# Methodology to prepare for UK's offshore wind Contract for Difference auctions

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## ARTICLE INFO

## ABSTRACT

In the UK, the Contract for Difference (CfD) subsidies for renewable energy generation are awarded through a competitive auction process. This paper simulates the most recent CfD auction for offshore wind, using a novel methodology to assist developers in preparing their bid strategy and for policymakers to test auction efficiency. The simulation's results show developer's leading strategy is to shade their bid to increase auction pay-off. A developer's incentive to shade their bid depends on the project's capacity and minimum bid price; the offshore wind farm Hornsea 3 has the greatest incentive to shade its bid as its optimum bid price is further from its cost price, and results in the highest expected value of additional auction pay-off. The median strike price estimated by the model is £39.23/MWh, and the most likely winners, as predicted from the simulations, are Hornsea 3, Inch Cape, East Anglia 3 and Norfolk Boreas. Published auction results show that the estimated strike price from the simulation is 5% higher than the £37.35/MWh awarded strike price; however, the model successfully predicted the winners. Further analysis of results demonstrates that developers adopted a risk-averse bidding strategy, bidding at a pre-determined floor (coexist) price, guaranteeing subsidy. As a result, £38 million of the subsidy budget was unused.

## 1. Introduction

Many governments worldwide have announced ambitious renewable energy generation targets due to anthropogenic global warming, energy security and volatility of fossil fuels prices [1]. For example, the EU has mandated that 43% of energy generation must come from renewable energy sources by 2030 [2]. Governments have introduced a series of policy tools to accelerate the deployment of these renewable energy technologies, including offshore wind. In the UK, the primary subsidy mechanism to help achieve these targets is the Contracts for Difference (CfD), awarded in competitive auction processes [3]. The CfD guarantees renewable energy asset owners a fixed price (£/MWh) for the electricity generated for the 15-year contract length [4].

The subsidy award heavily incentivises investment in renewable energy projects by protecting developers from volatile wholesale prices. Providing revenue certainty helps de-risk renewable projects, thus reducing the cost of raising capital and increasing the economic viability of renewable projects [5]. For many developers in offshore wind, the CfD is the only viable route to market [5]. Failure to win a CfD contract can result in significant project delays as developers await the next auction or attempt to secure alternative financing. There are several risks to consider while bidding at auction. Bid too high and risk not being awarded a contract, or bid too low and then risk experiencing the winner's curse, potentially leading to unprofitable sites and the non-realisation of projects [6].

Renewable energy developers must perform financial and strategic analyses to formulate a bidding strategy. Financial analysis is related to all known factors (e.g. seabed rental cost). Strategic analysis is associated with assessing uncertainties (e.g. level of competition, competition costs, future wholesale electricity market prices). This strategic element is crucial and is considered non-negligible [7]. Therefore, to determine a bid price, bidders must characterise the uncertainty to understand the auction dynamics and make predictions of the auction outcome. One way of achieving this is through auction simulation, which helps test the existence of dominant strategies in the presence of different bidder configurations, valuations and uncertainty [8].

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**Table 1**

Budget (million £), in monetary terms [2012 prices], for the fourth CfD Allocation Round. Illustrating pot structure for the auction [15–18].

| | Delivery and valuation years | | | | | |
|---|---|---|---|---|---|---|
| | 2023/4 | 2024/5 | 2025/6 | 2026/7 | 2027/8 | 2028/9 |
| Pot 1 - Wind & Solar (M£) | 10 | 10 | 10 | 10 | – | – |
| Pot 2 - including: (M£) | – | – | 75 | 75 | 75 | 75 |
| Minimum for floating wind (M£) | – | – | 24 | 24 | 24 | 24 |
| Minimum for tidal stream (M£) | – | – | 20 | 20 | 20 | 20 |
| Pot 3 - Fixed offshore wind (M£) | – | – | 210 | 210 | 210 | 210 |

Developer's incentive to bid strategically and deviate from marginal cost further complicates the CfD auction process. From an auctioneer's standpoint, strategic bidding, whereby developers do not reveal their true cost, is an example of auction inefficiency [9]. In auction-theoretic literature, when the auction concerns several homogeneous items (i.e. multi-unit auction), the dominant strategy is not to bid at cost, as seen in a perfectly efficient allocation process [10]. The design features of the CfD auction incentivise varying strategies. For example, the uniform pricing auction format means that all accepted bids receive the same price. One form of strategic bidding is shading, where players increase their bid above cost to increase their expected pay-off [11]. Bid-shading is explained further in Section 2.2. Simulation routed in game-theoretic principles can help quantify the likelihood of each player engaging in this form of strategic behaviour. In the context of CfD auctions, players participating in the auction are developers.

Simulation can test auction design and its effect on allocation efficiency, allowing empirical testing of several different rule configurations, which helps inform policymakers on auction design. Renewable energy subsidy (RES) auctions have not yet converged onto one design; therefore, further research is warranted to explore rule design changes for policy recommendations [3]. Additionally, simulating the auction can be useful to test any rule changes or parameters set (e.g. budget impact) [12].

This paper introduces a novel methodology for studying CfD auctions dynamics, building on the model methodology outlined in [13], and enables for detailed analysis of real-world Renewable Energy Subsidy auctions. Several novel elements associated with the methodology do not feature in the few studies conducted on Renewable Energy Subsidy (RES) auctions or in adjacent auction modelling literature. The closest model present in existing literature can be seen in work produced by Anatolitis et al. [14]. However, this work differs from the presented model for a number of reasons. Firstly, previous work considers fictitious case studies. This work couples an auction simulation with an offshore wind cost assessment tool that allows CfD auctions to be simulated by depicting real auction players characterised by real offshore wind projects. Basing case studies on real auctions allows for a realistic depiction of competition, allowing for auction dynamics to be analysed. Additionally, introducing stochastic simulation allows for better characterisation of the uncertainty experienced by auction participants. Secondly, this work incorporates game theory and probability theory elements to allow auction participants to test various bidding strategies. Previous work assumed that developers reveal their true value and bid at cost. Finally, the presented methodology uses auction simulation to analyse past auction results, which can be used to understand auction behaviour and inform future bidding strategies. It also enables policymakers to make conclusions on the auction's effectiveness at allocating resources.

The simulation results obtained in this paper have not been calibrated against the actual auction results and are based solely on information available before the auction. The results are then compared against the actual auction results to help inform future bidding strategies. Developers can use the methodology to prepare better auction strategies, which prevents the winner's curse and mitigates project non-realisation. Policymakers can also use the methods described to test new auction formats and ensure allocation efficiency. The remainder of this paper is structured as follows: Section 2 introduces the theoretical

background underpinning the methodology and the relevant literature. Section 3 outlines the novel methodology for simulating CfD offshore wind allocation rounds. In Section 4, the methodology is applied to an actual Case Study designed to replicate the most recent auction. Finally, Section 5 presents the results before concluding.

