The new economics of offshore wind

January 2018

This report reflects Aurora's independent analysis as a leading energy market modelling and analytics company.

The publication of this analysis was financially supported by a range of offshore wind industry participants.

Table of abbreviations

BEIS	Department of Business, Energy and Industrial Strategy
CAGR	Compound Annual Growth Rate
CCGT	Combined Cycle Gas Turbine plant
CfD	Contracts for Difference
EV	Electric vehicle
FiTs	Feed in Tariffs
GB	Great Britain
OCGT	Open Cycle Gas Turbine plant
PV	Photovoltaic
Recips	Reciprocating engines
RO	Renewables Obligation

Contents

Executive summary

The volume of offshore wind in the Great Britain (GB) capacity mix could be materially increased through intelligent market design and regulation, including the continuation of the Contract-for Difference (CfD) regime. Aurora has analysed 2 policy mechanisms to achieve greater offshore wind penetration:

Providing zero-subsidy CfD contracts: continuation of current government policy to provide wholesale market revenue stabilisation to offshore wind projects via CfDs. To create a cost-neutral CfD, Aurora has modelled a CfD that, in future, would be set at the level of the offshore wind 'capture price'[1] and therefore would result in no net subsidy payments over the 15-year term of the CfD contract. Aurora describes this as 'zero-subsidy' CfD support. Stabilising merchant revenues via CfDs significantly reduces risks for investors and is critical in attracting financing and supporting further offshore wind build-out

Allowing offshore wind to 'revenue-stack': level the playing field through regulatory adjustments to allow offshore wind to participate in the Capacity Market, provide upwards and downwards balancing in the Balancing Mechanism, and provide ancillary services, thereby improving the economics of offshore wind at an asset level – effectively, allowing offshore wind to access multiple revenue streams ('revenue-stack') in a manner similar to dispatchable generation or storage assets

Aurora's modelling indicates that together these measures should increase potential offshore wind capacity on the GB system up to approximately 30GW by the 2030s up from the 6GW of operational offshore wind on the GB system in 2017. This provides a range of benefits to the GB power system:

- Helps reduce carbon emissions to approximately 60 g/kWh by the late 2030s – significant additional offshore wind capacity will be a critical component if GB is to meet long-term carbon targets
- Reduces system costs by ~7% which results in an annual savings to consumers of ~£1-2 billion per year by the 2030s. This equates to a saving on household electricity bills of ~£20 per year
- Limits offshore wind's system integration costs ('cost of intermittency') to £6-7 per MWh in the 2030s
- Signals a viable long-term route to market for offshore wind to provide further confidence in the offshore wind industry in GB, helping to secure further investment, jobs and supply chain opportunities

Aurora has also modelled scenarios where offshore wind capacity reaches approximately 40GW by the 2030s. Aurora analysis indicates that to reach 40GW of offshore wind capacity on the GB system, the provision of zero-subsidy CfDs are critical, as is allowing offshore wind to revenue stack, but other external factors are also important – in particular, a higher CPS price reaching £100 per tonne by 2033, no new nuclear build beyond Hinkley Point C, limited additional future onshore wind build-out, and further capex and opex reductions for offshore wind as a technology.

[1] Capture price refers to the price an asset or technology achieves in the market – for example, because offshore wind production is correlated it can create additional supply in the wholesale market meaning its average capture price through the year may be below the baseload price

1.
2017 – a landmark year for offshore wind

1.1. Offshore wind in 2017

In 2017, industry and supply chain maturation, aggressive competition, rapidly falling costs, and clarity over future government support combined to create significant optimism and momentum for offshore wind in the GB market.

Aurora's analysis indicates that the same confluence of factors that fueled this optimism is set to transform the economics of offshore wind. Massive technological progress has fundamentally changed our understanding of offshore wind from a technology which provides carbon-free MWhs, to one which provides multiple economic benefits to the GB power system, spanning power, capacity and the ability to help balance the system.

The fierce competition that has driven down offshore wind costs has encouraged owners and operators to look for avenues to squeeze additional value from their assets. This has resulted in increased interest in alternative revenue streams and 'revenue-stacking' business models.

Finally, the intensifying attention paid to system integration costs has encouraged the industry to develop solutions that minimise offshore wind's externalities. Developers and operators are developing a range of solutions to make offshore wind a part of the solution to minimise system costs and ensure a balanced grid. This provides additional impetus for the emergence of the new modes of operating offshore wind assets.

1.2. Record low offshore wind auction prices

Recent CfD auctions have seen significant falls in the cost of offshore wind projects. In 2015, CfD Round 1, the average clearing price was approximately £117 per MWh. In 2017, that average price had fallen to £62 per MWh with clearing prices as low as £58 per MWh. This fall was driven by a range of factors: increasing turbine size; innovation in operating and maintenance strategies; stream-lined supply chains; and better financing arrangements.

This fall in offshore wind costs in the GB market has been matched by equally impressive cost reductions in the rest of Europe. In Germany, for example, Orsted and EnBW submitted bids to build offshore wind farms in 2024/25 without subsidies. By the time these projects are delivered in 5-7 years, developers expect 13-15 MW turbines to be available, resulting in significant further cost reductions, in particular from O&M. Similarly, in the Netherlands, Vattenfall and Statoil have made subsidy-free bids in a recent offshore wind auction held by the Dutch Government.

