prices derived from independent sources. First, we consider the European Commission's 2016 Reference Scenario, and scale projected prices from 50-150%. This accounts for structural changes in the electricity market (e.g. increased penetration of renewables and higher carbon prices), but is fundamentally a theoretical modelling exercise. To complement it, we take the average power prices from 2004-2018 in each country and apply a constant real-term annual growth rate from -2% to +2%, which more than spans the range of historical price growth seen in these countries.

We argue that the long-term prices are probably the better indicator. The EU 2016 Reference Scenario prices are set to double electricity prices in many countries between 2010 and 2020 and therefore we exercise caution using this price forecast alone. We provide the results of all described price scenarios in Supplementary Figure 2 as well as the means to test other price trajectories using Supplementary Software 1. From this assessment, we observe the large influence that the power price has on the harmonised revenues, an investigation that each bidder will have to face individually.

Moving towards subsidy-free offshore wind



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Figure 3: Effective subsidy for each offshore wind farm auctioned in Europe. Panel a assumes grid connection costs should be paid for by the developer and thus considered as part of the wind farm. Panel b assumes these should be socialised and considered as part of the overall grid infrastructure. Each marker shows the effective subsidy for each wind farm at the planned date of operation. Lines show the linear regression of effective subsidy against time across all countries, covering all bids, and recent bids from 2015 onwards. Shaded areas depict ± 1 standard deviation on each regression. Wholesale electricity prices are assumed to remain constant in real terms when calculating support level from each CfD. Other price scenarios are shown in Supplementary Figure 3.

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The harmonised expected revenues (including the support payments expected under each wind farm's CfD contract) can be compared to the expected revenues that would be generated on the wholesale market alone (as if each wind farm were a purely merchant project). The difference between these allows us to derive the effective subsidy that is being paid to each farm, as shown in Figure 3. This is the difference between the discounted income stream due to the RES support payments. If the expected harmonised bid is equal to the expected wholesale market price, the effective subsidy is zero and the project is subsidy-free. These subsidies are the amount of money that will have to be refinanced through the RES support scheme.

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200 This study does not deal with the question of whether grid construction costs should be paid
by developers (the allocation-by-cause principle) or be paid by society (socialised as part of a
country's infrastructure investment). Figure 3 therefore presents both versions, keeping in
mind that grid costs account for €13 /MWh on average. It must be noted that most countries
have chosen the latter option, and their funding models for grid infrastructure differ greatly.
205 In the UK, socialised grid costs are borne jointly by generators and demand through
transmission charges for the transmission grid whereas offshore connection is paid by the
wind farm only. Germany recovers grid charges (including for new offshore wind farms)
through final consumer bills only. Offshore grid connection costs remain a key uncertainty
despite efforts to gather data^{23,33,34} and model³⁵ these costs for each wind farm (given in
Supplementary Data and Supplementary Table 1).

210 With socialised grid connection costs, subsidies have reached –€12 /MWh for the latest UK
auction, with a large cluster between –€10 /MWh and €20 /MWh. This implies that several wind
farms could expect to earn less money under the RES support scheme than under wholesale
market terms alone (even with expected revenue cannibalisation effects). With the grid costs
being paid for by the developer, the lowest effective subsidy is at €2 /MWh when assuming
215 wholesale power prices grow at 0% p.a. in real terms. Even slight growth in market prices
(above 0.28% p.a.) means that the cheapest wind farms are therefore subsidy-free.

It can make sense for companies to forgo revenues in exchange for their predictability. The
funding from the RES support scheme minimises risk in several ways. Most notably, exposure
to future market prices is reduced, which in turn can reduce the cost of financing these
220 multi-billion Euro projects, allowing for a lower LCOE in the first place³⁶. Secondly, using the
RES support scheme in all cases comes with monetary (e.g. socialised grid connection) and
non-monetary privileges (e.g. site allocation, consenting and planning) thus limiting the
pre-development costs for each project.

225 Across all auctions and with grid support paid for by the developer, the expected support is
falling by €5.30 ±1.00 /MWh per year. Considering only auction results from the last 5 years,
the support has been falling even more dramatically, by €10.20 ±1.60 /MWh per year, implying
that offshore wind farms built from 2025 onwards will on average be subsidy-free if these cost
reduction rates continue. The rates of reduction are virtually identical if grid costs are
socialised, with €5.20 ±0.90 /MWh (all auctions) and €10.20 ±1.50 /MWh (2015-2019) per year.

230 This suggests that the era of subsidy-free wind farms will begin in 2023 based on recent
auctions, or in 2024 when all data are considered.

Sensitivity to future power prices

To analyse the significance of future price developments for subsidy-free offshore wind, we
vary future wholesale price assumptions and calculate resulting effective subsidies. Figure 4
235 summarises how the effective subsidies are affected by wholesale electricity prices changing
by between -2.5% and $+2.5\%$ per annum in real terms.

Countries which offer 2-sided CfDs (UK, Belgium and Denmark) show a greater sensitivity to
future wholesale prices, as higher reference prices can see farm developers paying money back
to society. The minimum bids received in Germany and the Netherlands show no sensitivity to
240 power prices (horizontal lines in Figure 4 right panels). These 1-sided $\text{€}0/\text{MWh}$ bids will only
see support paid if wholesale prices turn negative, which is only expected in a minority of hours
per year (see Methods). If these wind farms ought to pay for grid connections, this would be
added onto the zero bid (Figure 4, top-right). It is noteworthy that the UK with its latest auction
appears to offer the lowest support payment for any wind farm, with an effective subsidy of
245 less than $-\text{€}12/\text{MWh}$, which in part is due to the implementation of a two-sided CfD whilst
power prices are predicted to increase by the government³⁷.

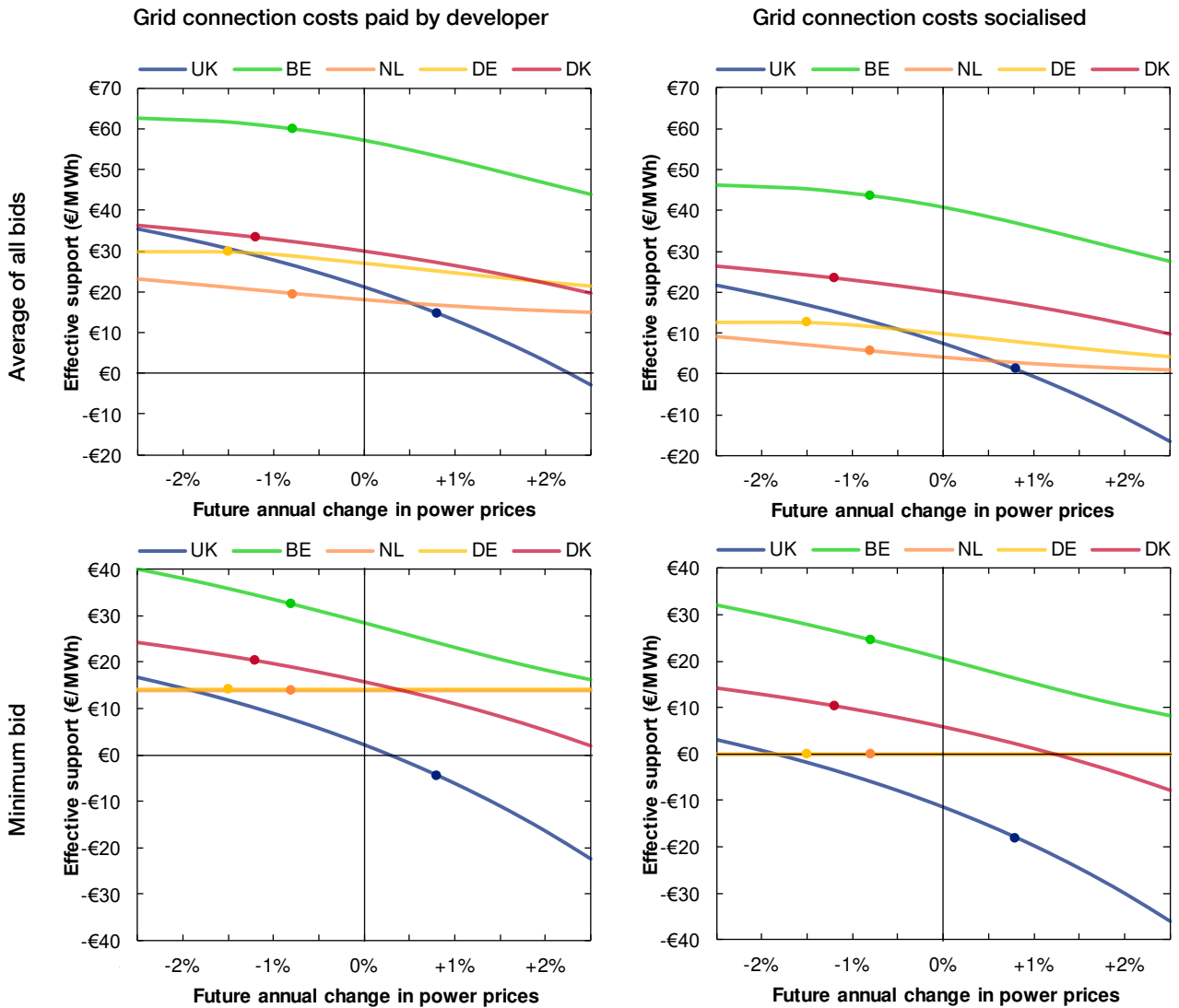


Figure 4: Effective subsidy given to offshore wind farms as a function of future real-terms growth in wholesale power prices. The panels show four variants, considering the average bid (panels a and c) and minimum bid (panels b and d) received in each country, assuming grid connection costs should be paid by the developer (panels a and b) or should be socialised (panels c and d). Circles on each line indicate the average real-terms growth in wholesale power between 2004 and 2018.

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The results of the latest UK auctions indicate that if wholesale prices continue to see moderate growth of above 0.3% p.a. (which is below the historical rates) then these farms will receive negative subsidy: and will be the first to pay money back to society. If grid construction costs are assumed to be socialised, UK offshore wind farms would be subsidy-free even if power prices fell by more than 1.5% p.a. in real terms. Wind farms in Germany and the Netherlands are subsidy-free under any price scenario, whereas Belgian are trailing the in terms of effective

subsidy. The last auction in Denmark took place in November 2016, resulting in a
260 comparatively high effective subsidy, but still showing comparable cost progression to the
industry as a whole.

Discussion & Conclusions

The era of 'subsidy-free' offshore wind turbines has begun. This conclusion is founded on zero
bids in the Netherlands and Germany which effectively track wholesale power prices, and bids
265 around £40 /MWh in the UK which will be below future wholesale prices if historical growth
rates are maintained. Recent projects in the Netherlands have bid €0 /MWh and will pay land
lease, indicating that offshore wind is at the point where it will likely to pay money back to the
system.

Despite significant variations in auction design, we find that once bids are harmonised the
270 expected lifetime revenues of wind farms are homogenous across countries, without specific
outliers that would be attributable to the auction design. This implies that policy makers have
managed to create auction designs which fairly reflect the actual costs of developing offshore
wind farms, and that the specific auction design is not particularly influential on the outcome.
This finding could aid in designing the upcoming auction schemes for offshore wind globally.
275 It also opens the door to further questions, such as whether auctions are suitable policy
instrument for driving down costs in less mature technologies such as wave, tidal, and floating
offshore wind energy. The study does not unveil whether policymakers should discontinue
support for renewables once price-parity is achieved, as the revenue stabilisation offered by
CfDs has been instrumental in making this possible for offshore wind².

280 Harmonising bids into expected revenues creates a proxy for the actual costs of offshore wind
which closely relates to the levelised cost of electricity (LCOE) plus profit for the company. We
show that wind farm costs are decreasing across Europe in a uniform fashion, having undercut
the €50 /MWh threshold recently. This makes offshore wind a competitive way to produce
electricity and is an extraordinary story of success for a relatively young industry. It is possible
285 that future wind farm developers will aim to build 'merchant' offshore wind farms without
financial support, completely free of government support. Development costs may however
rise as wind farms move to less favourable locations or to less mature technologies.