## 2. Theoretical background and literature review

### 2.1. CfD auction design

The UK CfD auctions have a multi-unit, sealed-bid, uniform price (pay-as-cleared) format. A multi-unit auction is where several homogeneous items are sold [19]. A uniform price format means that all successful bidders of the same delivery year receive the same remuneration, determined by the highest successful bid. In the CfD auction, this bid sets the *strike price* as it determines the remuneration bidders receive for each unit (£/MWh) of electricity generated. In uniform pricing auctions, such as the CfD, players can receive either the highest accepted bid (their own) or zero.

The total CfD subsidy budget is divided into different technology pots. Pot definitions are modified according to policy targets at the time of the auction [20]. The CfD subsidy is awarded in different allocation rounds; previously, each round occurred every two years. However, CfD auctions are now set to occur every year. The most recent CfD auction, the fourth auction to occur, is known as Allocation Round 4 (AR4) [21], which is the focus of the Case Study presented in this work. Table 1 illustrates the AR4 pot structure and allocated budgets. Pot allocation is dependent on the UK Government's renewable energy policy. For example, a lack of government support for solar and onshore wind saw the withdrawal of funding for these technologies in previous auction rounds [22]. Support for these technologies has been reinstated for AR4. The government can also ring-fence budget for particular technologies, this guarantees that support is awarded to those technologies and is frequently done to support the deployment of less mature technologies. In AR4, only floating wind and tidal technologies received ring-fenced support.

The allocation process for CfD contracts is as follows: The process begins with National Grid Electricity System Operator (National Grid ESO) inviting eligible applicants to bid for the available budget in each pot. Bidders must first satisfy several pre-qualification criteria to compete in the allocation process. For example, developers must obtain all the necessary consent for their site and a grid connection agreement. Additionally, for projects exceeding 300 MW, a *supply chain plan* which outlines how the project will promote competition, innovation, and skills in the supply chain must be submitted and approved. Other important considerations, such as local content, will also play a part in the eligibility of projects [23].

Prior to the auction, a budget notice is issued, which declares a capacity minima, capacity maxima, or total budget for the auction. Any singular project exceeding the capacity maximum is rejected. A minimum capacity results in projects with the lowest bids automatically accepted up to the minimum, providing the bid price is equal to or below the ceiling price. Finally, the budget dictates how many projects are accepted by assessing the budget impact of each project using the Valuation Formula (described in Section 3.1.3). Typically, the capacity maximum or budget notice is the limiting factor in determining the
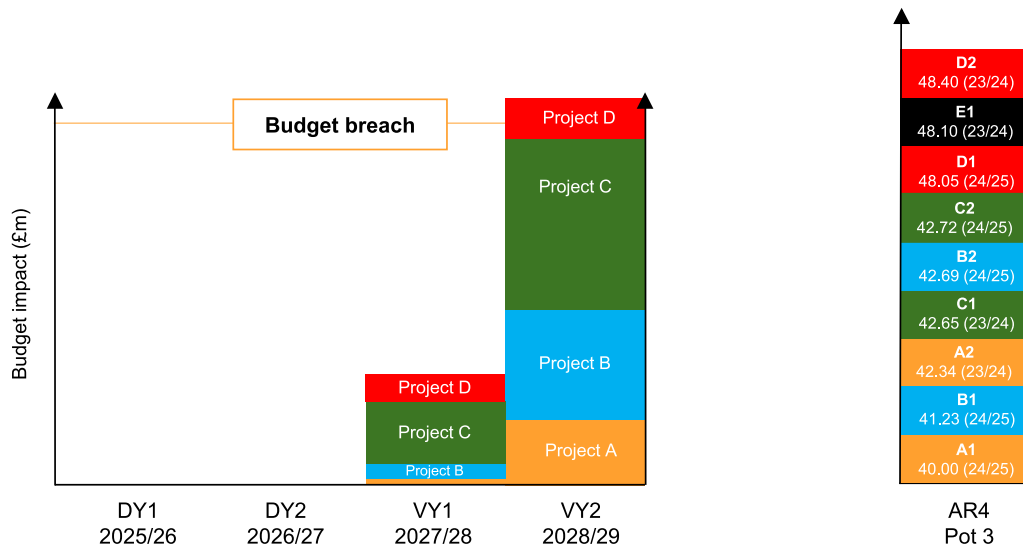
**Fig. 1.** Illustration of how the stack of bids is assessed against a budget, resulting in a budget breach.

volume of capacity procured. The UK government did not apply a maxima or minima to Pot 3 in AR4, so an auction determined by the budget will occur. Therefore, this type of auction will be the focus of this paper. Not imposing a capacity cap on the auction is frequently done to drive competition between developers. Six months prior to the auction the government issued a revised budget revision for Pot 3, increasing the budget by £10 m to £210 m. This budget revision's effect on auction dynamics is analysed in Section 4.2.

Developers in the UK CfD auction submit up to four flexible bids. The flexibility applies to the bid's capacity, price, and delivery year. Developers can only submit a maximum of two bids into each delivery year. The flexible bids allow developers to submit a number of different capacities into the auction. Developers can, therefore, choose to submit multiple bids for varying proportions of their total consented capacity, reducing the bid's total budget impact and increasing the probability of being awarded a contract.

After receiving all sealed bids from all developers, National Grid ESO combines all bids arranged in ascending order based on the bid price to create a bid stack. The bids are then considered in the order of the bid stack, starting with the cheapest bid. If accepted, the auctioneer assesses the budget impact of the next bid. A bid is rejected if the addition of the bid results in a budget breach (as seen from Fig. 1). If this occurs, the next flexible bid of this project is considered under the interleaving rule. For more detail on the UK CfD allocation mechanism, refer to the CfD allocation framework [24].

The interleaving rule allows the auctioneer to consider the flexible bids of developers. Under the interleaving mechanism, a participant's next flexible bid is considered after the original bid is rejected. In the illustrative example shown in Fig. 1, Project D results in a budget breach, resulting in an interleaving loop forming which includes all bids between the first rejected bid and the next flexible bid of that project. Therefore, in this example, Project E1 and D2 are considered together, as E1's bid price is between D1 and D2, so it forms part of the interleaving loop. For D2 to be accepted, both E1 and D2 must fit into the budget and not result in a budget breach of VY2 (Valuation Year 2). If either E1 or D2 results in a budget breach of either VY, then both bids are rejected, and the auction is closed. This is an example of unsuccessful interleaving. In this example, as Project C is the last accepted bid, it is the project which sets the strike price for both delivery years of the auction. However, if neither E1 nor D2 results in a budget breach, interleaving is successful, so both bids are accepted, and D2 becomes the strike price for both delivery years. If two bids are submitted with an equal bid price, and accepting both bids results in a

budget breach, then the accepted bid is decided by a tiebreaker. During a tiebreaker, the Delivery Body must choose one of the Qualifying Applications at random [24].

One significant change from previous CfD auction rounds is simplifying the role of delivery years. In AR4, the whole auction closes if the monetary budget is breached in one delivery year. Therefore, a single strike price will apply across the auction, which is subject to the Administrative Strike Price (ASP). The auctioneer sets the ASP, the ceiling price awarded to a technology. For further information on determining the ASP, refer to the UK Government website [25]. However, qualifying applicants will still bid into individual delivery years as before. In previous ARs, typically, there were separate strike prices for each delivery year; this is unlikely to happen in AR4. The two strike prices in previous auction rounds occurred because a budget breach would result in delivery year closure instead of entire auction closure. This meant that in the case of a budget breach, the auctioneer could continue allocating capacity to the other delivery year until a second breach occurred, resulting in auction closure [22]. The effect of this rule change on the auction dynamics has been analysed in Section 4.2.4.