1.3. Ongoing government support for offshore wind

Recent announcements by the Department of Business, Energy & Industrial Strategy (BEIS) indicate ongoing strong government support for offshore wind. Following the last successful CfD auction, in October 2017 BEIS announced up to £557 million of annual funding for further Pot 2 CfD auctions, with the next auction scheduled for the spring of 2019. Low offshore wind clearing prices in CfD auctions means future pots of funding can on average buy significantly more capacity per pound spent.

Subsequently, in the 2017 Autumn Budget statement, the Government confirmed up to £557 million for further CfDs and also announced the new Control for Low Carbon Levies. The Control sets out that the Government will not introduce new low carbon electricity levies until the burden of such costs is falling or once total levy costs are falling. Even if costs are not falling, new levies may still be considered where they have a net reduction on bills and are consistent with the Government's energy strategy. In addition, all existing contracts and commitments, including up to £557 million for further CfDs, will be respected.

BEIS also announced plans to work with the offshore wind industry as it develops an ambitious sector deal as part of the broader industrial strategy program. In addition, the Crown Estate has also recently announced it intends to work with stakeholders to consider leasing further offshore wind sites.

1.4. Rising demand for balancing and ancillary services

Rising demand for balancing and ancillary services is a corollary of the changes the GB system is undergoing. Aurora forecasts that growth in zero-carbon generation, including from offshore wind, will lead to a significant increase in output variability and a fall in system inertia. These changes and the potential growth of largest infeed loss at Hinkley Point C will boost the requirements for balancing and ancillary services by 2030, with a commensurate increase in revenues from these markets.

This expected growth is already transforming the system. Grid scale batteries and other flexible generation technologies are entering the GB power market at a rapid rate – often with investment cases based almost entirely on balancing and ancillary revenues.

While flexible capacities stand to benefit, thus far offshore wind has been contributing predominantly to the demand for balancing and ancillary services. Aurora research indicates offshore wind can also contribute to the supply of those services.

Although intermittent, wind can also rapidly ramp its output up and down and so can contribute to balancing the system and keeping the grid stable. As demand for these services increases across the system, Aurora modelling indicates there is space for both flexible and renewable technologies to contribute to balancing and ancillary markets in complementary ways. Broadening the range of balancing and ancillary service providers should also increase competition in these markets and ultimately lower the cost to end consumers.

1.5.
European progress in the use of wind power in balancing and ancillary markets

Many European markets are significantly ahead of the curve in utilising wind power for balancing and grid stabilisation, or adjusting the regulatory framework now so as to enable such utilisation in the future.

Ireland, for example, plans to have ~30% of fast frequency response provided by wind by the early 2020s under the DS3 ancillary service system reforms.[2]

In addition, some companies on the continent have strategically invested in trading and technical capabilities that allow them to trade wind power between markets to capture price arbitrage opportunities. For example, Acciona in Spain first provided upward balancing services to the Spanish grid in February 2016. This means that Acciona's wind farms in Spain are able to increase (as well as decrease) output in response to changing system demand. In addition, Acciona now reportedly allocates 2GW of wind power capacity to provide balancing and management of frequency deviations to the electric power system in real-time.

[2] Ireland's DS3 reforms are part of a wide-ranging set of market reforms to the Irish market. DS3 refers to the portion of reforms designed to streamline ancillary services and make them fit-for-purpose for a more renewables intensive system

2. Policies to unlock additional offshore wind deployment

2
Policies to unlock additional offshore wind deployment

Aurora analysed two policy tools that could unlock additional potential from offshore wind:

Providing zero-subsidy Contract for Difference (CfD):
Stabilising offshore wind market revenues via the Government guaranteeing a per MWh price at the level that results in no net payments either from or to the asset over a 15-year period (a 'zero-subsidy' CfD)

Enabling revenue stacking:
removing barriers that currently preclude offshore wind from participating in the Capacity Market, Balancing Mechanism and ancillary services, thus leveling the playing field to create genuinely technologically-neutral and more efficient markets

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Aurora's analysis indicates that both policies result in additional, cost-effective, economically-efficient offshore wind capacity on the GB system, which, in turn, has significant, tangible benefits to the GB system:

A. Reduces system emissions

B. Minimises system costs that are ultimately borne by the GB consumer

C. Limits system integration costs or the 'cost of intermittency'

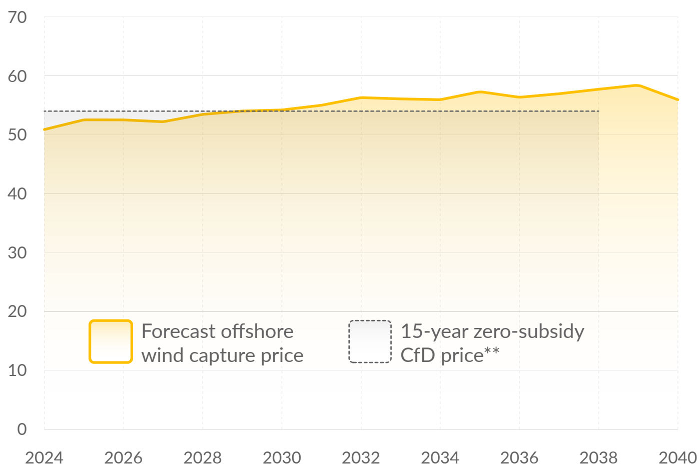
2.1.
Zero-subsidy CfDs for offshore wind