There are several reasons why the harmonised expected revenues we report may diverge from underlying costs. Auction results can be seen as an 'option to build' which need not be realised if costs do not fall sufficiently³⁵. However, the final investment decision (FID) has already been taken for some recent bids (including the cheapest ones), including one on the day of the auction result (see Supplementary Data and Supplementary Table 1). We interpret these tangible financial commitments as a sign of developers' intent to go forward with the awarded bids. The breadth and heterogeneity of our sample (41 projects in different countries and auction rules) also suggests that such 'option bidding' effects are unlikely.

The presence of market power could also distort revenues away from underlying costs in either direction. If the industry is going through a shakeout period, investors may bid below cost to deter new entrants from providing competition, accepting short-term losses in return for gaining market share and higher long-term profits. This would mean true costs were above the harmonised expected revenues we report. Alternatively, an oligopoly of large developers could exploit the lack of competition to artificially inflate auction prices. This would mean true costs lie below our harmonised expected revenue, and that offshore wind was more competitive than our analysis suggests.

To facilitate market access, electricity generated from offshore wind is often sold through power purchase agreements (PPAs), especially in the UK. PPAs provide long-term revenue stability and offtaker risks are assumed by a counterparty. These could yield agreed prices below the wind-weighted average wholesale price used here, if for example limited competition between providers facilitated excess profits. This would lower expected revenues, suggesting that offshore wind is cheaper than our results indicate. Evidence on the discounts offered in PPAs is not publicly available, so we cannot establish whether they are reflective of the underlying revenue cannibalisation found across the investigated countries.

Policymakers can take the rapid price decreases shown here as evidence that offshore wind will deliver in the future as a low-cost and low-carbon technology. Hence, the initial spending made on support schemes has been successful in helping to create a new industry. This opens up questions around the next steps to support the further rollout of offshore wind. This will likely entail designing schemes which move away from support payments and instead focus on planning issues, market integration, grid connection and ease of access to financing.

Building on the story of success, policymakers may want to extend their attention to support less mature technologies such as floating offshore wind, which would allow access to deeper

320 waters with higher wind speeds. These technologies are currently at a less mature stage but
may prove vital in harnessing the world's best wind resources².

Our findings are derived from wind farms in Europe, but hold relevance for other parts of the
world. Europe has been at the forefront of offshore wind due to its favourable conditions of
relatively shallow waters and high wind speeds. This enabled cost-efficient monopile
325 foundations to be used in most, but not all offshore wind projects. One-fifth of the capacity
we consider uses jacket or gravity-based foundations. Regions of Asia and North America also
benefit from shallow waters², and could expect some of the learning of Europe (e.g. turbine
size increase, construction techniques, financing) to play a key role in achieving similar results.
The rates of price reduction found here may prove equally applicable to other world regions,
330 and to other foundation types if they achieve comparable scale up, albeit from a higher starting
price level. Regions that are yet to develop a supply chain and innovation system for offshore
wind energy may require longer for these technologies to become subsidy-free.

As decarbonisation of the world's electricity systems gains traction, attention must be given to
the issues of balancing and flexibility, and to the decarbonisation of heat, transport and
335 industrial applications. With offshore wind at competitive prices, numerous sector-coupling
applications are coming into reach that could not have been imagined as cost-competitive just
a decade ago.

Methods

340 General principle

Both auction and product design vary significantly between different countries. We identified major differences from a review of government literature and present these in Supplementary Data and Supplementary Table 1. Many of the differences directly influence the costs and/or revenues of projects, and thus influence the bids. This is obvious for the support duration but
345 also e.g. for one-sided vs. two-sided support schemes where the former has an implied option to profit in the event of future wholesale price increases. Consequently, one-sided CfDs require lower bids to make projects profitable.

The differences between auction designs were accounted for by developing a methodology to harmonise the winning bids in European auctions for offshore wind. Our harmonization
350 accounts for the most significant factors identified in Table 1. The bids are harmonised using a monthly cash-flow analysis, which addresses seasonal variation in wind capacity factors and allows volume-based support schemes to expire part-way through a year. Hence, we define the 'harmonised expected revenue' as the (discounted) average revenue per MWh of electricity generated over the lifetime of the project. This can be interpreted as the bid that would give
355 an equivalent NPV over the project life if it were offered into a hypothetical auction that offered a 2-sided CFD with 25-year duration, indexed with inflation. On this basis, we can compare the bids (and the implied expected revenues) over each wind farm's entire lifetime, and e.g. include revenues for later in the project's lifetime when support has run out. Details on each wind farm were sourced from developer and manufacturer websites and professional databases
360 (e.g. 4COffshore) as well as renewables and offshore wind news outlets, primarily ³⁹⁻⁴³.

The following sections detail how we adjust each bid's strike prices to obtain harmonised expected revenue. Each adjustment changes the monthly cash-flow, which results in monthly payments to the wind farm from the market and the 'effective' payments from the RES support scheme. The payment over the lifetime of the project is then aggregated. This yields the
365 average payment per MWh received for the total (supported) payments. We also calculate the payments which would have resulted if the electricity would have been sold exclusively on the wholesale market. Finally, we calculate the difference between both, representing the actual average subsidy paid.

Harmonising length of payments

370 Support durations vary between projects. For most projects, legislation specifies an explicit time duration d_s . For the Danish projects with an energy-based limit, we calculated the resulting support duration $d_{s,DK}$ as follows:

$$d_{s,DK} = \frac{E_s}{P_{inst} * h_y * CF} \quad (1)$$

375	With	$d_{s,DK}$	Support duration for Denmark
		E_s :	Supported Energy
		P_{inst} :	Installed Capacity
		h_y :	Hour in one year
		CF	Capacity factor

The capacity factor CF is estimated using the Renewables.Ninja model with the appropriate wind turbine model for each project^{44,45}. The numbers are validated against external data points where possible^{46,47}, and are found to be highly correlated. For projects using next-generation turbines we developed parametric power curves⁴⁸ if these were not publicly available. While we attempt to use representative capacity factors, these have no influence on the main results presented as both harmonised revenue and expected support are normalised per MWh. They can have second-order effects due to output-dependent support duration, but this yields minimal changes.

External factors that could influence capacity factors over the farm's lifetime (such as degradation^{49,50}, wake effects⁵¹, stalling⁵² or climate change⁵³) are not considered as they are currently subject to much uncertainty. These could be incorporated once better understood using the cashflow models that we make available open source.

390 We model each wind farm's revenue over its whole lifetime, both from their strike price and the wholesale market alone. While the total lifetime of offshore wind projects is still debated, most publications estimate them between 20 and 30 years (e.g.⁵⁴⁻⁵⁸). Therefore, we assume that the lifetime d_l for all projects is 25 years. This is needed to calculate the income after RES support from the auction has run out. Variations to this assumption have limited impact on results due to the effect of discounting.

Strike prices and market revenues

As explained above, projects' annual revenues are determined either based on the strike price or based on the market price. Before we can identify which applies in any given year for any given project, we first must derive a consistent time series for both. Among other things, we
400 normalise currencies to Euros and all values to real monetary values for the year 2019.

We assume that wind farms sell their output on the wholesale market (or at least receive payments based on the sold electricity's wholesale market value). Historic wholesale power prices are obtained from ENTSO-E and Open Power Systems Data^{59,60}. Large uncertainties exist regarding the future of power prices, in particular as we need them more than 25 years in the
405 future. The influence of power prices is paramount for our considerations as it affects the bids in a significant way. Obtaining consistent price forecast scenarios is challenging as the national price forecast would show inconsistencies on the input assumptions (fuel prices, CO₂-emission prices, etc.).

To address the uncertainty around future power prices we choose a diversified approach.
410 (1) The EU 2016 Reference Scenario PRIMES model provides a consistent output covering all of Europe⁶¹, which forecasts annual average power prices for every fifth year until 2050. It is to note that the prices are significantly higher than today's prices. Therefore, we multiply the prices provided with factors of 0.5, 1.0, and 1.5 to create an understanding of the impact of price variations. (2) Whilst best efforts have been made to model future power prices, we aim
415 to mitigate the influence of modelling altogether, by using the average annual power prices to establish the long-term price variations. We use long-term prices (2004-2018) averages and assume an annual growth between -2% and 2% in 1% steps based on this.

We can establish that the time-weighted average wholesale price for the time period t is dependent on the assumed price growth pr . Latter can either be given in % growth p.a., or
420 predetermined by external inputs, such as the time series from the EU 2016 Reference Scenario.

$$twp_t = twp_0 * pr^{\frac{t}{12}} \quad (2)$$

With:

twp_0	time-weighted average wholesale price at project start
pr	rate of price growth
t	time in months since project start

425 However, it is well known that electricity generation from wind does not receive the average
price⁶². The price that offshore wind turbines will be able to realise on the market on average
shall be called 'capture value' (also referred to as market value factor, see⁶³). We derive a
capture value is a multiplier typically below one which subtracts from the average power prices
based on the linear interpolation between today's empirically determined data and the price
430 scenarios for 2030⁶⁴. The capture value cr is a multiplier which determines the percentage that
wind can capture of the time-weighted wholesale price. It is a large source of uncertainty for
wind farm developers, as it is expected to decrease over time. The results from our modelling
for the country-specific average values are shown in Supplementary Table 3:

$$cr = \frac{\sum_h output_h * price_h}{\sum_h output_h * \overline{price}} \quad (3)$$

With:

$output_h$	output in hour h
$price_h$	price in hour h
\overline{price}	time-weighted average price across all hours
h	hours

435

This further allows us to calculate the wind-weighted average wholesale price wwp_t :

$$wwp_t = twp_t * cr_t \quad (4)$$

Linear interpolation of the market value cr between today and 2030 is assumed and can be
440 justified using the different scenarios in the UK National Grid Future Energy Scenarios annual
publications⁶⁵ shown in Supplementary Figure 5. The modelling shows a roughly linear relation
between installed wind power and the merit-order effect. We therefore can assume a linear
relationship in our assessment as well, both for the merit-order effect as well as the capture
value derived from hourly time series analysis between today's data and 2030's estimation.

445 Determination of strike price time series is relatively straightforward: In a first step, we convert
strike prices to € (if applicable) using market exchange rates⁶⁶. In a second step, we convert
nominal values to real monetary values of 2019 using country-specific averages for the years
1998 to 2017⁶⁷. The long-term inflation for all five countries was 1.65% p.a.. For the UK
auctions, the strike price is adjusted by the inflation rate, which derived from the data⁶⁷ and
450 amounts to 1.89% p.a.. All available inflation data is shown in Supplementary Table 4. Note
that the indexation measure used is based on the GDP deflation index rather than consumer

price indexation, as often used by central banks. This is believed to get a more accurate representation of indexation⁶⁸. The strike price SP_t at time t is by auction design either to be discounted or kept constant in real terms:

$$SP_t = \frac{SP_0}{ir^{t/12}} \quad (5)$$

455 With: SP_0 Strike price at project start
 ir Inflation rate (GDP deflation)
 t Time in months since project start

Determining revenues during support duration

460 At this point, we have two normalised time series for the years of the support duration (the strike price time series and the market revenue time series, both calculated above). Which one is applicable is determined as follows:

For projects under two-sided CfDs, the strike price essentially determines a fixed payment. Hence, the relevant time series during the support duration is the strike price.

465 For projects under one-sided CfDs, the situation is more attractive: These projects have the right (but not the obligation) to choose the market revenues even during support duration in case they exceed the strike price. We address this optionality in two ways: first, we select the maximum of monthly strike price and market revenue as the resulting revenue during those months. This is in analogy to the option's intrinsic value. Second, the option has an additional 'time value' – reflecting the fact that the wholesale revenue described above is uncertain. It
 470 could increase – and the projects under one-sided CfDs would profit. It could also decrease, but the projects under one-sided CfDs would lose less (as they can choose not to exercise the option and sell at the strike price). Note again that in contrast to option terminology, we use "strike price" equivalent to "bid price" in this paper.