### 2.2. Background to bidding into CfD auctions

An awarded CfD strike price can significantly affect the profitability of offshore wind developments. Therefore, CfD bids must be carefully considered, allowing developers to cover costs and give investors the required return on their investment. Determining a CfD bid price requires an analysis of costs and revenues throughout the entire lifetime of the wind farm. This is necessary to estimate the project's cash flow and then calculate a minimum CfD bid price which satisfies the investment criteria. However, estimating cash flows accurately is challenging, as significant uncertainty exists. For example, there is uncertainty associated with one's cost of components, such as foundation, cables and steel costs [7]. Therefore, Monte Carlo sampling from cost distributions produces stochastic outputs, which better characterises the uncertainty associated with each cost component [26].

The relevant corporate finance theory can explain developers' motives for bidding in a CfD auction. Offshore Wind developments are large capital-intensive projects where developers must raise significant capital before reaching a final investment decision on a project. Recent surveys on costs of capital of onshore wind energy projects across the EU have found shares of debt of between 55% and 80% [27–29], largely because debt is cheaper than equity, and so minimises project costs.
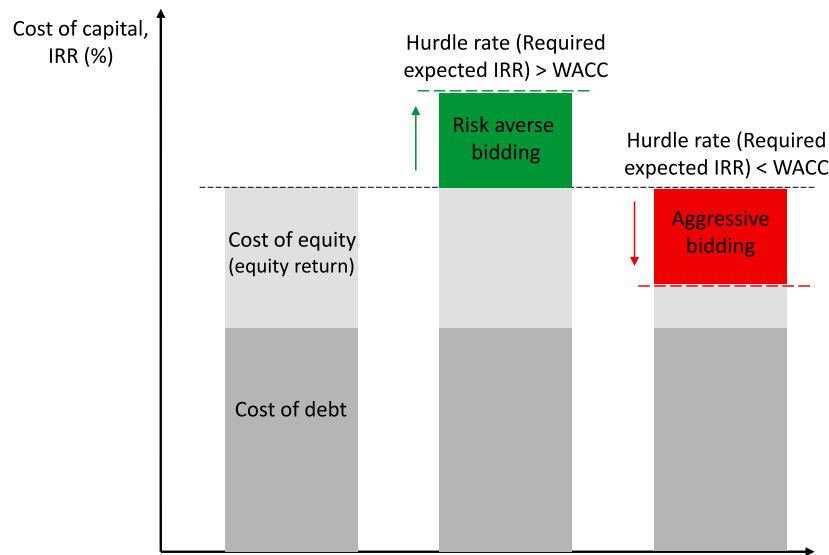
**Fig. 2.** Developers may differentiate their hurdle rate (required IRR for project execution) from the calculated WACC as part of their bid strategy.
*Source:* Adapted from [33].

Moreover, to raise a high proportion of debt at preferred lending rates, banks typically require that projects have revenue certainty and are protected from merchant risk [30].

The cost of capital is the costs under which lenders invest debt or equity into a company or project [31]. The overall cost of capital is weighted by the shares and cost of debt, which forms the weighted average cost of capital (WACC) [32]. Developers use the WACC to discount cash flows and calculate the Net Present Value (NPV). A positive NPV indicates that the project creates value and should be undertaken. However, in practice, companies only undertake projects which meet or surpass an internal hurdle rate (required IRR). The hurdle rate is typically based on the WACC and is usually higher but, in some instances, can be lower depending on the strategic motivation of a company. For example, in project finance, hurdle rates can be lower than WACC if trying to gain a strategic advantage in a new market [33]. Therefore, in simulating auctions, it is the internal hurdle rates which can be set by developers and varied according to risk appetite [34]. This dynamic can be seen in Fig. 2. The risk appetite represented by the hurdle rate can vastly impact a developer's CfD bid value. As a result, developers can alter their risk profiles and significantly alter their CfD bid price (discussed further in Section 4.3.1).

### 2.3. Auction simulations review

Bidding behaviour in auctions is a well-studied area of research. Wilson et al. [35] were the first to formalise the multi-unit auction. They noted that an offer is made according to a private value. Goeree et al. [36] used an auction theoretical model to demonstrate how uncertainty experienced by bidders harms allocation efficiency and efforts to reduce uncertainty by the auctioneer results in increased efficiency and sellers' revenue. There is substantial literature which utilises auction theory to describe expected auction outcomes and optimum strategies for multi-unit auctions for electricity spot markets [37–39]. For example, Wolfram et al. [40] demonstrate that in multi-unit auctions, such as in electricity spot markets, developers typically strategically bid to increase their auction pay-off. The above examples have focused on varying auction formats, which are related but not equivalent to the auction dynamics, design rules, or behaviour of players in Renewable Energy Subsidy (RES) auctions. Therefore, further research is required on RES auctions specifically, to draw recommendations which is useful for auction preparation and design.

RES auctions, such as the CfD auction, are a widely studied area of research. Significant literature has addressed auction design to optimise allocation efficiency to ensure policy targets are met. For example, Matthaus et al. [41] used empirical data from previous auction rounds to determine the effect of penalties and pre-qualification criteria on the realisation rates of projects. Kreiss et al. [42] used auction theory to assess the impact of uncertainty on bidders and the implications of this on the non-realisation of projects. This work builds on both examples, by not only focusing on making recommendations for policymakers, but also developing a methodology for developers to better prepare a bid price, which mitigates against the non-realisation of their project.

Welisch et al. [43] used a previously developed agent-based model to empirically test the effect of non-realisation penalties on developers bidding truthfully and revealing their costs. However, this work was based on fictitious case studies, therefore it does not portray a realistic depiction of competition. Anatoloitis et al. [44] used the same agent-based model to test the allocation efficiency of two major auction formats, pay-as-bid versus pay-as-clear, for German onshore wind power auctions. In both these previous examples, the simulations assume that agents bid truthfully in uniform price auctions. However, several pieces of literature demonstrate that in multi-unit auctions with uniform pricing, players have the incentive to bid strategically [10], particularly if bidders hold estimations of the valuations of other players. Additionally, it is assumed that players bid according to an estimated LCOE (Levelised Cost of Energy). In reality, auction bid prices are related to but are not equal to the LCOE of the project, as LCOE does not take into account estimate future revenues [45].