Stabilising merchant wholesale revenue streams significantly improves the investability of generating assets. For offshore wind, Aurora has modelled a continuation of the current CfD auction structure, and has identified when build could occur at 'zero-subsidy' bid levels – i.e., when the CfD bid for an offshore wind farm equals its expected capture price in the wholesale market over 15-years. This 'zero-subsidy' CfD would deliver approximately the same revenue as the wholesale market for an offshore wind asset over a 15-year period on a discounted basis.[3] This allows asset owners to discount the wholesale market revenue at a lower rate by transferring a portion of the price and volatility risk to the Government (and indirectly to consumers).[4] In short, the Government effectively de-risks wholesale merchant revenues, reducing the cost of capital and facilitating greater offshore wind build-out.

As an example of the operation of a zero-subsidy CfD in a wholesale market with gradually increasing wholesale baseload prices, in the early years of a given asset's life the Government (and ultimately consumers) may pay top-ups to the asset owner to make up the difference between the wholesale capture price and the CfD price. In later years, the asset owner might pay back money to the Government (and again consumers) if the offshore capture price exceeds the CfD strike price.

Aurora analysis indicates that for a zero-subsidy 15-year CfD to be cost-neutral versus offshore wind wholesale market capture price the CfD should be approximately £53-54 per MWh in 2016 terms which equates £48-49 per MWh in 2012 terms. The most recent CfD auction saw successful offshore wind clearing prices of £58 per MWh for delivery in 2022/23 in 2012 terms. Aurora estimates a further approximately 15% reduction is required in bids for offshore wind assets to hit 'zero-subsidy', reductions that seem achievable given the current rate of cost declines.

Capture price in wholesale market when both policies enacted*
£/MWh, real 2016



Source: Aurora Energy Research

* The calculation of offshore wind capture prices excludes half-hours corresponding to negative wholesale prices, in accordance with a CfD design which does not provide any payments during periods of negative wholesale prices

** For purposes of analysis, we have used government social discount rate of 3.5% for discounting to determine strike price

Under this zero-subsidy proposal, it is assumed offshore wind will continue to effectively bid into CfD auctions at their 15-year capture price until the impact of offshore price cannibalisation is such that the marginal offshore wind unit cannot recover its costs on an NPV basis.

In addition to future zero-subsidy support, clarifying the timings and size of future CfD auctions is critical. Clarity around future timings and volumes allows further supply chain development and in turn assists with additional offshore capex reductions.

[3] Aurora has used the Government social discount rate of 3.5% for discounting to determine the appropriate strike price. This assures that the Net Present Value of all payments to and from the Government is equal to zero under the Government's standard discounting assumptions

[4] Aurora assumes that contracted revenue streams are discounted at 8% nominal, unlevered, pre-tax, and merchant revenue streams are discounted at 13% nominal, unlevered, pre-tax

2.2.
Alternative markets: offshore wind as a provider of balancing and ancillary services

Offshore wind can, in theory, provide a range of balancing and ancillary services to the grid largely because it has the technical capabilities to rapidly ramp-up and down. If offshore wind is able to monetise the provision of these services, then it can in effect 'revenue-stack' much like traditional, dispatchable plants do today.

Revenue streams		Potential for offshore wind participation	Relevant issues/barriers
Wholesale Market		Current revenue stream	Offshore wind capture prices will decrease with greater penetration due to correlated production
Balancing Mechanism		✓	Value could potentially be unlocked by reserving wind capacity to bid in the Balancing Mechanism
Capacity Market		✓	More sophisticated approach to de-rating needed, recognising dependency on location and correlation with other wind asse
Ancillary services	Frequency Response	✓	Technically possible; successful test by Ørsted's Burbo Bank offshore wind farm in the UK in September 2016*
	Reserve	✓	Technically possible; offshore wind farms controllable for reserve purposes**
	Reactive Power	✓	Technically possible, but certain transmission connection issues need to be taken into account**
	Inertia Control	✓	Possible for offshore wind; obstacle regarding offshore wind farm decoupling from onshore system could be overcome***

Sources: Aurora Energy Research, IEEE, Ecofys

* Based on Ørsted's announcement on 27.09.2016, "Ørsted's 90-megawatt Burbo Bank offshore wind farm in Liverpool Bay has successfully completed tests demonstrating its ability to provide frequency response to support the national grid network", in cooperation with National Grid.

** Based on findings of Ecofys study on "Ancillary services to the grid: Potentials and benefits for offshore wind" (2014) with a focus on Germany and the Netherlands

*** Based on the conclusions of IEEE study on "Inertial Response from Offshore Wind Farms Connected through DC Grids" (IM Sanz, 2015).

Given there is rising demand in the GB system for balancing and ancillary services, opening these markets to offshore wind appears to be a pragmatic policy response to an increasingly salient issue. Current market design is still largely a legacy of a system dominated by dispatchable gas and coal units, giving rise to barriers to participation in balancing and ancillary markets by other technologies.

Aurora analysis suggests that leveraging the full technical capabilities of all technologies on the system and creating a level playing field would result in material reductions in the cost of provision of these services.