475 We further establish the uplift premia up as a function of the strike price sp . The uplift premia term describes the additional income for the generator over the market prices that is caused by capturing the upside under a 1-sided CfD. The uplift premium is a function of the ratio between strike price and wholesale market price and differs for every wind farm.

Supplementary Figure 4 allows deriving the value for each wind farm. It is not applicable for 2-sided CfDs:

$$up(sp) = \frac{\sum_h output_h * \max\{price_h, sp\}}{\sum_h output_h * price_h} \quad (6)$$

480 With: $output_h$ output in hour h
 $price_h$ price in hour h
 sp strike price
 h hours

Harmonising bids

485 Having calculated one specific revenue time series for each project, we then adjust these time series to reflect the (country-specific) weighted average cost of capital (WACC). This discount rate is also called the real cost of capital (over and above the inflation rate). Financing costs of wind power projects are dependent on the local funding conditions and ease of access to capital. Supplementary Table 5 presents WACC from different sources for onshore and
 490 offshore wind, with offshore wind being more expensive. The average from across these sources was used, with country-specific values ranging from 6.2–7.9%, and the average across all countries being 7.3%.

As all input parameters are defined now, the revenue for three different cases can be calculated. (1) Revenues without any RES support scheme payments $r0_t$, (2) revenues under a
 495 1-sided CfD $r1_t$ and (3) under a 2-sided CfD $r2_t$.

$$revenue = \begin{cases} r0_t = output_t * wwp_t & no\ support \\ r1_t = r0_t * up_t & 1 - sided\ CfD \\ r2_t = SP_t & 2 - sided\ CfD \end{cases} \quad (7)$$

With: $r0_t$ Revenue at market prices

The 'harmonised expected revenues' HER for each case then results in:

$$HER = \begin{cases} \sum_t \frac{r0_t}{(1+dr)^t} & \text{no support} \\ \sum_{t \in ST} \frac{r1_t}{(1+dr)^t} + \sum_{t \notin ST} \frac{r0_t}{(1+dr)^t} & \text{1-sided CfD} \\ \sum_{t \in ST} \frac{r2_t}{(1+dr)^t} + \sum_{t \notin ST} \frac{r0_t}{(1+dr)^t} & \text{2-sided CfD} \end{cases} \quad (8)$$

With: dr Discount rate
 ST Support time from 1 to sd
 sd Support duration in years

500

This allows us to calculate the effective subsidy ES as follows:

$$ES = HER - \sum_t \frac{r0_t}{(1+dr)^t} \quad (9)$$

505

510

In a final step, we account for the fact that some auction designs pay for grid connection and others put the costs onto the developer. Harmonising the effective subsidy ES by subtracting the grid costs CG accounts for the difference in the auction conditions and happens after the cash-flow analysis. The implied cost differences can be regarded as a significant subsidy (see³⁵). We have collected wind farm-specific connection costs were available in the overall data table in Supplementary Data and Supplementary Table 1, averaging country-specific data where primary data was missing. In some cases (e.g. Germany) connection costs are given in €/kW following the methodology in³⁵, which then can be converted into €₂₀₁₉/MWh using capacity factors. The UK is the only country where wind farms pay in full for the grid connection. The effective subsidy with grid connection $ES_{GridConn}$ therefore only applies to the UK auction results, as $ES_{GridConn} = ES_{UK}$. For all other countries $ES_{NoGridConn} = ES_{DK,NL,BE,DE}$. The relationship between $ES_{GridConn}$ and $ES_{NoGridConn}$ are:

$$ES_{NoGridConn} = ES_{GridConn} - CG$$

515

In the results section of the paper, we opt to show results with and without grid connection costs as equally valid options. The discussion on cost recovery of grid infrastructure is to be held at a different occasion.

Data availability

The datasets used in this study are available in the ZENODO repository as Supplementary Data, DOI: 10.5281/zenodo.3840134 (<https://doi.org/10.5281/zenodo.3840134>). This includes the raw data for all results presented here and input data for Figures 1-4.

Code availability

The cashflow model produced for this study is available in the ZENODO repository as Supplementary Software 1, DOI: 10.5281/zenodo.3733604 (<https://doi.org/10.5281/zenodo.3733604>). The model is set up to recreate results of this paper. Please refer to the README in the instructions.

References

1. IRENA. *Renewable Energy Capacity Statistics 2020*. (2020).
- 530 2. IEA. *World Energy Outlook 2019*. (OECD, 2019). doi:10.1787/caf32f3b-en
3. European Commission. *A Clean Planet for all: A European long-term strategic vision for a prosperous, modern, competitive climate neutral economy - In-Depth Analysis in Support of the Commission (Communication Com (2018) 773)*. (2018).
4. Bosch, J., Staffell, I. & Hawkes, A. D. Temporally-explicit and spatially-resolved global onshore wind energy potentials. *Energy* (2017). doi:10.1016/j.energy.2017.05.052
- 535 5. Arent, D. *et al.* *Improved Offshore Wind Resource Assessment in Global Climate Stabilization Scenarios*. (2012). doi:10.2172/1055364
6. Toke, D. The UK offshore wind power programme: A sea-change in UK energy policy? *Energy Policy* **39**, 526–534 (2011).
- 540 7. Green, R. & Vasilakos, N. The economics of offshore wind. *Energy Policy* **39**, 496–502 (2011).
8. PwC. *Unlocking Europe's offshore wind potential. Moving towards a subsidy free industry*. (2018).
9. Aurora Energy Research. *The new economics of offshore wind*. (2018).
- 545 10. NewEnergyUpdate. *Offshore wind developers see ripe conditions for zero-subsidy bids*. *New Energy Update* (2018). Available at: <http://newenergyupdate.com/wind-energy-update/offshore-wind-developers-see-ripe-conditions-zero-subsidy-bids>.

11. Creutzig, F. *et al.* The underestimated potential of solar energy to mitigate climate change. *Nat. Energy* **2**, 17140 (2017).
- 550 12. Schmidt, O., Hawkes, A., Gambhir, A. & Staffell, I. The future cost of electrical energy storage based on experience rates. *Nat. Energy* **2**, 17110 (2017).
13. Heptonstall, P., Gross, R., Greenacre, P. & Cockerill, T. The cost of offshore wind: Understanding the past and projecting the future. *Energy Policy* **41**, 815–821 (2012).
- 555 14. Vieira, M., Snyder, B., Henriques, E. & Reis, L. European offshore wind capital cost trends up to 2020. *Energy Policy* **129**, 1364–1371 (2019).
15. Dismukes, D. E. & Upton, G. B. Economies of scale, learning effects and offshore wind development costs. *Renew. Energy* **83**, 61–66 (2015).
16. Bolinger, M. & Wiser, R. Understanding wind turbine price trends in the U.S. over the past decade. *Energy Policy* **42**, 628–641 (2012).
- 560 17. Wiser, R. *et al.* Expert elicitation survey on future wind energy costs. *Nat. Energy* **1**, 16135 (2016).
18. Hoffman, C. S. Financial Viability of Offshore Wind on the Texas Gulf Coast. (The University of Texas at Austin, 2019).
- 565 19. Klinge Jacobsen, H., Hevia-Koch, P. & Wolter, C. Nearshore and offshore wind development: Costs and competitive advantage exemplified by nearshore wind in Denmark. *Energy Sustain. Dev.* **50**, 91–100 (2019).
20. Beiter, P., Musial, W., Kilcher, L., Maness, M. & Smith, A. *An Assessment of the Economic Potential of Offshore Wind in the United States from 2015 to 2030*. (2017). doi:10.2172/1349721
- 570 21. Noonan, M. *et al.* *IEA Wind Wind Technology Collaboration Programme Task 26: Offshore Wind Energy International Comparative Analysis*. (2018).
22. Lazard. *Lazard's levelized cost of storage analysis — version 12.0*. Lazard (2018).
23. OWPB. *Transmission Costs for Offshore Wind Final Report April 2016*. (2016).
24. Algemene Rekenkamer. *Focus on the cost of offshore wind energy*. (2018).
- 575 25. Aldersey-Williams, J., Broadbent, I. D. & Strachan, P. A. Better estimates of LCOE from audited accounts – A new methodology with examples from United Kingdom offshore wind and CCGT. *Energy Policy* **128**, 25–35 (2019).
26. Kitzing, L. Risk Implications of Energy Policy Instruments. (Department of Management Engineering, Technical University of Denmark, 2014).
- 580 27. EWEA. *Design options for wind energy tenders*. (2015).
28. Fitch-Roy, O. An offshore wind union? Diversity and convergence in European offshore wind governance. *Clim. Policy* **16**, 586–605 (2016).
29. Grothe, O. & Müsgens, F. The influence of spatial effects on wind power revenues under direct marketing rules. *Energy Policy* **58**, 237–247 (2013).
- 585 30. Partridge, I. Cost comparisons for wind and thermal power generation. *Energy Policy* **112**, 272–279 (2018).

31. Aldersey-Williams, J. & Rubert, T. Levelised cost of energy – A theoretical justification and critical assessment. *Energy Policy* **124**, 169–179 (2019).
- 590 32. Heptonstall, P., Steiner, F. & Gross, R. The costs and impacts of intermittency – 2016 update - A UKERC TPA report. (2017).
33. Cleijne, H. Cost of offshore transmission. *DNV GL* (2019). Available at: https://www.tennet.eu/fileadmin/user_upload/Company/News/Dutch/2019/20190624_DNV_GL_Comparison_Offshore_Transmission_update_French_projects.pdf.
- 595 34. Hundleby, G. Dong's Borssele Costs – a landmark Dutch auction by Giles Hundleby. *BVG Associates* (2016). Available at: <https://bvgassociates.com/dongs-borssele-costs/>.
35. Müsgens, F. & Riepin, I. Is Offshore Already Competitive? Analyzing German Offshore Wind Auctions. in *2018 15th International Conference on the European Energy Market (EEM)* 1–6 (IEEE, 2018). doi:10.1109/EEM.2018.8469851
- 600 36. Egli, F., Steffen, B. & Schmidt, T. S. A dynamic analysis of financing conditions for renewable energy technologies. *Nat. Energy* **3**, 1084–1092 (2018).
37. BEIS. Energy and emissions projections. (2019). Available at: <https://www.gov.uk/government/collections/energy-and-emissions-projections>.
38. WindEurope. Wind energy in Europe in 2018 - Trends and statistics. (2018). Available at: <https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2018.pdf>.
- 605 39. reNews. Home - reNews - Renewable Energy News. *reNews* (2019). Available at: <https://renews.biz/>.
40. 4COffshore. Home - 4C Offshore Website. *4COffshore* (2019). Available at: <https://www.4coffshore.com/>.
- 610 41. OffshoreWind.biz. Home - OffshoreWind.biz. *OffshoreWind.biz* (2019). Available at: <https://www.offshorewind.biz/>.
42. WindPowerOffshore. Home - Offshore wind power projects & companies. *Windpower Offshore* (2019). Available at: <https://www.windpoweroffshore.com/>.
43. RenewablesNow. Home - Renewable energy news & research. *RenewablesNow* (2019). Available at: <https://renewablesnow.com/>.
- 615 44. Pfenninger, S. & Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy* **114**, 1251–1265 (2016).
45. Staffell, I. & Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **114**, 1224–1239 (2016).
- 620 46. Aldersey-Williams, J., Broadbent, I. D. & Strachan, P. A. Analysis of United Kingdom offshore wind farm performance using public data: Improving the evidence base for policymaking. *Util. Policy* **62**, (2020).
47. Smith, A. Offshore Wind Capacity Factors. (2020). Available at: <https://energynumbers.info/>. (Accessed: 24th January 2020)
- 625 48. Saint-Drenan, Y.-M. *et al.* A parametric model for wind turbine power curves incorporating environmental conditions. *Renew. Energy* (2020).