The literature survey suggests that there have been recent attempts to simulate renewable energy subsidy (RES) auctions to understand auction dynamics better and ensure allocation efficiency. However, most published work focuses on fictitious case studies and does not make recommendations for auction participants. To the best of our knowledge, no published literature has used auction simulation and estimated project-specific costs to predict and analyse a CfD auction result and then make recommendations evidenced by simulation for auction participants. Simulating auctions is helpful for developers and policymakers; it allows to test whether the auction is efficient at allocating resources and will enable developers to test hypotheses used to prepare bidding strategies. A well-thought-out bidding strategy can help prevent the winner's curse, mitigating the non-realisation of renewable projects [45].
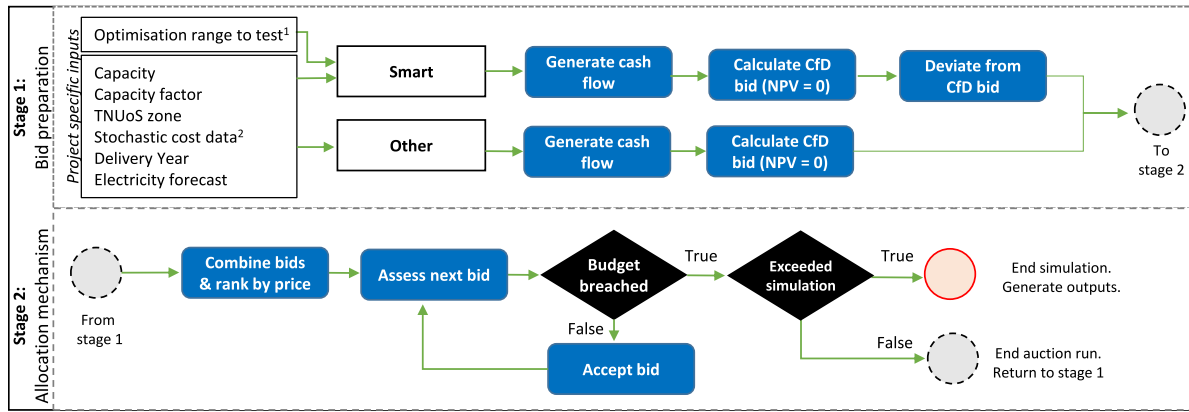
**Fig. 3.** High-level flow diagram illustrating one auction run process [13].[1] Highlights the optimum bid price range to test, which is user input and gives the *smart* agent added flexibility to deviate from the calculated CfD bid price. The range provided allows the *smart* player to test the success of a range of bids given the competition it expects.[2] Stochastic cost data includes the DEVEX, CAPEX, OPEX and DECEX.

## 3. Methodology

### 3.1. Model summary

The scope of work outlined in Section 1 uses a novel modelling approach for simulating CfD auctions. For a detailed presentation of the numerical framework used to carry out this analysis, refer to work produced by the authors in Kell et al. [13]. The auction modelling tool has been modified to allow for CfD auction rule changes made for AR4 and to enhance the pre-auction analysis; Section 3.1.3 outlines the modifications made to the tool.

The auction modelling tool is a stochastic, agent-based, modelling approach which utilises game-theoretic principles to generate bid strategies for generators attempting to win a CfD contract. The model utilises the Python framework for agent-based modelling: Mesa [46]. The model allocation mechanism is based on the CfD allocation framework; however, the theory underpinning the model applies to other RES auctions. The model uses Monte Carlo sampling from cost data to produce stochastic outputs that better characterise the uncertainty experienced by developers (as described in Section 2.2). Therefore, each complete simulation typically contains over 20,000 auction runs to average over stochastic inputs. There are two main stages of each auction run. These are defined as the *Bid Preparation* and *Allocation Mechanism* sections; further explained in this Section.

The game-theoretic aspect of the model is utilised to determine a bid price for a selected *smart* player based on the expected value E[X] of auction pay-off. This player differs from the others based on their knowledge and capabilities, as shown in Table 2. The *other* players in the simulation bid truthfully and reveal their costs to the auctioneer. Bidding truthfully is how auction designers and policymakers would hope all players will act. However, the smart player's added capability allows for optimising a bid price based on increasing the expected value E[X] of its auction pay-off in £/MWh. The uncertainty means many possible probabilistic outcomes are feasible, and given the uncertain outcome, E[X] gives a basis for selecting a bid price. An overall flow diagram illustrating the game-theoretic feature of the model is shown in Fig. 3.

The smart player can deviate from the calculated minimum CfD bid price $b_i$, for player $i$, calculated in the bid Preparation stage (see Section 3.1.1). In deviating from this bid price, by an amount known as $x$, it obtains a new bid price, $b_i + x$, which it tests many times to assess the success of this bid price. The smart player collects information on the strike price, $P$, and whether the project was successful for each auction run. The *smart* player can predict $P$ using its additional capabilities as highlighted in Table 2; it is then used to determine the amount bid-shaded. The E[X] of additional auction profit for a particular bid price is calculated using Eq. (1). Where $W\%$ is the mean

**Table 2**
Demonstration of the knowledge and capabilities of each category of an agent in the model.

| Capability/Knowledge | Smart | Other |
|---|---|---|
| Competitor cost and capacity | Yes | No |
| Number of competing projects | Yes | No |
| Total capacity auctioned | Yes | No |
| Deviate CfD bid price | Yes | No |
| Optimisation of E[X] | Yes | No |

probability of winning for that bid deviation. $W\%$ and $P$ are a function of the bid price submitted by the smart player. For a detailed theoretical derivation of Eq. (1), and for more detail on the theory relating to the model's game-theoretic element, refer to the work produced by Kell et al. [13].

$$E(b) = \sum_x ([P(b_i + x) - b_i] \cdot W\%(b_i + x))\qquad(1)$$

### 3.1.1. Bid preparation

The bid preparation stage converts input project data into a CfD bid price, $b_i$, for a player $i$. To generate a bid price for each player, it samples project data from a unique distribution for each player. For each auction run, a bid price is generated through independent samples of the same distribution. The bid function $b_i(c_i, r_i)$ is a function of one's total discounted costs $c_i$ and also the total expected discounted revenue $r_i$ generated by a project. Costs and revenue streams are discounted to determine a $b_i$, which gives discounted equity return. Calculating cash flows of renewable generating projects to determine a bid price is consistent with previous analysis on this topic [4].

Cost streams include capital, operational, decommissioning, development, rent, interest payments, tax and TNUoS (transmission network use of system) charges. Revenue streams include CfD payments, contracted power, and wholesale revenues. An AEP (annual energy production) value calculated for each wind farm enables the model to estimate future revenues. AEP (MWh) is calculated by multiplying the wind farm's capacity, capacity factor and total hours in a year. The capacity factor is determined considering the mean wind speed, the power curve of a generic turbine, and estimated losses. The calculated bid price, $b_i$, is mapped to each player. The submitted bid of each player consists of the bid price, capacity and delivery year.

### 3.1.2. Allocation framework

After the bid preparation stage is completed, the allocation framework collects and then sorts in ascending order all bids from each

player. Then, the budget impact of bids is assessed against the auction budget, using a Valuation Formula to decide which bids are accepted.

The model replicates the uniform price auction format (as described in Section 2), assessing bids one at a time. Bids are combined into a bid stack arranged in ascending order. If a bid is accepted, it elevates the auction's strike price to the price of the last accepted bid. Once a bid is accepted, all other flexible bids associated with this project are removed from the bid stack. All previously accepted bids will have their payment price elevated, which ensures that all successful bids receive the same price. Once the total budget is exceeded, then the bid which causes the capacity breach is rejected. An interleaving loop forms (as described in Section 2) between the rejected bid and the second flexible bid from that player. The auction closes if the second flexible bid also breaches the budget.