Recent proposed market changes signal that both the regulator Ofgem and National Grid recognise the benefits of opening balancing and ancillary markets to more technologies. For example, the National Grid System Needs and Product Strategy (SNaPs) suggested that it intends to move the procurement of ancillary services closer to real-time, which may remove a significant barrier from offshore wind's participation.[5] For example, the current requirement to bid in 1 month ahead for the provision of frequency response services effectively prevents offshore wind from participating, given the uncertainty around future wind profiles over that period. Shortening this to near real-time would allow participation from renewables alongside thermal generators and storage, which in turn would introduce significant new competition into the ancillary services market and lower the cost to the consumer.

As an indication of future, broader market design changes, National Grid has indicated that in 2018 they will develop the necessary rules and technical platforms to trial wind and solar's participation in frequency response markets.

[5] National Grid, 'System Needs and Product Strategy', 2017

Aurora has modelled opening 3 major markets to offshore wind:

1

Capacity Market: offshore wind projects are currently barred from participating in the Capacity Market on the grounds that they already receive subsidies under the RO and CfD system. Following the move to zero-subsidy CfDs, offshore wind projects could be compensated for their contribution to security of supply, measured by Equivalent Firm Capacity (EFC). When assessing the levels of additional capacity to be procured in each year's Capacity Market, National Grid and BEIS currently assume that onshore and offshore wind capacity has an EFC of around 20% (i.e., 1GW of wind capacity provides the same contribution to security of supply as 200MW of 'firm' capacity). Under this proposal, subsidy-free or zero-subsidy offshore wind would be allowed to participate in the Capacity Market, but offshore wind with existing CfDs or Renewable Obligations would not. In addition, in the 2018 T-4 auction, subsidy-free onshore wind attempted to pre-qualify – this highlights the urgency of a review of existing rules to admit zero-subsidy or subsidy-free renewables (including co-located hybrid sites) into the Capacity Market. Finally, offshore wind's future derating factors may be decoupled from onshore wind to reflect offshore wind's higher average load factors

2

Balancing Mechanism: allowing offshore wind to provide upwards and downwards balancing where load factors and Balancing Mechanism operational demands permit. There would be some technical market design challenges in facilitating offshore wind's greater participation in the Balancing Mechanism (particularly in upward balancing) – for example, rules governing the parameters of bid-offers, timings of final physical notifications and subsequent balancing actions. While the exact shape of regulatory changes has to be tailored to GB needs, lessons can be drawn from Europe. European markets with high wind penetration have worked through these challenges over the past 2-3 years