doi:10.1016/j.renene.2020.04.123

49. Staffell, I. & Green, R. How does wind farm performance decline with age? *Renew. Energy* **66**, 775–786 (2014).
- 630 50. Olauson, J., Mikael, B., Edström, P. & Carlstedt, N.-E. *Wind turbine performance decline in Sweden. Wind Energy* **20**, (2017).
51. Porté-Agel, F., Bastankhah, M. & Shamsoddin, S. Wind-Turbine and Wind-Farm Flows: A Review. *Boundary-Layer Meteorol.* **174**, 1–59 (2020).
52. Zeng, Z. *et al.* A reversal in global terrestrial stilling and its implications for wind energy production. *Nat. Clim. Chang.* **9**, 979–985 (2019).
- 635 53. Hdidouan, D. & Staffell, I. The impact of climate change on the levelised cost of wind energy. *Renew. Energy* **101**, 575–592 (2017).
54. Ziegler, L. Assessment of monopiles for lifetime extension of offshore wind turbines Thesis. (Norwegian University of Science and Technology, 2018).
- 640 55. Geuss, M. Offshore, Act Two: New owner repowers 20-year-old wind farm off Swedish coast. *Ars Technica* (2018). Available at: <https://arstechnica.com/information-technology/2018/12/offshore-act-two-new-owner-repowers-20-year-old-wind-farm-off-swedish-coast/>.
56. Smith, P., Costa-Ros, M., Lange, B., Stiesdal, H. & Pollicino, F. Question of the Week: Are offshore projects built to last? *Windpower Monthly* (2014). Available at: <https://www.windpowermonthly.com/article/1320109/question-week-offshore-projects-built-last>.
- 645 57. Foxwell, D. Research claims 30-year lifespan is within reach for offshore wind projects. *Riviera Maritime Media* (2017). Available at: <https://www.rivieramm.com/news-content-hub/research-claims-30-year-lifespan-is-within-reach-for-offshore-wind-projects-28324>.
- 650 58. Kolios, A. & Martínez Luengo, M. The end of the line for today's wind turbines - Renewable Energy Focus. *Renewable Energy Focus* (2016). Available at: <http://www.renewableenergyfocus.com/view/43817/the-end-of-the-line-for-today-s-wind-turbines/>.
- 655 59. Wiese, F. *et al.* Open Power System Data – Frictionless data for electricity system modelling. *Appl. Energy* **236**, 401–409 (2019).
60. ENTSO-E. ENTSO-E Transparency Platform. (2019). Available at: <https://transparency.entsoe.eu/>.
- 660 61. Capros, P. *et al.* *EU Reference Scenario 2016. European Commission* (2016). doi:10.2833/9127
62. Twomey, P. & Neuhoff, K. Wind power and market power in competitive markets. *Energy Policy* **38**, 3198–3210 (2010).
63. Engelhorn, T. & Müsgens, F. How to estimate wind-turbine infeed with incomplete stock data: A general framework with an application to turbine-specific market values in Germany. *Energy Econ.* **72**, 542–557 (2018).
- 665 64. Collins, S., Deane, P., Ó Gallachóir, B., Pfenninger, S. & Staffell, I. Impacts of Inter-annual

Wind and Solar Variations on the European Power System. *Joule* **2**, 2076–2090 (2018).

- 670 65. National Grid. Future Energy Scenarios 2019. 162 (2019). Available at: <http://fes.nationalgrid.com/media/1409/fes-2019.pdf>.
66. World Bank. Official exchange rate (LCU per US\$, period average). *World Bank Database* (2019). Available at: <https://data.worldbank.org/indicator/PA.NUS.FCRF?locations=GB-DK-XC>.
- 675 67. World Bank. Inflation, GDP deflator (annual %). *World Bank Database* (2019). Available at: https://data.worldbank.org/indicator/NY.GDP.DEFL.KD.ZG?end=2017&locations=DE-DK-BE-GB-NL&name_desc=false&page=2&start=1971&view=chart.
- 680 68. Alcidi, C., Busse, M. & Gros, D. Is There a Need for Additional Monetary Stimulus? Insights from the Original Taylor Rule. *CEPS Policy Brief* (2016). Available at: <https://www.ceps.eu/wp-content/uploads/2016/04/PB342TaylorRule.pdf>.

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Author contributions

- 690 MJ, FM, IS and IR conceived the study and developed the analysis. All authors contributed to data gathering and data analysis. All authors wrote and edited the paper.

Competing interests

The authors declare no competing financial or non-financial interests.

Supplementary Material to *Offshore wind competitiveness in mature markets without subsidy*

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Supplementary Note 1.

The term Contract for Difference (CfD) stems from finance practice, where CfD is a derivative allowing traders to capture price movements, as a seller will pay the buyer the difference between the current value of an asset and its value at contract time. In renewable energy support application, they refer to a contract between the support provider (e.g. a government body) and a RES producer ensuring that the producer always receives (at least) an agreed guaranteed reference price for each produced kWh of energy. For this, the support provider pays the difference between the applicable market price and the agreed guaranteed price in each settlement period. Depending on the implementation of the CfD payments stream come from the RES support scheme only, or from other sources as well.

Especially the allocation of market upside to respectively the producer or the public creates a fundamental difference in the revenue streams. We thus distinguish here between two different types of CfD: two-sided and one-sided.

The type of CfD directly impacts the risk allocation, whether it is on the society or the developer to bear price forecasting risks. It has been an ongoing discussion amongst economist for some time now. Borenstein and Bushnell¹ point out that one of the key aspects of energy market liberalisation in general is that price risk should lie with investors: "Firms that do not have the security of a guaranteed rate of return on their investments will be more prudent in their capital

expenditures and the way they manage risk.” This paper cannot conclude whether either option is favourable over the other and therefore presents them without any preference.

A two-sided CfD is symmetrical and implies payments to and from the generator, offsetting any fluctuation of the spot market price, so that effectively the CfD strike price is achieved by the generators. Two-sided CfDs do not allow for the market upside to be monetised by the wind farm. This means that in times where the market price is higher than the CfD strike price, the payment direction is reversed, and the producer pays back some of the market revenue to the support provider. In Denmark, the ‘negative support payments’ are deferred and deducted from positive support payments in subsequent settlement periods.

Two-sided CfDs allocate the price risk solely on the funding counterparty. This allows for derisking of the investment which reduces the average cost of capital. The two-sided CfD is used in Denmark, the UK and the Netherlands.

Payments under a one-sided CfD occurs to the generator whenever the market price (or another applicable price) is below the agreed guaranteed price or strike price. This means that any shortfalls in the market price are compensated by the counterparty. Any market upside can be captured by offshore wind farms. Some type of one-sided CfD create a bigger market exposure for the wind farms, whilst securing a basic level of income. It requires a more thorough analysis of future prices to predict market outcomes. The one-sided CfD find application in Germany, Netherlands and Belgium.

Offshore wind farms under a sliding premium scheme, a specific type of one-sided CfD, receive payments from at least two sources. Firstly, wind farms are selling their energy on the market.

Secondly, support payments are provided on top of the wholesale market price up until the guaranteed price level is reached by the wind farms’ counterparty (often the grid operator, regulatory body or state-owned company). The guaranteed price, also called ‘strike price’ or ‘bid price’ is determined through the auction. We use ‘strike price’ and ‘bid price’ synonymously. For the purpose of this paper we are willing to forgo a detailed discussion on different RES support scheme and choose to provide further reading instead. The support payment is the difference between CfD strike price and e.g. the applicable market price (e.g. the hourly wholesale spot price or another agreed price index). The support is paid out as a time-variable premium to the producers by the counterparty. The compensation is determined by the difference between the guaranteed price and the price on the power exchange prices, but the developer can have a PPA or OTC contract to sell its power and may achieve a higher or lower than the price at the Exchange.

Supplementary Note 2.

Denmark was the first country to introduce offshore wind auctions in 2005, with the most recent one held in 2016. Each auction is negotiated as part of the parliamentary energy agreements and specifically designed for each auction round. It is the only country that limits the support length based on the cumulative energy production of the project.

The UK held auctions for CfDs in 2015, 2017 and 2019. The UK and Denmark are the only countries in the group to employ a two-sided CfD, and the UK is the only country to include transmission costs in bids, rather than these costs being socialised. Bids from UK auctions are also the only ones that are adjusted for inflation throughout the lifetime.

The Netherlands has had five offshore wind energy auctions since 2015³⁰. Initial assessments of site conditions and environmental impacts are conducted by the government prior to the auction, the results are available free of charge. The Netherlands is providing RES support for 15 years including a cap on the maximum support, within this period by limiting the number of subsidised full load hours. Zero bids have won in the last two auction rounds, with the latest project being obliged to pay in excess of €1m per year in land lease for the used area within the 12-mile zone (implying the wind farm receives below the average market price).

Germany's first auction took place in April 2017. Projects needed to showcase an advanced stage of development to be eligible to participate in the 2017/2018 auctions. Germany has attracted notable competition, with 29 projects bidding in total and only ten winners (so far). The support length of 20 years is the longest of all countries. Three out of four winning projects commissioned in the North Sea bid €0 /MWh in 2017. The second auction in 2018 on average had higher prices, despite further bids at €0 /MWh.

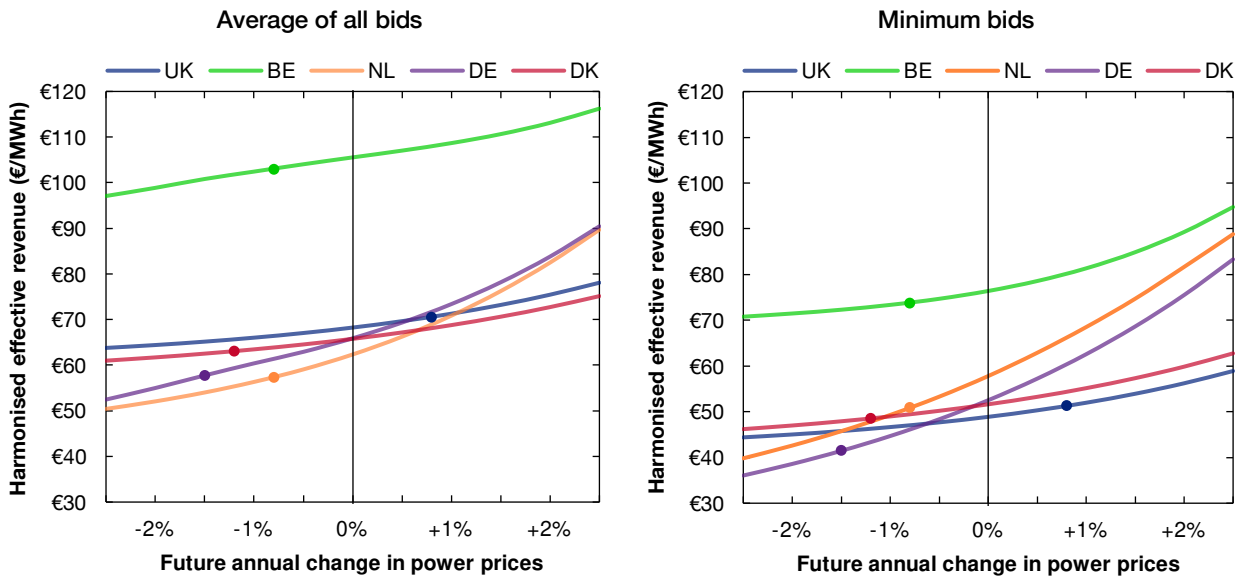
Belgium is running a certificate allowance system with an auction system due to be introduced in 2019. The conditions of Belgium's RES support scheme are comparable to those in the Netherlands, and subsidy levels are directly derived from their results³¹. It can therefore be seen as an extension of the Dutch auction scheme.