The model accepts up to four flexible bids for each project, of which a maximum of two bids can be submitted for each delivery year. Submitted bids must be of varying capacities. Therefore, the outputs from one auction run of the model are as follows: strike price, winning projects, all project bids and the total amount of capacity procured.

### 3.1.3. Modification of numerical framework

The auction modelling tool has been adapted to account for rule changes made in this allocation round, so it has been modified from the methodology outlined in Kell et al. [13]. The novelty of this paper is associated to the application of the model to study CfD auctions. The methodology is demonstrated through a case study designed to replicate a live auction process. The auction type has been changed from a maximum-only auction, where a maximum total capacity limit determines total accepted bids, to an auction concerning an overall budget. Previously, the auctioneer was set to procure a fixed amount of capacity (MW) from developers. This set amount of capacity was then used to assess the number of bids accepted and close the auction when this total amount of capacity was met or exceeded. This simplification of the auction procedure has been repeated in other published work in this research area, such as by Welisch et al. [47]. While it is reasonable to make this simplifying assumption for the AR3 Pot 2, it does not truly replicate the actual auction procedure outlined in the AR4 allocation framework [20]. In previous auctions (e.g. AR3), a capacity maxima of 6 GW of offshore wind was applied to the auction and this set the total amount of capacity procured [24].

Discussed in Section 2, the limiting factor in determining the volume of procured capacity is a monetary annually capped budget issued by BEIS. Therefore, one cannot accurately predict the capacity procured in pre-auction analysis without estimating the budget impact of each auction participant. For this reason, the auction model has been updated to procure capacity as a function of the stated budget. The model is updated to assess each bid and its impact on the budget before deciding whether to accept or reject it. The model considers the budget impact of each project as outlined in Section 2, and utilises the Valuation Formula (shown in Eq. (2)) as outlined in the Valuation Framework document produced by BEIS [20]. Where $BI$ is the budget impact, $SP$ is the strike price, $RP$ is the reference price, $LF$ is the given Load Factor for offshore wind, $YR1F$ is a factor applied to each project to account for partial year generation, $C$ is the capacity, $TLM$ is the Transmission Lost Multiplier, $RQM$ is the Renewable Qualifying Multiplier and determines the payments made to generators based on the renewable content of their fuels, and $CHPQM$ is the $CHP$ Qualifying Multiplier which ensures that developers are producing good quality Combined Heat and Power.

$$BI = (SP - RP) \cdot LF \cdot YR1F \cdot C \cdot (Days_{yr} \cdot 24) \cdot (1 - TLM) \cdot RQM \cdot CHPQM$$

(2)

The values for each term in the above equation are summarised in Table 3. The values for the constants are released along with the budget by BEIS, and are known parameters. The applicable BEIS reference

**Table 3**

Values are constant for all developers and have been obtained from the Allocation Framework document produced by BEIS [20].

| Term | Value | Unit |
|---|---|---|
| RP | 32.85 | £/MWh |
| LF | 63.1 | % |
| YR1F | 1 | |
| Days | 365 | |
| TLM | 0.9 | % |
| RQM | 1 | – |
| CHPQM | 1 | – |

price used in this analysis is £32.85/MWh, given for the valuation year 2028/29. As this is the lowest reference price for all valuation years, it is the price which will set the affordability.

As mentioned in Section 3, the role of delivery years has been simplified. This change has, therefore, also been implemented in the numerical framework, meaning that the auction will close once the budget has been breached in any delivery year. This means that one strike price will be issued for all projects regardless of the delivery year they bid. This rule change will impact the auction dynamics and, thus, the potential bidding strategies of developers. A comparison of the effect this has on strike prices awarded can be seen in Section 4.2.4.

### 3.2. Modelling methodology

#### 3.2.1. Affordable capacity

The monetary budget issued by BEIS gives an indication of affordable capacity if used alongside the Valuation Framework Formula (Eq. (2)) outlined in Section 3.1.3. Therefore, an affordable capacity analysis can be used to estimate the competitiveness of the auction based on the monetary budget and the expected eligible capacity competing. As mentioned in Section 2, a budget notice revision was issued by the Secretary State of BEIS to increase the budget by £10 m to £210 m. Therefore, the affordable capacity for the old and new budgets is analysed. Using the known budget and constants outlined in Table 3 it is possible to solve for $C$ with a range of $SP$ values using Eq. (3).

$$C = \frac{BI}{(SP - RP) \cdot LF \cdot YR1F \cdot (Days_{yr} \cdot 24) \cdot (1 - TLM) \cdot RQM \cdot CHPQM}$$

(3)

#### 3.2.2. Game-theoretic methodology

The model has been used to demonstrate how the incentive to engage in strategic bidding (e.g. bid shading) depends on the player and its project. The model is run seven times (once for each player), altering the smart player for each simulation. This means that only one player at a time will have additional capabilities (seen in Table 2) and, therefore, knowledge of other competitors' bids. Therefore, only one player at a time uses its additional competence to test for the existence of a bid price that maximises E[X].

When running the model for each smart player, the smart player's costs are assumed to be deterministic. This is because the game-theoretic simulations are computationally expensive, and stochastic bid prices for the smart player would require many more thousand auction simulations for results to converge. If it can be assumed that the smart player's costs are known, then computational times are reduced significantly. Therefore, a deterministic cost modelling tool (OWCAT) [48] has been used to generate input data for the project, acting as the smart player. The *other* players will utilise stochastic cost data to generate bid prices. This cost modelling tool is described in Section 4.

Players are assumed to be unwilling to reduce their bid price below the minimum CfD bid price calculated, which gives them a minimum equity return. In doing so, the developer would risk not meeting the hurdle rates required for the project, which could result in non-realisation. For this reason, the players only consider increasing their

**Table 4**

High-level overview of some of the publicly available site/project specific input data which was used to generate cost estimations [49,50].

| Project | Capacity | Average depth (m) | Mean wind speed @ hh (m/s) | Distance to port (km) | Foundation type | Export type | TNUoS zone |
|---|---|---|---|---|---|---|---|
| Hornsea 3 | 3000 | 38 | 10.47 | 250 | Monopile | HVDC | 18 |
| Norfolk Boreas | 1800 | 33 | 10.30 | 92 | Monopile | HVDC | 18 |
| East Anglia 3 | 1480 | 39 | 10.23 | 80 | Monopile | HVDC | 18 |
| Moray West | 850 | 45.4 | 10.13 | 70 | Monopile | HVAC | 1 |
| Inch Cape | 1000 | 52 | 9.97 | 45 | Monopile | HVAC | 11 |
| Seagreen 1A | 500 | 54 | 10.55 | 65 | Jacket | HVAC | 4 |
| Seagreen | 1075 | 54 | 10.55 | 65 | Jacket | HVAC | 4 |

**Table 5**

Overview of cost input data used to generate a bid price for each player.