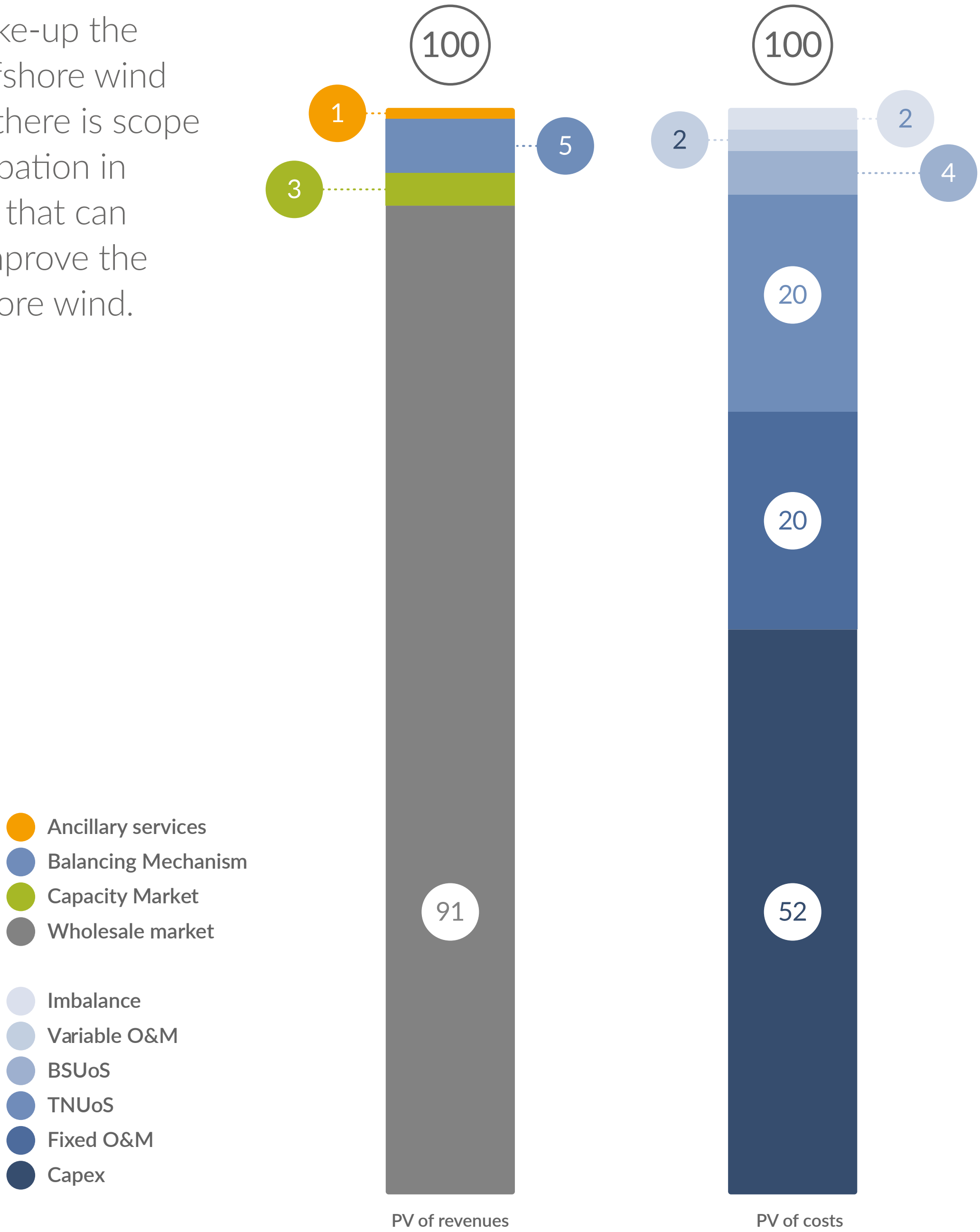
3

Ancillary services: allowing offshore wind to contribute to ancillary services where it has the technical capabilities to do so.[6] As with allowing offshore wind to participate in the Balancing Mechanism, there would be some technical challenges to creating genuinely technology neutral ancillary service markets. For example, ancillary markets would all have to move closer to real-time procurement (a move already flagged under National Grid's SNaPs report), and the technical response times of offshore wind would have to be carefully calibrated against frequency response requirements

[6] Aurora has modelled frequency response and reactive power as example ancillary services that offshore wind could participate in

Aurora's analysis indicates that under a revenue-stacking model, wholesale market revenues are likely to still make-up the clear majority of offshore wind revenues, but that there is scope for selective participation in alternative markets that can lift revenues and improve the economics of offshore wind.

Indicative PV* breakdown of revenues and costs for offshore wind assets in 2025 when both policies enacted
Index (100 = total PV of costs)



Source: Aurora Energy Research

* Present Value has been calculated over a period of 30 years, using a nominal, unlevered, pre-tax discount rate of 8% for revenues from the wholesale market (assuming a zero-subsidy CfD) and the Capacity Market and for capex, Fixed O&M costs and TNUoS costs, and 13% for all other revenue streams and cost categories. Please note that gross profits highly dependent on asset location, imbalance costs.

3. Impact of zero-subsidy CfDs & access to alternative markets

3.1. Offshore wind capacity under pre-existing government announcements

In this report, Aurora estimates that offshore wind capacity will reach approximately 20-24GW by the mid-2020s under current and announced CfD funding arrangements.

All auctions that have been conducted to late 2017 will deliver approximately 14GW of offshore wind. The pot of £557 million recently announced by the Government could potentially deliver between 6 and 10GW of additional offshore wind capacity depending on the clearing prices, and the accounting methodology utilised.[7]

The increasing capacity of offshore wind on the system is driven by a range of technical and operational improvements. Most significantly, Aurora forecasts a further 25-30% reduction in capital cost from 2017 to 2025[8], largely driven by an increase in turbine size to 13-15MW by the mid-2020s. These assumptions have been stress-tested with a wide-range of industry participants.

3.2. Increasing offshore wind capacity

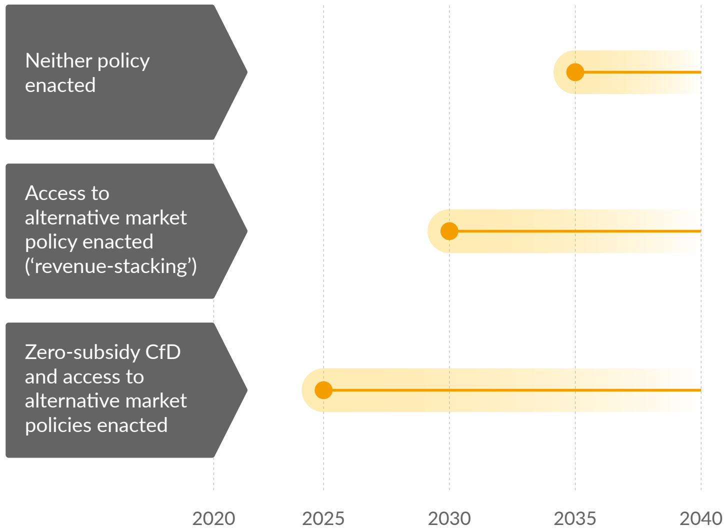
Allowing offshore wind access to zero-subsidy CfDs and revenues from capacity, balancing and ancillary markets improves the asset-level economics of offshore wind sufficiently to allow the deployment of significantly more offshore capacity wind in the GB system. Aurora analysis indicates that 'revenue-stacking' may allow offshore wind to increase revenues by 9-14% versus a wholesale-only model, (even after accounting for the loss of wholesale revenue required to provide power in the Balancing Mechanism and ancillary service markets). Clearly, these estimates are very dependent on the trading strategy utilised by the asset owner.

[7] Aurora analysis indicates that approximately 10GW could be procured using the current CfD reference price that is linked to the wholesale market baseload price. Alternatively, if the offshore wind capture price was utilised as the reference point, Aurora analysis indicates 6GW could be procured with the £557 million of funding. The amount of offshore wind procured will also depend on underlying price forecasts and load factors

[8] These estimates are consistent with forecasts from US National Renewables Laboratory, European Wind Energy Association, Berkley Labs, and BVG Associates

Improved asset returns bring forward the date at which offshore wind can effectively bid into a CfD auction on a zero-subsidy basis (i.e., at the forecast offshore wholesale market capture price).