Despite these different designs, auctions across several countries have attracted competition between developers and yielded bids that are approaching the wholesale cost of electricity. Only one case (the 2010 Anholt tender in Denmark) had just a single bidder, partly due to tight restrictions in the auction design and the early development stages of the European offshore wind energy industry. Likewise, up to now only the Danish Rødsand 2 project failed to materialise as auctioned in 2006, because the reduced availability of wind turbines at that time had challenged

the business case post-auction. The project was successfully built in a second attempt, albeit at a higher price.

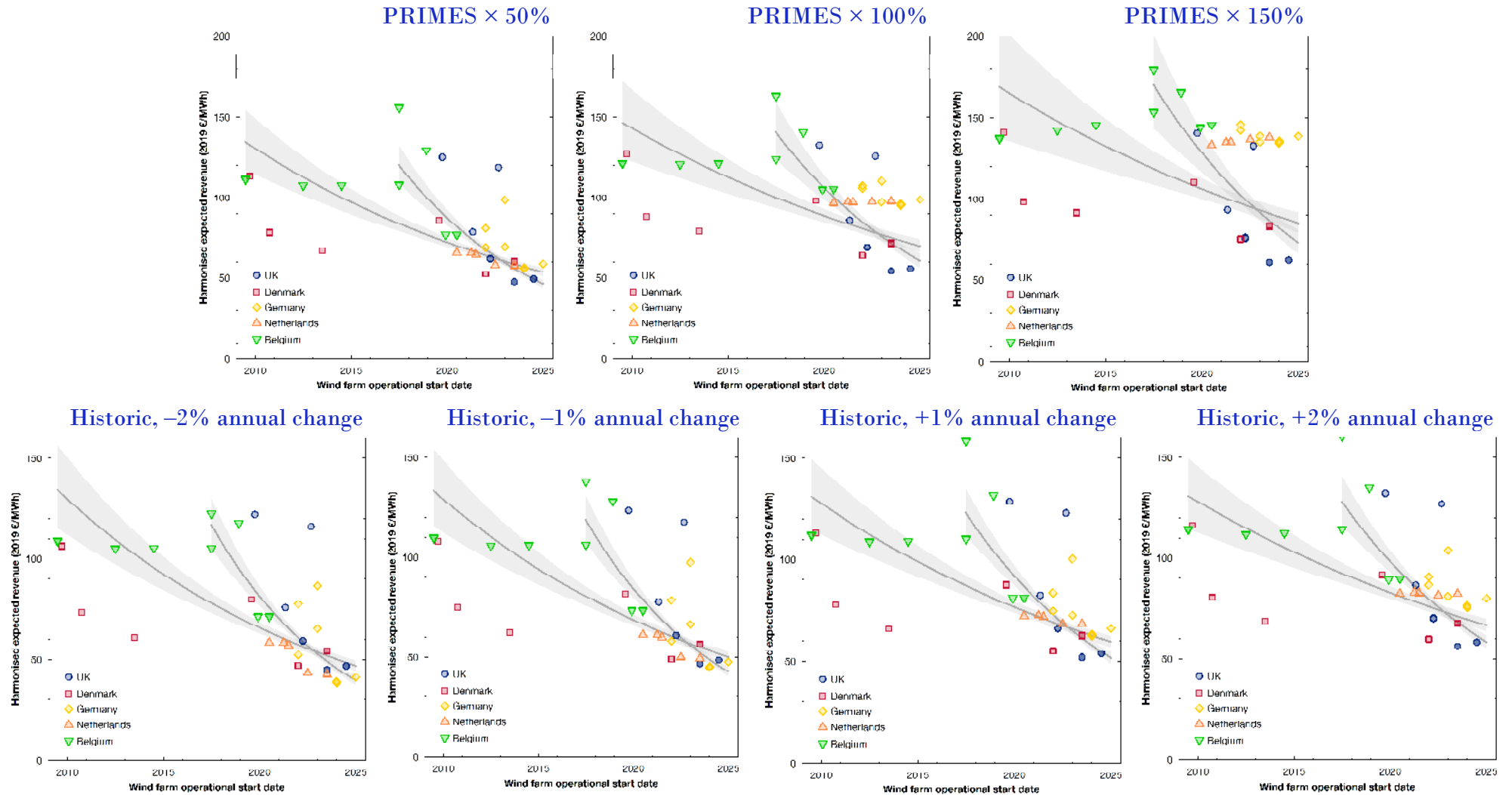
Supplementary Figure 1.

The sensitivity of harmonised expected revenue to future wholesale electricity prices.

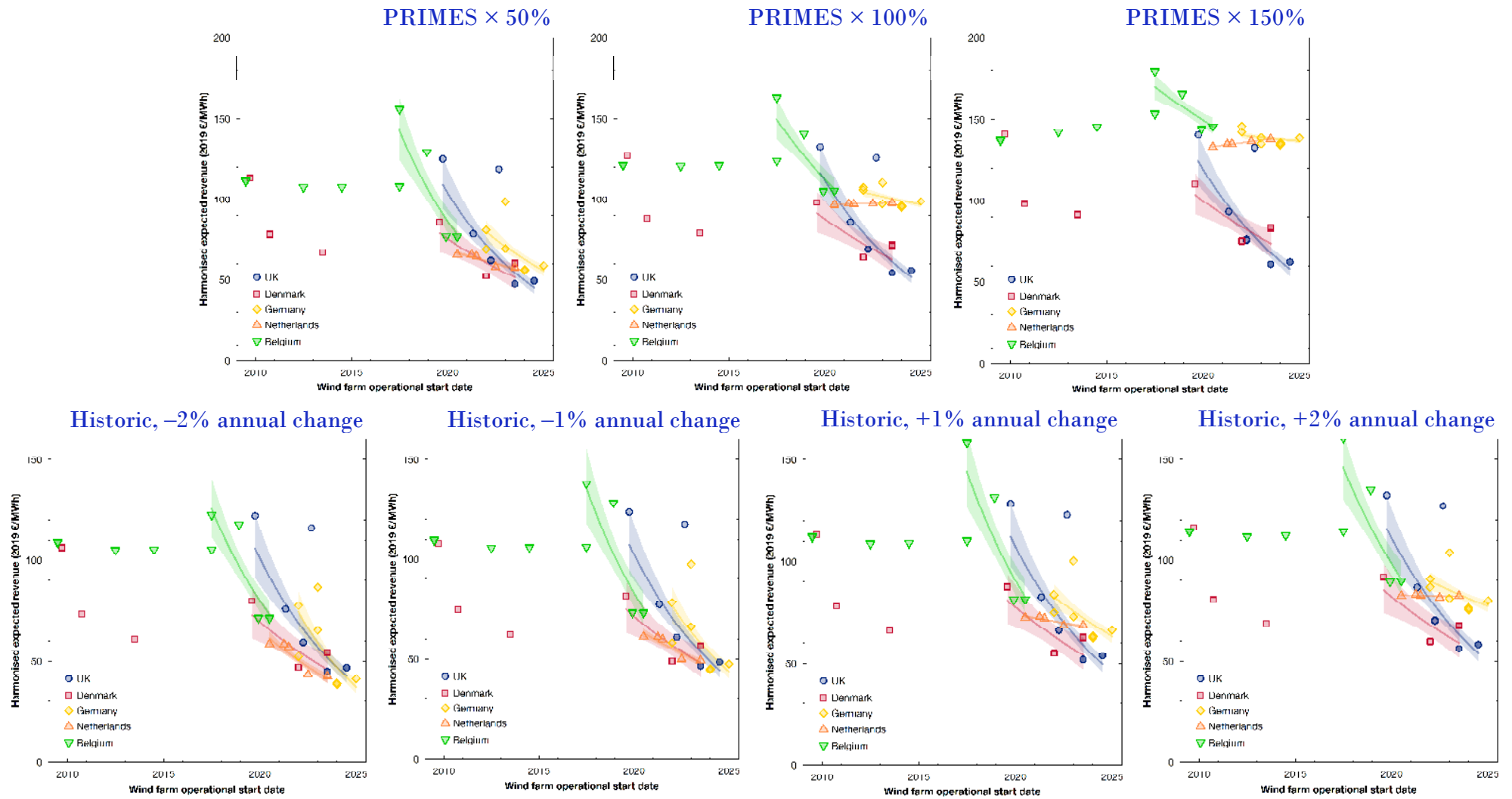


Supplementary Figure 2.

The harmonised expected revenues for various scenarios for future power prices. The following panels consider the prices emerging from the PRIMES model runs (scaled by 50%, 100% and 150%), and prices that evolve from the historic (2004-2018) averages with various annual rates of change.



The harmonised expected revenues (as above), highlighting individual trends for each country's bids since 2015.



Supplementary Table 1.

The rate of reduction for expected offshore wind revenues calculated for individual countries based on the auction results. The revenues are closely related to the levelised costs of electricity (LCOE) plus a profit margin for the developer. Rate of reduction in revenues is therefore synonymous to the rate of reduction in LCOE.

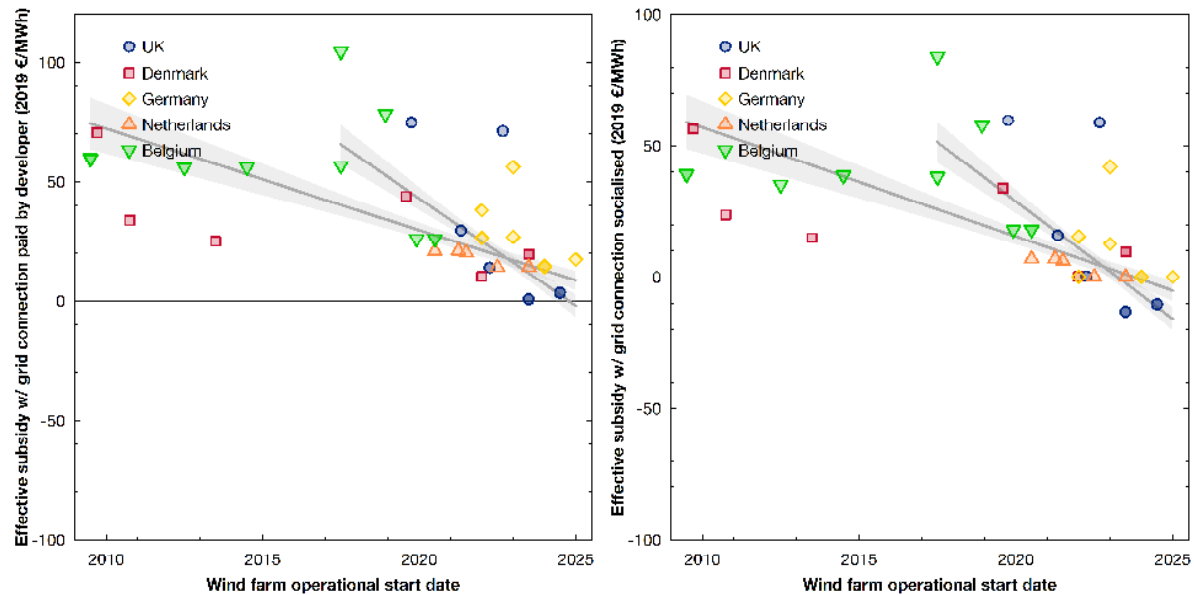
	All auctions	Since 2015
Denmark	1.7 ± 1.7%	10.3 ± 5.5%
United Kingdom		16.4 ± 3.3%
Netherlands		5.1 ± 1.2%
Germany		12.8 ± 3.7%
Belgium	2.4 ± 2.0%	18.0 ± 5.1%

Supplementary Figure 3.