| Project | Capacity (MW) | DEVEX (£m) | CAPEX[a] (£m) | OPEX[a] (£m/year) | DECEX (£m) | Capacity factor[a] |
|---|---|---|---|---|---|---|
| Hornsea 3 | 3000 | 172.6 | 5752.6 | 83.2 | 232.0 | 0.480 |
| Norfolk Boreas | 1800 | 134.1 | 3634.2 | 52.6 | 132.4 | 0.477 |
| East Anglia 3 | 1480 | 121.3 | 2839.4 | 44.4 | 106.8 | 0.475 |
| Moray West | 850 | 92.2 | 1524.3 | 29.3 | 72.1 | 0.479 |
| Inch Cape | 1000 | 99.9 | 1783.8 | 27.7 | 78.4 | 0.499 |
| Seagreen 1A | 500 | 71.2 | 939 | 19.4 | 56.8 | 0.507 |
| Seagreen | 1075 | 107.1 | 1953.1 | 40.4 | 91.9 | 0.507 |

[a]Inputs, show the median data for stochastic inputs, distribution of stochastic data is shown in Fig. 4.

bids beyond the minimum acceptable CfD bid price. Therefore, the players observe the effect of increasing their bid price by a maximum of £5/MWh, with an interval of £0.50/MWh. This range was chosen as it considers a wide possible bid range which also identifies a peak in the E[X] graphs produced in the results (see Fig. 11). Each player observes the success of 10 bid prices beyond their minimum calculated CfD bid price. For every bid price tested by the model, 1000 auction simulations are generated. This auction simulation number is chosen because there is a strong convergence of results after 1000 simulations per bid price [13].

*3.2.3. Delivery year rule change*

AR4 delivery year rules stipulate that if the monetary budget is breached in one delivery year, the whole auction closes. Therefore, a single strike price applies across the auction (subject to ASPs). This reduces the strategic complexity of the auction, as it means that the success of a bid is irrespective of what delivery year it bids into.

To model the effect the rule change has on the auction outcome, the case study described in Section 4 is modelled with AR3 delivery year rules and compared to the AR4 rules. To model the AR3 delivery year rules, a similar procedure as described in Section 3.1.3 is followed. The budget impact of each bid is assessed using the Valuation Formula; however, the delivery year that the bid is submitted determines which reference price is used to calculate the budget impact. For example, if the bid is submitted into the first delivery year, a reference price of £38.77/MWh applies. Similarly, if the bid is submitted into the second delivery year, a price of £32.85/MWh applies. Once the £210 m budget is breached in either of these delivery years, that delivery year is closed, and all other bids associated with that delivery year are removed from the bid stack. Allocation continues to the other delivery year until the £210 m budget for that year is breached; the last accepted bid into that delivery year sets the strike price. The auction then closes. As the reference price for the second delivery year is significantly lower, the budget impact is greater, meaning that the second delivery year is likely to close first. The results generated from the simulation using AR3 delivery year rules are then compared to the results from AR4.

## 4. Case study and results

### 4.1. Case study description

The eligible projects expected to compete in AR4 are first introduced in this Section. As projects must have obtained the necessary consent

and approval from the UK government, details surrounding eligible projects are publicly available on the Planning Inspectorate (PINS) website [49]. The consenting documents outline a significant amount of information for each project, such as allowable build-out capacity, cable landfall point, export type and maximum turbine rating.

The project costs are modelled using publicly available site-specific and project-specific characteristics, which can be seen in Table 4. The data presented in this Table has been obtained from various sources such as PINS [49], and 4C Offshore's database [50]. Using this publicly available information, cost data is generated for each project using a previously validated proprietary stochastic cost modelling tool. The costs generated from this costing tool have been validated to an accuracy of ±15% [48]. Stochastic cost data is used to better characterise the uncertainty associated with projecting costs. The cost model produces stochastic outputs based on uncertainties associated with the individual cost parameters. Stochastic values drawn from this model are used to derive an empirical distribution of costs rather than assuming a specific distribution shape. The cost distributions used for the AR4 prediction can be seen in Fig. 4 and the median cost data for each project is shown in Table 5).

In addition to generating cost data for each project, several other inputs are required to estimate the CfD bid price of different projects. Financial assumptions such as WACC, IRR, and gearing ratios required for detailed financial modelling, are difficult to assume with any confidence for each player, so they are left generic for all developers. Hence, the site/project characteristic data is the key driver of differentiation between projects and determines the estimated bid price merit order of projects.

The following additional assumptions are the author's own and are made to simulate the AR4 auction. The assumptions are required to reduce the complexity surrounding unknowns of the auction process and do so without sacrificing the detail of the auction design.

1. **Forecast wholesale electricity market price** - Future wholesale electricity prices 30 years into the future are extremely challenging to predict. Forecasts will differ between developers and can impact the calculated CfD bid. As it cannot be estimated which forecast each player may use, to keep calculations relative, all developers use the same curve, which has an average market price forecast of £55/MWh for the next 30 years. This is based on the medium economic growth forecast produced by BEIS [51].
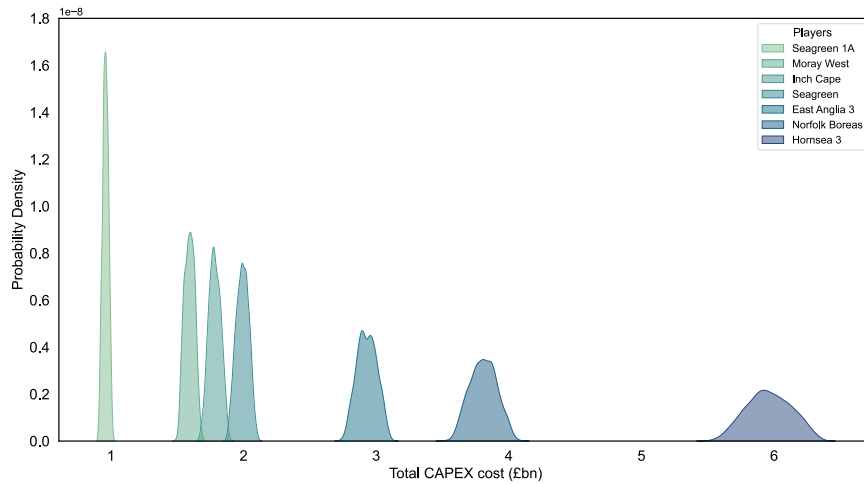
(a) Empirical distribution of generated CAPEX costs.
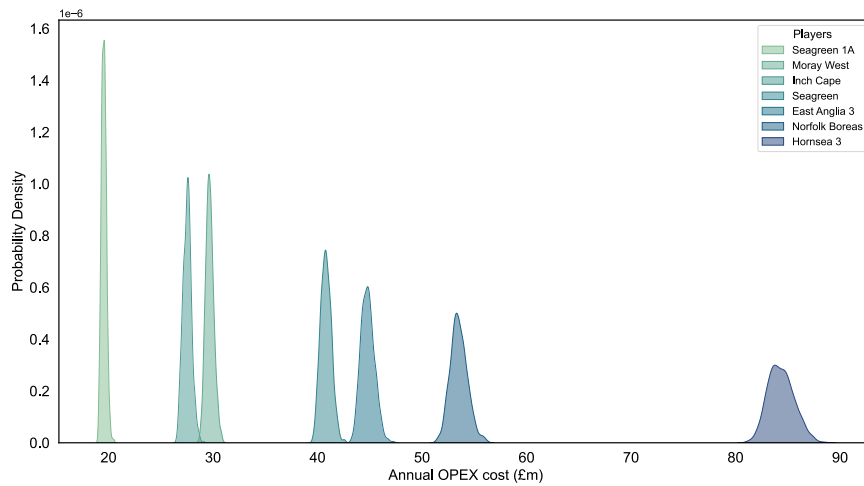