First deployment of additional offshore wind under alternative policy scenarios

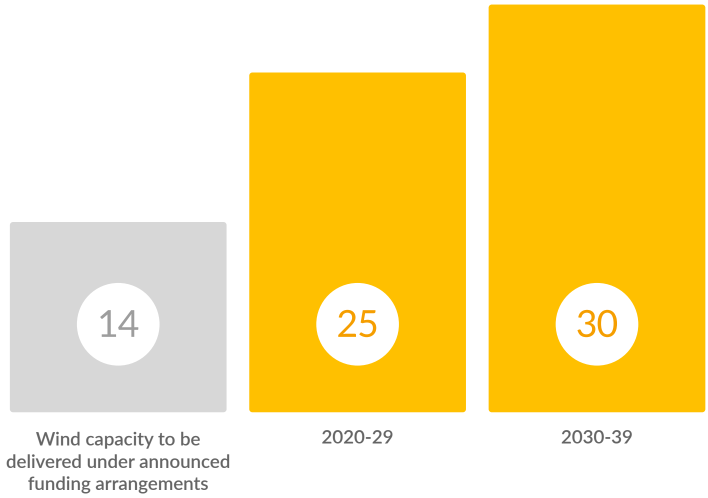


Source: Aurora Energy Research

Critically, if offshore wind CfDs were to be discontinued, Aurora's analysis indicates that the very earliest subsidy-free offshore wind projects would then be built would be 2030 and likely even later into the mid-2030s. This would have negative implications both for meeting the UK's carbon budgets as well as the developing British offshore wind supply chain.

Aurora's analysis indicates that the provision of zero-subsidy CfDs and allowing offshore wind to access capacity, balancing and ancillary markets could result in offshore wind reaching approximately 30GW by the 2030s.

Offshore wind capacity when both policies enacted
GW



Source: Aurora Energy Research

These 2 new policies facilitate additional offshore wind deployment due to a series of inter-linked factors:

Revenue-stabilisation: by stabilising wholesale market revenues, offshore wind becomes more investable for a range of investors and a lower cost of capital is achieved. Across technology types in the GB market, developers are struggling to convince financiers and lenders to support projects that depend primarily on merchant revenue streams. Given the transformational changes occurring in the GB energy market – the rise in renewables, the growth in flexibility, the decline of coal - financiers and lenders remain uncertain both about future prices and the degree of volatility in the wholesale market and Balancing Mechanism. Revenue-stabilisation is therefore critical in attracting financing and subsequent build-out

Alternative revenue streams: by switching between wholesale, ancillary and balancing markets, offshore wind projects can generate additional revenues. Aurora modelling indicates it could increase revenues by ~9-14% – this incentivises earlier and greater build-out of offshore wind

Mitigate price cannibalisation: diversifying revenue streams also helps mitigate price cannibalisation in the wholesale market. If some offshore wind capacity switches from the wholesale market to balancing and ancillary markets, this decreases the negative pressure on wholesale prices from zero-marginal cost generation

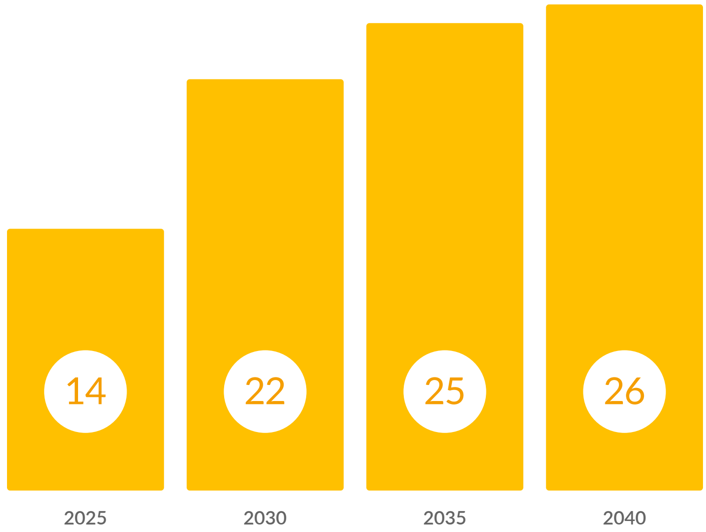
Reward equivalent firm capacity: access to the Capacity Market rewards offshore wind for the contribution it makes to security of supply (on an equivalent firm power basis)

In Aurora's analysis, the primary factor that slows further build-out of offshore wind is the impact of wholesale market price cannibalisation. When offshore wind capacity reaches approximately 30GW, Aurora analysis indicates that high total offshore wind load factors across all assets will more frequently create very low or negative prices in the wholesale market. Even if revenue stabilisation is provided via a capture price-linked CfD, the marginal additional unit of offshore wind will struggle to generate sufficient returns to justify the required capex, even assuming significant capex reductions.

There are a few major factors that could increase the economically-efficient maximum level of offshore wind on the system in the 2030s: a higher CPS price reaching £100 per tonne by 2033; no new nuclear build beyond Hinkley C; limited additional future onshore wind build-out; and further capex and opex reductions for offshore wind as a technology. In this future scenario, we see offshore wind capacity reaching approximately 40GW by the late 2030s assuming additional capacity is allowed to revenue-stack and receives a zero-subsidy CfD for the wholesale portion of its revenues.