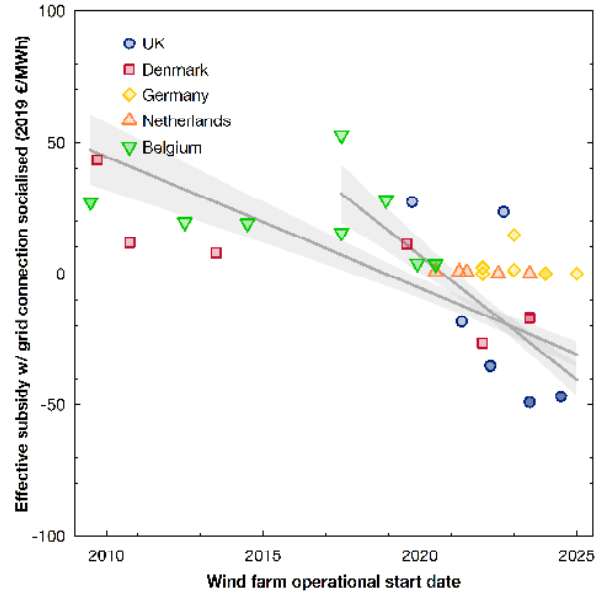
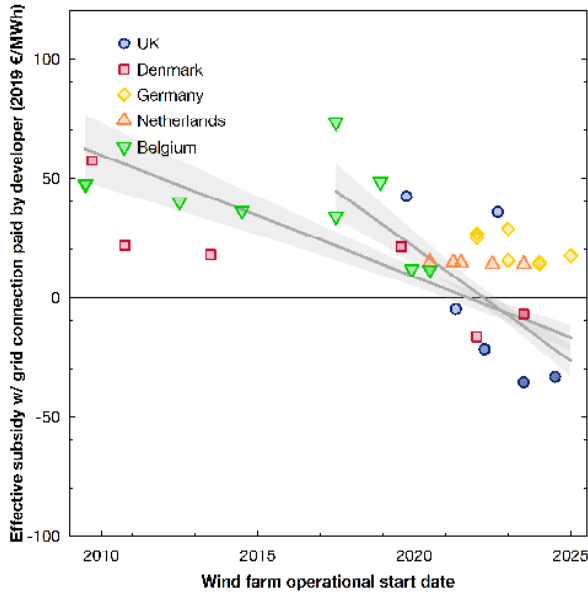
Results for the effective subsidies for various scenarios for future power prices. The following subsections consider the prices emerging from the PRIMES model runs (scaled by 50%, 100% and 150%), and prices that evolve from the historic (2004-2018) averages with various annual rates of change.

The charts below consider two cases, where the grid connection should be paid for by the developer and so are considered part of the subsidy if paid for by government (left panels); and where they should be socialised, and so they are not considered part of the subsidy (right panels).

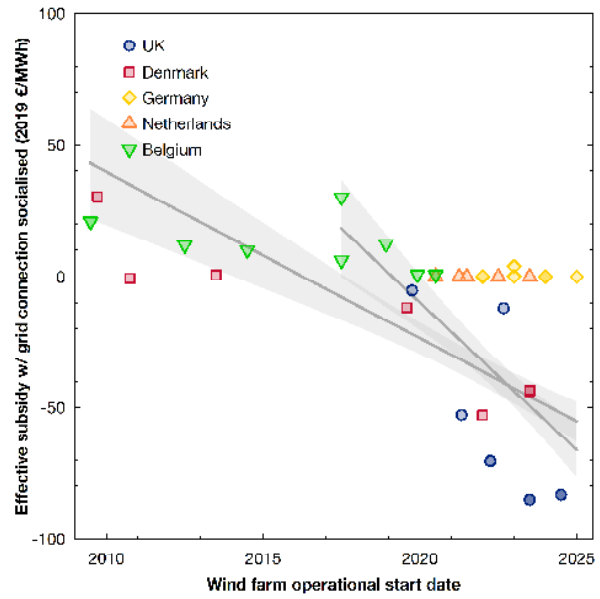
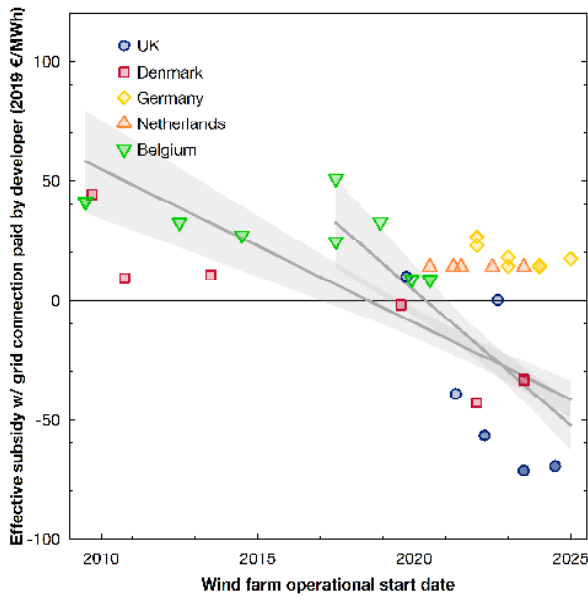
PRIMES \times 50%



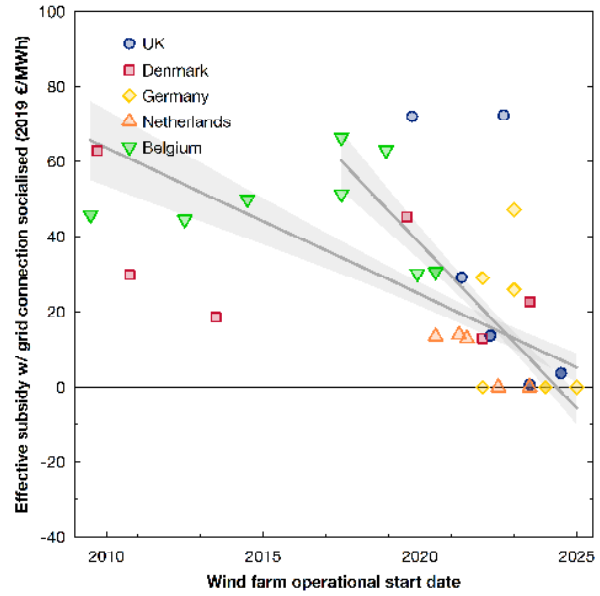
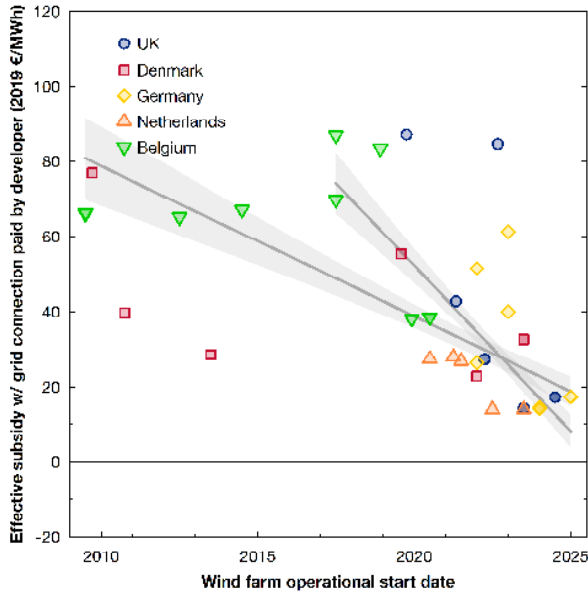
PRIMES \times 100%



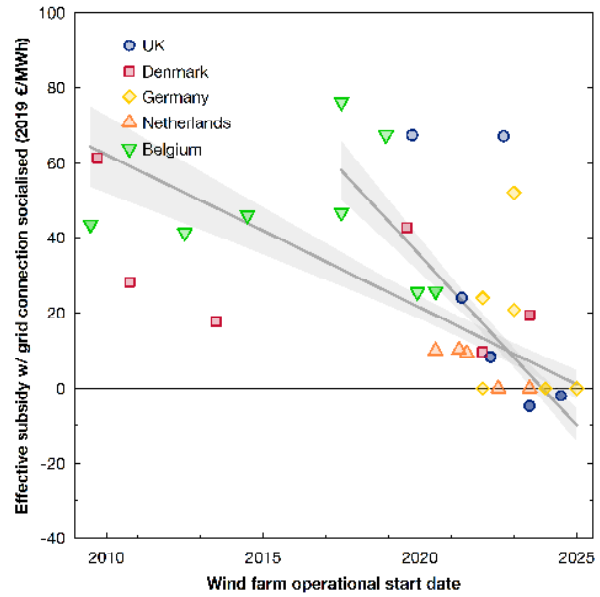
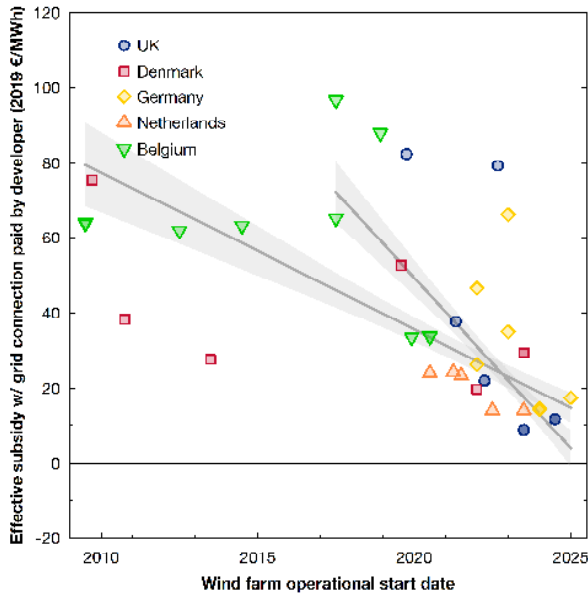
PRIMES \times 150%



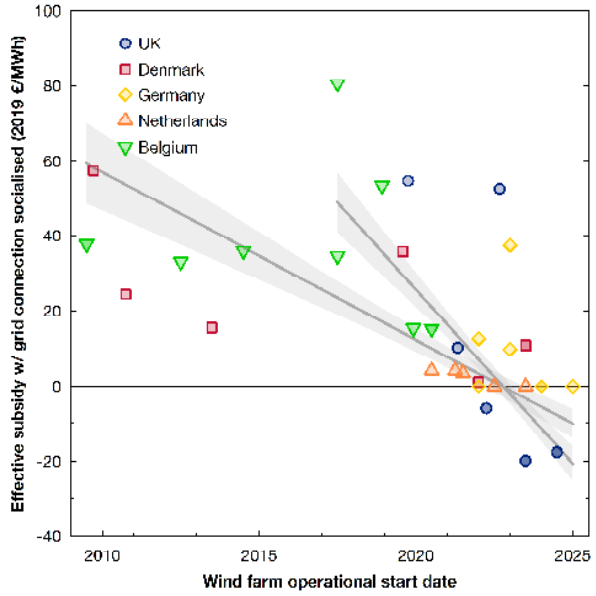
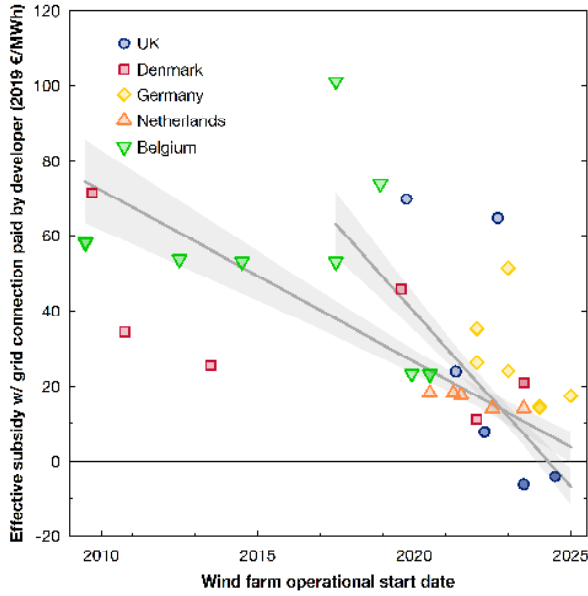
Historic, -2% annual change