(b) Empirical distribution of generated OPEX costs.
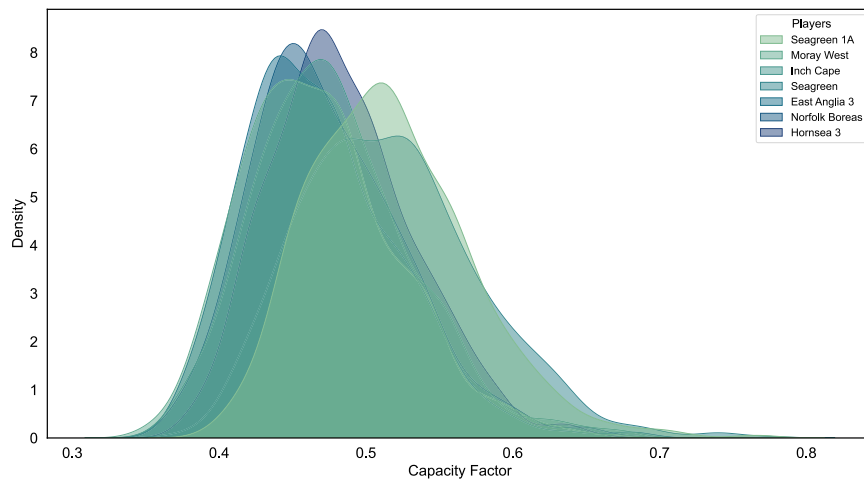


(c) Empirical distribution of generated Capacity Factors.

**Fig. 4.** Distributions of stochastic inputs for each player in the case study.

2. **TNUoS forecasts** - Transmission Network Use of System (TN-UoS) charges over the operational lifetime of a wind farm are required to estimate total costs. TNUoS charges are levied on generators as a cost for transmitting electricity on the electricity grid. The charges reflect the cost of building and maintaining transmission infrastructure. National Grid ESO provides forecasts only up to 2027/28. Therefore, this final forecast is extrapolated from the last forecast in a straight line to provide
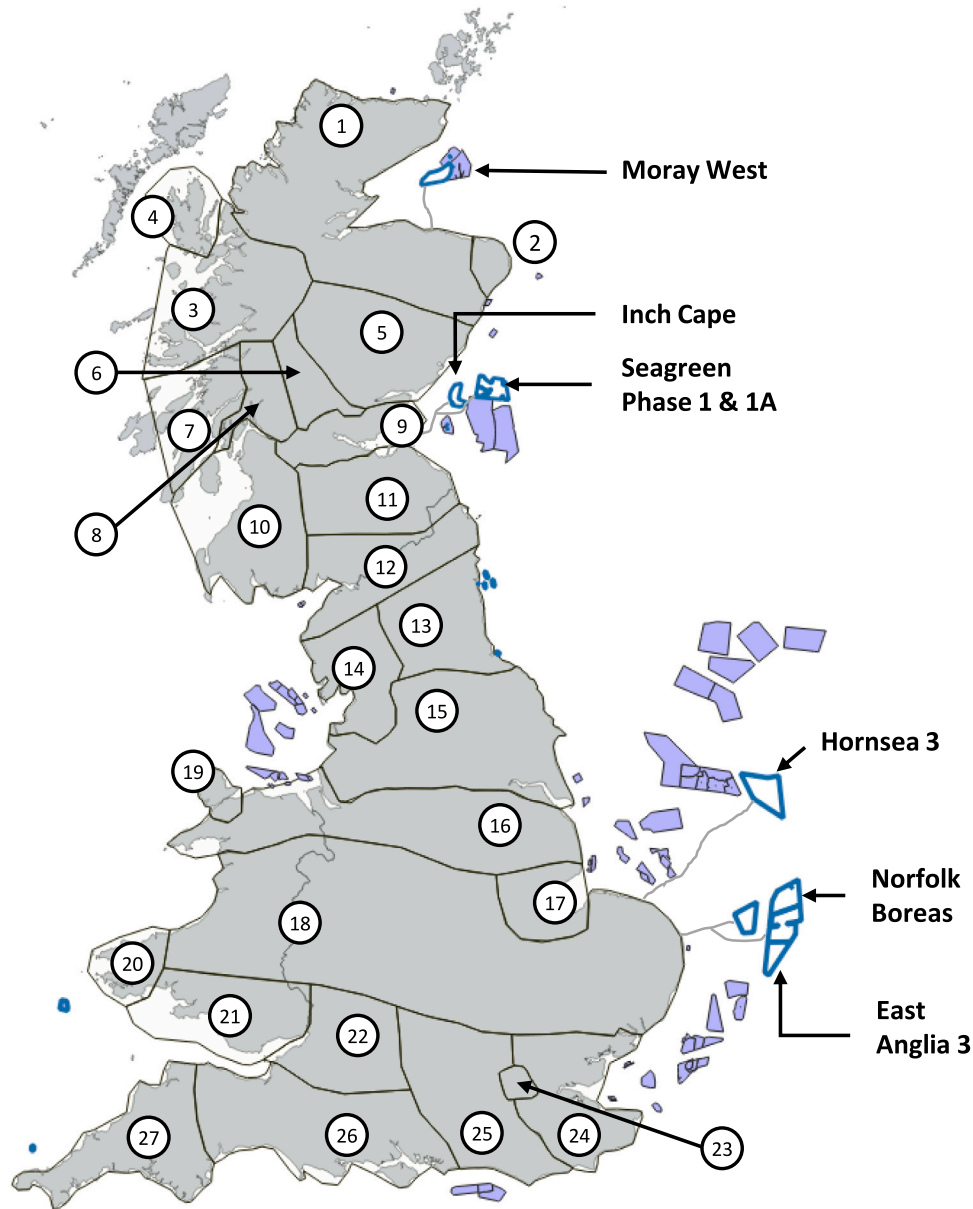
**Fig. 5.** Geographical location of offshore wind farms expected to compete in Pot 3 AR4. The 28 TNUoS zones, as outlined by National Grid ESO, are displayed on the map.

estimated charges for the entire 30-year wind farm period. All projects will derive their TNUoS charges from the same forecast.

3. **Discount rate** - Discount rates used by different developers are likely to vary based on risk appetite and business models. Variation between developers cannot be predicted; therefore, all developers are modelled using the same central discount rate of 6.3%, based on BEIS estimates [52].

4. **Flexible bids** - Developers can submit variations of their primary bid by varying the total amount of capacity of their bid. Flexible bids trigger the interleaving rule (as explained in Section 2). Flexible bids submitted by each player for each project are difficult to predict. However, as large eligible projects compete in AR4, the interleaving rule is expected to be of more importance (discussed in Section 2). For this reason, it is assumed that each player submits two bids, one at their total consented capacity and one at half this value.

5. **Real terms** - The auction modelling tool is set to analyse revenues and costs in 2012 in real terms, as this is the reference year used in the CfD auction.