Managing a system with significant volumes of offshore wind will require an increase in flexible generation technologies to support and complement the variable generation profile from wind. Aurora estimates that if the Government were to implement the two proposed policies (subsidy free CfDs and revenue stacking) then the total flexible generation capacity would need to increase to approximately 26GW in 2040.

Flexible technology capacity* to support renewable capacity when both policies enacted
GW



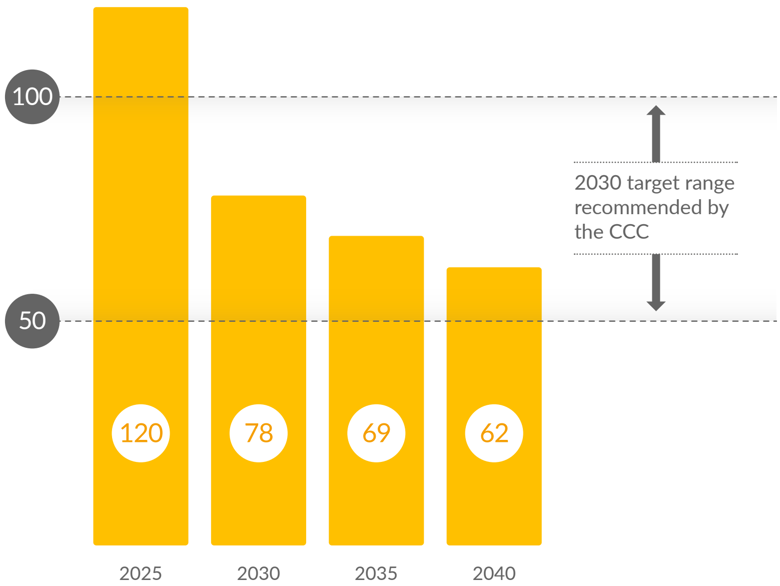
Source: Aurora Energy Research

* Flexible technologies include batteries, peakers, OCGTs, pumped storage, and DSR

3.3. Reducing carbon missions

The additional growth in offshore wind reduces system carbon intensity significantly. Reaching deployment of approximately 30GW of offshore wind through the 2030s materially drives reductions in system carbon intensity as the additional offshore wind largely displaces future CCGT. Offshore wind could play a crucial role in the further decarbonisation of the GB power system, particularly if other technologies such as nuclear are delayed. Aurora analysis indicates offshore wind – supported by zero-subsidy CfDs and revenue-stacking – could be the main driver of carbon reductions that helps GB meet the 2030 targets recommended by the CCC and achieve further reductions on the path to carbon-neutrality by 2050.

System carbon intensity when both policies enacted
gCO_2e/kWh



Source: Aurora Energy Research

3.4.
Reducing system costs to the consumer

Delivering approximately 30GW offshore wind by the 2030s also assists in reducing system costs to GB consumers. To calculate the difference in cost to consumers, Aurora accounts for costs accrued in the capacity, wholesale and balancing markets, and from subsidies including Renewables Obligations, CfDs, and FiTs.

The impact of additional offshore wind capacity can be seen most clearly in the wholesale market where the baseload price is significantly lower with 30GW of offshore wind generating on the GB system. Because the marginal cost of offshore wind is very low, Aurora analysis indicates deploying additional offshore wind pushes down wholesale market prices by an estimated 10-15% in 2030s.

Overall, adding together savings across the wholesale, capacity, balancing and ancillary markets and subsidies, Aurora analysis suggests that enacting zero-subsidy CfDs and facilitating 'revenue-stacking' for offshore wind would yield savings to consumer of ~£1-2 billion per year by 2040. This represents a saving of approximately £20 per household per year.

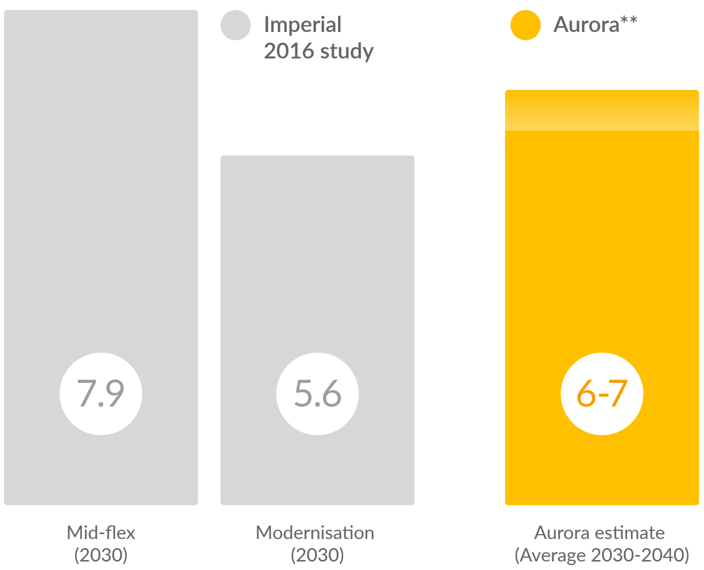
[9] In generating this cost of integration Aurora has adopted the methodology used by Imperial. The cost of integration is calculated by comparing the additional costs imposed on the system from offshore wind versus a technology that delivers the same number of MWh over a year but with a completely flat generation profile

3.5.
Limiting system integration costs

Aurora analysis indicates that the costs of integrating offshore wind into the GB system with appropriate levels of flexible generation remain manageable. In the 2030s, Aurora analysis indicates the cost of integration is £6-7 per MWh[9] – analysis consistent with findings by Imperial College London in their October 2016 report 'The costs and impacts of intermittency – 2016 update'.