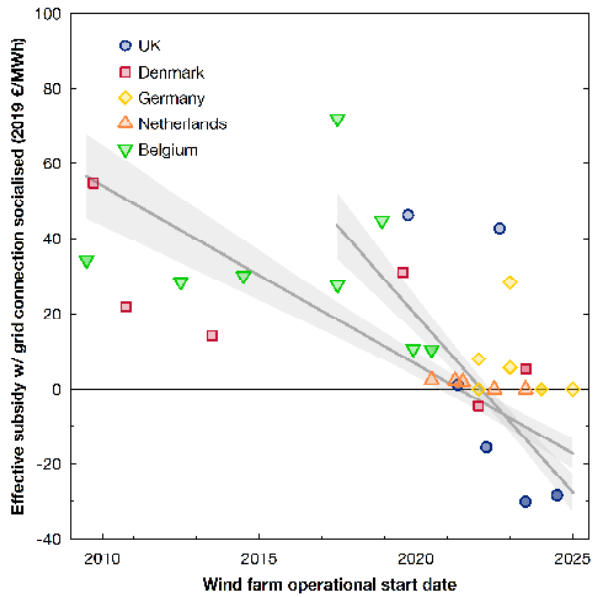
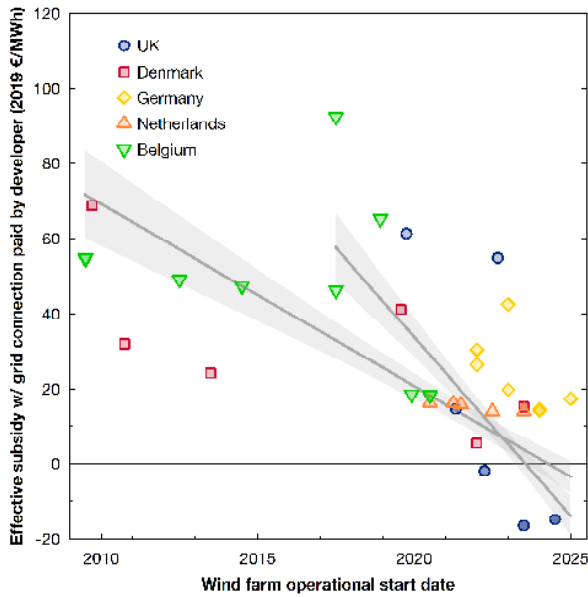
Historic, -1% annual change



Historic, +1% annual change



Historic, +2% annual change



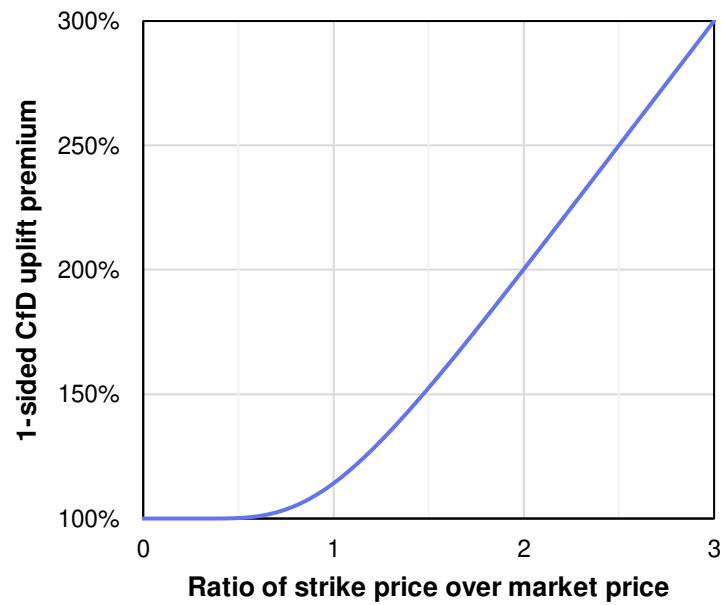
Supplementary Table 2.

The capture value describes the ratio of the wholesale market prices which wind farms are able to capture. We give today's values, which are empirically determined from 2015-2018 historic data, and values for 2030 based on the EU 2016 Reference Scenario PRIMES model.

	Current	2030
Denmark	91%	82%
United Kingdom	97%	83%
Netherlands	95%	87%
Germany	93%	85%
Belgium	94%	90%

Supplementary Figure 4.

The uplift premium describes the additional income that stems from having a 1-sided CfD, thus capturing the market upside. The uplift premium is a function of the ratio between strike price and wholesale market price and differs largely for each wind farm. The following figure describes the relationship for any wind farm.



Supplementary Table 3.

Long-term country-specific inflation rates, based on GDP deflators.⁶⁴

Country	Value
Denmark	1.84% p.a.
United Kingdom	1.89% p.a.
Netherlands	1.72% p.a.
Germany	1.13% p.a.
Belgium	1.66% p.a.

Supplementary Table 4.

Weighted average cost of capital for onshore and offshore wind farm projects. The average offshore wind values (final column) are calculated as the mean of the three literature sources, and are used in this study.

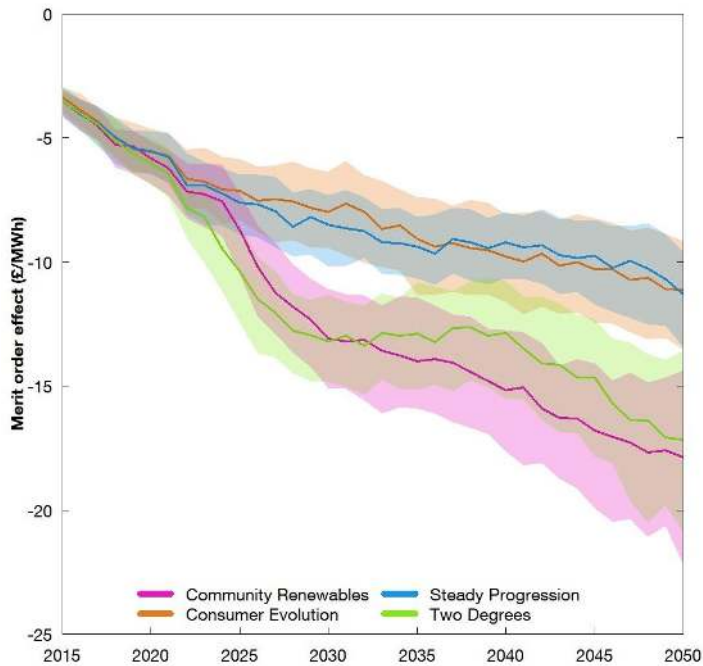
Thornton⁶⁵ suggests the increase in WACC from onshore to offshore is 1.0-1.3 percentage points, whereas Kost *et al.*⁶⁶ suggest a 2.3 percentage point increase for Germany. The average difference of 1.45 percentage points was applied to Ecofys⁶⁷ to obtain an estimated WACC for offshore wind.

Country	Thornton		Kost <i>et al.</i>		Ecofys		Average Offshore Wind
	Onshore Wind ⁶⁵	Offshore Wind ⁶⁵	Onshore Wind ⁶⁶	Offshore wind ⁶⁶	Onshore Wind ⁶⁷	Estimated Offshore Wind ⁶⁷	
UK	6.8%	7.8%	-	-	6.5%	8.0%	7.9%
Denmark	5.8%	7.0%	-	-	5.8%	7.3%	7.3%
Germany	5.0%	6.3%	4.6%	6.9%	4.0%	5.5%	6.2%
Belgium	-	-	-	-	5.5%	7.0%	7.0%
Netherlands	-	-	-	-	6.4%	7.9%	7.9%

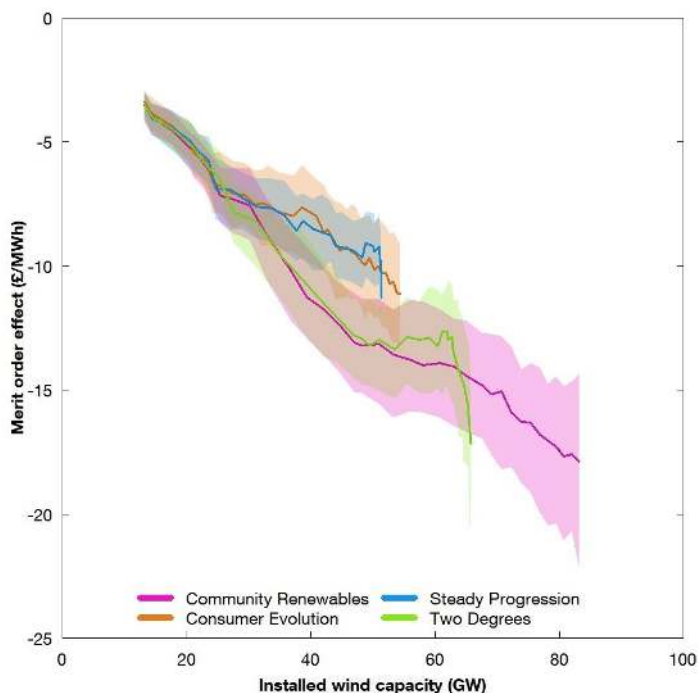
Supplementary Figure 5.

Electricity generation from wind does not receive the average price and the price that offshore wind receives can be called 'capture value' or 'merit-order effect'. Below we show this effect for different scenarios in the UK National Grid Future Energy Scenarios annual publications⁶⁸. Despite some uncertainty, we assume a linear relation between installed wind power and the effect.

The evolution of the merit-order effect over time:



The evolution of the merit-order effect against installed wind capacity:



Supplementary References

1. Borenstein, S. & Bushnell, J. Electricity Restructuring: Deregulation or Reregulation. *Regulation* **23**, (2000).
2. reNews. Home - reNews - Renewable Energy News. *reNews* (2019). Available at: <https://renews.biz/>.
3. 4COffshore. Home - 4C Offshore Website. *4COffshore* (2019). Available at: <https://www.4coffshore.com/>.
4. OffshoreWind.biz. Home - OffshoreWind.biz. *OffshoreWind.biz* (2019). Available at: <https://www.offshorewind.biz/>.
5. WindPowerOffshore. Home - Offshore wind power projects & companies. *Windpower Offshore* (2019). Available at: <https://www.windpoweroffshore.com/>.
6. RenewablesNow. Home - Renewable energy news & research. *RenewablesNow* (2019). Available at: <https://renewablesnow.com/>.
7. OSPAR Commision. *OSPAR database on offshore windfarms. 2013 UPDATE (revised in 2014). OSPAR Biodiversity Series* (2014).
8. Staffell, I. & Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **114**, 1224–1239 (2016).
9. Cleijne, H. Cost of offshore transmission. *DNV GL* (2019). Available at: https://www.tennet.eu/fileadmin/user_upload/Company/News/Dutch/2019/20190624_DNV_GL_Comparison_Offshore_Transmission_update_French_projects.pdf.
10. Cleijne, H. Cost of offshore transmission. *DNV GL* (2019).
11. Vattenfall. Vesterhav Nord - Vattenfall. (2019). Available at: <https://group.vattenfall.com/dk/vores-forretning/vindprojekter-i-danmark/vesterhav-nord>. (Accessed: 4th October 2019)
12. Vattenfall. Vesterhav Syd - Vattenfall. (2019). Available at: <https://group.vattenfall.com/dk/vores-forretning/vindprojekter-i-danmark/vesterhav-syd>. (Accessed: 4th October 2019)
13. 4C Offshore. East Anglia ONE - 4C Offshore. (2019). Available at: <https://www.4coffshore.com/windfarms/east-anglia-one-united-kingdom-uk64.html>. (Accessed: 30th May 2019)
14. OWPB. *Transmission Costs for Offshore Wind Final Report April 2016*. (2016).
15. Iberdrola. East Anglia ONE offshore wind farm - Iberdrola. (2020). Available at: <https://www.iberdrola.com/about-us/lines-business/flagship-projects/east-anglia-one-offshore-wind-farm>. (Accessed: 3rd February 2020)
16. OffshoreWIND.biz. Final Investment Decision in Place for East Anglia ONE | Offshore Wind. (2016). Available at: <https://www.offshorewind.biz/2016/02/24/final-investment-decision->

in-place-for-east-anglia-one/. (Accessed: 4th October 2019)