Allowing offshore wind to 'revenue-stack' helps mitigate system integration costs by fully utilising its technical capabilities. In Aurora analysis, offshore wind provides relatively inexpensive balancing and ancillary services which helps keep integration costs relatively low even in high offshore wind penetration scenarios.

Offshore wind system integration cost* ('cost of intermittency') when both policies enacted
£ per MWh, real 2016



Sources: Imperial College London, Aurora Energy Research

* Aurora has replicated the cost-to-system approach used by Imperial College London which quantifies the system integration cost as the sum of the operating cost (OPEX) associated with existing and new generation and investment cost (CAPEX) of new builds

** Cost does not include distribution and transmission network investment which are negligible in both the Mid-flex and Modernisation scenarios in Imperial's study

4.
Technical appendix

4.1.
Modelling methodology and approach

Aurora's modelling approach is grounded on 4 overarching principles:

Take a full system perspective.
Aurora models the Capacity Market, wholesale electricity market, Balancing Mechanism and ancillary services in an integrated way so that outcomes in one market inform all other markets and results are internally consistent

Understand markets dynamically, holding nothing constant.
Aurora only makes input assumptions about core technical parameters and policy – all other elements of the market (e.g., price shape, capacity mix, technology entry) are dynamically calculated outputs

Ground forecasts in commercial reality, not theory.
Aurora's models are optimised around the investment decisions of individual market participants (not a theoretical metric like lowest system cost)

The past is not a good guide to the future.
We are in a period of discontinuous change – linear or simplified extrapolations from the past will not be good forecasts of the future

For all analysis in this report, Aurora has used **AER-ES GB** – Aurora's market-leading dynamic dispatch model. Key structural features underpinning AER-ES GB model include:

- Dynamic dispatch of plant, considering ramping costs and rate restrictions, and stochastic availability of plants and individual generators
- Emulating the entire GB grid, simulating more than 100 plants at an individual level at half-hourly granularity to 2040
- Detailed modelling of Capacity Market mechanism from year 2018 onwards, replicating the policy as it currently stands
- Detailed modelling of the Balancing Mechanism, considering plant availability for balancing actions and stochastic imbalance
- Financial module to capture investment decisions. Plant mothball, de-mothball, retire and are built endogenously according to their short and longer-run economic prospects
- Endogenous interconnector flows according to estimated gradient between domestic and foreign electricity spot prices
- Endogenous demand adapting to both economic growth and electricity prices
- Spatial aspects of the transmission grid and fuel transport costs

Key elements of the AER-ES GB baseline parameterisation include:

- Plant characteristics such as efficiencies, ramping costs and rate restrictions calibrated using historic data since 2005
- Demand projections incorporate future behavioural change and load shifting because of the adoption of new technologies
- Econometrically-estimated uplift function, calibrated on historical generation and spot price data
- Stochastic wind calibrated to historic output both across and within plant to generate an accurate picture of performance characteristics of the entire GB wind fleet

Aurora also developed a bespoke offshore wind asset dispatch model to reflect the realities of offshore wind's potential participation in multiple markets. This model captures the technical and operational parameters and constraints of future offshore wind assets and dispatches these assets against the price signals across markets.

4.2.
Summary of key assumptions

Aurora has made a set of assumptions about the cost and technical capabilities of offshore wind based on extensive consultation with industry and academic experts:

- 13-15MW turbines available to market participants from the mid-2020s
- Load factors for these turbines may be as high as 51-53% depending on location
- Capex reductions are forecast to be ~25-30% from current available wind turbine technologies on a £ per kW basis. Opex reductions are forecast to follow a similar trajectory
- In addition, response times of offshore wind turbines (i.e., their ability to vary output) are assumed to be under 2 seconds through both speed/inverter control and blade control

Aurora has made a broader set of assumptions that are consistent with offshore wind making a leading contribution to reducing the carbon intensity of the GB power system:

- Aurora assumes that contracted revenue streams are discounted at 8% nominal, unlevered, pre-tax, and merchant revenue streams are discounted at 13% nominal, unlevered, pre-tax
- Aurora assumes interconnection reaches 8.4GW by 2023 and then no further capacity is added to 2040. In addition, Aurora assumes nuclear capacity drops and then plateaus at approximately 7GW out to 2040
- Aurora uses data from National Grid's 'Future Energy Scenarios' to forecast demand – total electricity demand increases by approximately 7% to 2040 and ACS peak demand increases approximately 4% from current levels
- Aurora assumes significant growth in electric vehicles to 2040 – approximately 10 million electric vehicles in GB by 2040
- Aurora forecasts gas prices to rise slowly as the global LNG market rebalances – prices stabilise at ~£6-8 per MMBTu through the late-2020s and 2030s
- Aurora assumes a lower carbon price trajectory than BEIS with a combination of Carbon Price Support and EU ETS allowance reaching £40 per tonne by 2040

For any press enquiries, questions or comments related to the content of the present report, please email *contact@auroraer.com.*