17. DECC. Contracts for Difference (CFD) Allocation Round One Outcome. *Department of Energy & Climate Change* (2015). Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/407059/Contracts_for_Difference_-_Auction_Results_-_Official_Statistics.pdf.
18. ScottishPower Renewables. Work begins on construction of 'home' for East Anglia ONE windfarm as £2.5m contract is signed with Great Yarmouth's 3sun Group - ScottishPower Renewables. (2018). Available at: https://www.scottishpowerrenewables.com/news/pages/work_begins_on_construction_of_home_for_east_anglia_one_windfarm_as_25m_contract_is_signed_with_great_yarmouths_3sun_group.aspx.
19. OWPB. *Transmission Costs for Offshore Wind Final Report April 2016*. (2016).
20. EDF. Construction of Neart na Gaoithe offshore wind farm project to go ahead following financial agreements | EDF Energy. Available at: <https://www.edfenergy.com/media-centre/news-releases/construction-neart-na-gaoithe-offshore-wind-farm-project-go-ahead>. (Accessed: 3rd February 2020)
21. LCCC. Neart na Gaoithe. *Low Carbon Contracts Company* (2019). Available at: <https://www.lowcarboncontracts.uk/cfds/neart-na-gaoithe>.
22. Durakovic, A. Neart na Gaoithe Construction to Start This Year. (2019). Available at: <https://www.offshorewind.biz/2019/05/16/neart-na-gaoithe-construction-to-start-this-year/>.
23. Tisheva, P. UPDATE - Dong to build Hornsea 2 after CfD win at GBP 57.5/MWh. *RenewablesNow* (2017). Available at: <https://renewablesnow.com/news/update-dong-to-build-hornsea-2-after-cfd-win-at-gbp-575mwh-582912/>.
24. OffshoreWIND.biz. DONG Reaches FID for World's Biggest Offshore Wind Farm. *OffshoreWind.biz* (2017). Available at: <https://www.offshorewind.biz/2017/09/11/dong-reaches-fid-for-worlds-biggest-offshore-wind-farm/>.
25. LCCC. Hornsea Project 2 Phase 1. *Low Carbon Contracts Company* (2019). Available at: <https://www.lowcarboncontracts.uk/cfds/hornsea-project-2-phase-1>.
26. Foxwell, D. Moray East takes step towards FID with V164-9.5MW turbine deal. *Riviera Maritime Media* (2018). Available at: <https://www.rivieramm.com/news-content-hub/moray-east-takes-step-towards-fid-with-v164-95mw-turbine-deal-23632>.
27. LCCC. Moray Offshore Windfarm (East) Phase 1. *Low Carbon Contracts Company* (2019). Available at: <https://www.lowcarboncontracts.uk/cfds/moray-offshore-windfarm-east-phase-1>.
28. LCCC. Triton Knoll Offshore Wind Farm Phase 1. *Low Carbon Contracts Company* (2019). Available at: <https://www.lowcarboncontracts.uk/cfds/triton-knoll-offshore-wind-farm-phase-1>.
29. SSE. GE Renewable Energy's Haliade-X turbines to be used by Dogger Bank Wind Farms.

- SSE (2019). Available at: <https://sse.com/newsandviews/allarticles/2019/10/ge-renewable-energys-haliade-x-turbines-to-be-used-by-dogger-bank-wind-farms/>.
30. SSE. Dogger Bank Wind Farms announces OHT as preferred supplier for foundation installation. (2019). Available at: <https://sse.com/newsandviews/allarticles/2019/11/dogger-bank-wind-farms-announces-oht-as-preferred-supplier-for-foundation-installation/>. (Accessed: 3rd February 2020)
 31. SSE. GE Renewable Energy's Haliade-X turbines to be used by Dogger Bank Wind Farms. SSE (2019).
 32. Hundleby, G. Dong's Borssele Costs – a landmark Dutch auction by Giles Hundleby. *BVG Associates* (2016). Available at: <https://bvgassociates.com/dongs-borssele-costs/>.
 33. Offshorewind.biz. 13 Foundations Up at Borssele 1&2 | Offshore Wind. (2020). Available at: <https://www.offshorewind.biz/2020/01/30/13-foundations-up-at-borssele-12/>. (Accessed: 4th February 2020)
 34. Hundleby, G. Dong's Borssele Costs – a landmark Dutch auction by Giles Hundleby. *BVG Associates* (2016).
 35. OffshoreWIND.biz. Van Oord-Led Consortium Wins Borssele Demo Site Tender. *OffshoreWind.biz* (2018). Available at: <https://www.offshorewind.biz/2018/04/06/van-oord-led-consortium-wins-borssele-demo-site-tender/>.
 36. Weston, D. Borssele III and IV reaches financial close. *Windpower Offshore* (2018). Available at: <https://www.windpoweroffshore.com/article/1486358/borssele-iii-iv-reaches-financial-close>.
 37. Shell. Blauwwind Consortium reaches Financial Close on Borssele III/IV | Shell United Kingdom. (2018). Available at: <https://www.shell.co.uk/media/2018-media-releases/blauwwind-consortium-reaches-financial-close-on-borssele-iii-iv.html>.
 38. MHI Vestas. MHI Vestas Inks Firm Order for Borssele V Innovation Site. *MHI Vestas* (2018). Available at: <http://www.mhivestasoffshore.com/mhi-vestas-inks-firm-order-borssele-v-innovation-site/>.
 39. Durakovic, A. First Borssele III & IV Monopile In Place | Offshore Wind. *Offshorewind.biz* (2019). Available at: <https://www.offshorewind.biz/2019/10/25/first-borssele-iii-iv-monopile-in-place/>. (Accessed: 4th February 2020)
 40. Skopljak, N. Sif Receives Borssele V Monopile Order. *OffshoreWind.biz* (2019). Available at: <https://www.offshorewind.biz/2019/05/20/sif-receives-borssele-v-monopile-order/>.
 41. Siemens-Gamesa. Siemens Gamesa is on track with the new SG 10.0-193 DD wind turbine for the world's first zero subsidy offshore wind farm. (2019). Available at: <https://www.siemensgamesa.com/en-int/newsroom/2019/04/190415-siemens-gamesa-news-offshore-sg-10-0-193-dd-for-zero-subsidy-offshore-wind-farm>.
 42. Foxwell, D. Riviera Maritime Media - News Content Hub - Vattenfall firms-up Hollandse Kust turbine installation deal. (2020). Available at: <https://www.rivieramm.com/news-content-hub/news-content-hub/vattenfall-firms-up-hollandse-kust-turbine-installation->

deal-57456. (Accessed: 4th February 2020)

43. Russel, T. Vattenfall wins Hollandse Kust Zuid 3&4 battle. *4COffshore* (2019). Available at: <https://www.4coffshore.com/news/vattenfall-wins-hollandse-kust-zuid-3264-battle-nid13925.html>.
44. Richard, C. SGRE's 10MW in line for zero-subsidy Vattenfall project. *Windpower Offshore* (2019). Available at: <https://www.windpoweroffshore.com/article/1582030/sgres-10mw-line-zero-subsidy-vattenfall-project>.
45. Siemens-Gamesa. Siemens Gamesa is on track with the new SG 10.0-193 DD wind turbine for the world's first zero subsidy offshore wind farm. (2019).
46. Skopljak, N. Arcadis Ost 1 First to Use Floating Turbine Installation Method | Offshore Wind. (2019). Available at: <https://www.offshorewind.biz/2019/11/26/arcadis-ost-1-first-to-use-floating-turbine-installation-method/>. (Accessed: 4th February 2020)
47. Windmesse. Deutschland als Standort für innovativen Installationstest | windmesse.de. (2019). Available at: <https://w3.windmesse.de/windenergie/news/33202-parkwind-hereema-marine-contractors-mhi-vestas-turbine-schiff-installation-schwimmend-arcadis-ost-1-ostsee-bodenbedingungen-standort-montage-innovation>. (Accessed: 4th February 2020)
48. Esteban, M., López-Gutiérrez, J.-S. & Negro, V. Gravity-Based Foundations in the Offshore Wind Sector. *J. Mar. Sci. Eng.* **7**, 64 (2019).
49. Smulders. Thornton Bank II & III Offshore Windpark | Smulders. (2012). Available at: <https://www.smulders.com/en/thornton-bank-ii-en-iii>. (Accessed: 4th February 2020)
50. EEW Group. EEW SPC produces the foundations for Nobelwind OWF. (2016). Available at: <https://eew-group.com/about/news/detail/eew-spc-produces-the-foundations-for-nobelwind-owf/>. (Accessed: 4th February 2020)
51. van der Kloet, R. Foundation installation progressing at Rentel | 4C Offshore. (2017). Available at: <https://www.4coffshore.com/news/foundation-installation-progressing-at-rentel-nid6276.html>. (Accessed: 4th February 2020)
52. Russel, T. Sif and Smulders to produce Norther foundations | 4C Offshore. *4COffshore* (2017). Available at: <https://www.4coffshore.com/news/sif-and-smulders-to-produce-norther-foundations-nid5115.html>. (Accessed: 4th February 2020)
53. Durakovic, A. Offshore Construction Starts on Northwester 2 Wind Farm | Offshore Wind. (2019). Available at: <https://www.offshorewind.biz/2019/07/19/offshore-construction-starts-on-northwester-2-wind-farm/>. (Accessed: 4th February 2020)
54. Skopljak, N. All SeaMade Foundations In Place | Offshore Wind. (2020). Available at: <https://www.offshorewind.biz/2020/01/07/all-seamade-foundations-in-place/>. (Accessed: 4th February 2020)
55. DECC. Contracts for Difference (CFD) Allocation Round One Outcome. *Department of Energy & Climate Change* (2015).

56. Skopljak, N. Ørsted Bundles German Offshore Wind Projects. *OffshoreWind.biz* Available at: <https://www.offshorewind.biz/2019/09/10/orsted-bundles-german-offshore-wind-projects/>.
57. Ørsted. DONG Energy awarded three German offshore wind projects. *Press release* (2017).
58. Ørsted. Ørsted wins 551.75MW in German offshore wind auction. *Press release* (2018).
59. Güsewell, D., Kancy, S. & Münch, M. . (EnBW). EnBW press conference. (2018).
60. Innogy. Innogy successful in German offshore auction. *Press release* (2018).
61. REUTERS. Iberdrola Plans One Billion Euro Investment in Baltic Sea Wind Farms. *The New York Times* (2018).
62. German Federal Network Agency (Bundesnetzagentur). Offshore-Netzentwicklungs-plan 2025: Bestätigung Az.: 613-8572/1/1. (2016).
63. Durakovic, A. Elia Gives MOG Construction Update. *OffshoreWind.biz* (2019). Available at: <https://www.offshorewind.biz/2019/03/29/elia-gives-mog-construction-update/>.
64. World Bank. Inflation, GDP deflator (annual %). (2019).
65. Grant Thornton & Clean Energy Pipeline. Renewable energy discount rate survey results – 2017. (2018). Available at: <https://www.grantthornton.ie/globalassets/1.-member-firms/ireland/insights/publications/grant-thornton---renewable-energy-discount-rate-survey-2017.pdf>.
66. Kost, C., Shammugam, S., Jülch, V., Nguyen, H.-T. & Schlegl, T. Levelized Cost of Electricity Renewable Energy Technologies. (2018).
67. Noothout, P. *et al.* DIA-CORE - The impact of risks in renewable investments and the role of smart policies - Final Report. (2016).
68. National Grid. *Future Energy Scenarios 2018*. (2018).