### 4.2. Case study results and discussion

#### 4.2.1. Affordable capacity results

Fig. 6 shows the relationship between affordable capacity against strike prices. The intersection between the vertical lines and the curve shows how much capacity will be afforded at different strike prices of interest. It can be seen by comparing the £210 m and £200 m budget lines that the budget revision has made a marginal difference to the expected outcome of the results. The first vertical line represents the strike price which would be achieved if all 9250 MW of eligible projects (as depicted in Table 4) receive a CfD. This strike price is £36.85/MWh and £36.80/MWh for the £210 m and £200 m budgets, respectively. This is the coexist price and acts as a bid floor, the minimum price developers bidding in the auction will achieve. The coexist strategy is possible in AR4 as there is no capacity maxima cap and because a monetary budget determines the allocation process (as discussed in Section 2). As the coexist price is a function of the total eligible capacity expected to bid into the auction, developers must accurately predict the capacities of other competing projects. This price
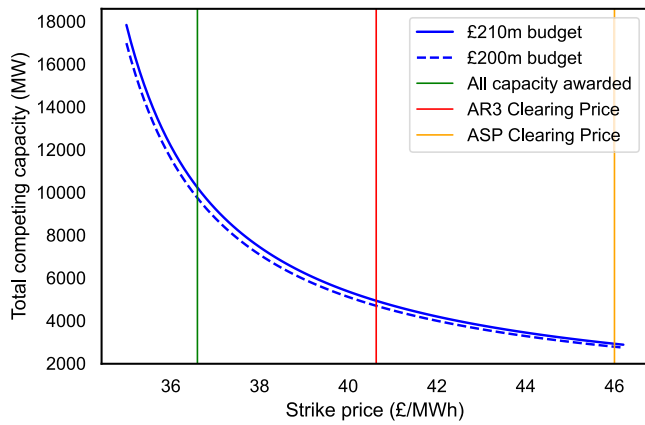
Fig. 6. Affordable capacity by the auctioneer due to the budget notice. The intersection of vertical lines and curves illustrates affordable capacity at three different strike prices.



Fig. 7. Stochastic results indicating the estimated likely strike price for AR4.



Fig. 8. Estimated total capacity procured by the auctioneer in AR4.

would remain true considering the assumptions based on the eligible projects and their build-out capacities are valid. The second vertical line depicts the total affordable capacity if the same average strike price of £40.63/MWh, achieved in AR3 (2019), occurs again in AR4. However, a repeat of the 2019 CfD strike price is unlikely, as historically, the price has decreased between auction rounds [15–18]. Under this scenario, 4950 GW of offshore wind capacity would be procured for the revised budget, compared to 4600 MW for the previous budget. The final vertical line on Fig. 6 shows the minimum amount of capacity that the auctioneer will procure. This represents the ASP set before the auction at £46/MWh and is the maximum strike price awarded to offshore wind generators. Under this scenario, a total of 2915 MW and 2800 MW will be procured for the revised and old budgets.

Fig. 6 also demonstrates to developers and the auctioneer the expected effect of increasing the budget by £10 m. It shows that the change in capacity procured and strike price is marginal. Therefore, it is unlikely that developers will aim to significantly change their bidding strategy due to the revised budget notice. However, suppose the government's intention by issuing the budget notice is to dramatically increase the amount of offshore wind capacity procured in line with their renewable targets. In that case, a larger increase in a budget revision is required.

Bidding at the coexist price depends on a developer's estimated costs, financial assumptions, risk appetite, outlook on future wholesale electricity prices, and eagerness to be awarded a CfD contract. If winning a CfD contract in AR4 is imperative to the project's viability, then there are several financial levers, such as sell-downs, project financing and hurdle rates that developers can adjust to reduce their CfD bid.

### 4.2.2. Stochastic results

Fig. 7 highlights the most likely strike price, which is the subsidy priced given to each successful developer and has been predicted by the stochastic simulations of AR4. The peak in the graph illustrates that the most likely strike price is between £37.50/MWh–£40.50/MWh. The most likely strike price, with a 14% probability of occurring, is £39.26/MWh. The simulated strike price range for AR4 is between £25.30/MWh and £48.24/MWh, with a standard deviation of £3.13/MWh.

A developer could use the predicted strike price probability density graph to determine where the strike price is most likely expected to fall and then bid below this value to increase the probability of being awarded a contract. It will also indicate to developers the competitiveness of their site and whether the hurdle rate should be altered (as described in Section 2.2) to increase/decrease profitability to alter their CfD bid price closer to the estimated strike price.
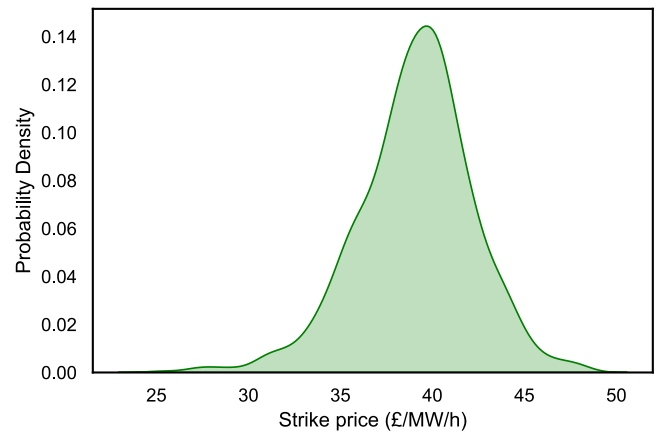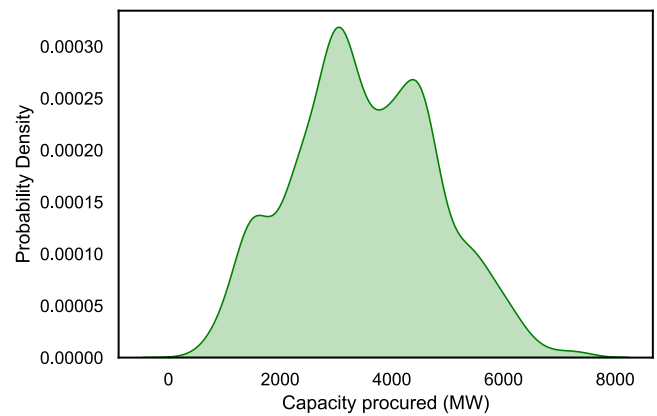
The results indicate that the estimated procured capacity ranges from 1500 to 8000 MW (Fig. 8). The median result from the simulation is that 3450 MW will be procured. This is considerably lower than the 9600 MW of eligible capacity. However, there is a 35% possibility that greater than 4000 MW of capacity will be procured and a 14% probability that greater than 5000 MW will be procured.

Fig. 9 illustrates the spread of bid prices submitted by each project. The figures are in ascending order, sorted by the median bid price for each project; this demonstrates the bid merit order of projects based on the assumptions outlined in Section 4.1. It can be seen that Hornsea 3 has the lowest expected bid price. Conversely, three Scottish projects have a significantly higher spread of bid prices. There is a spread of close to £10/MWh–£20/MWh in median bid prices between Hornsea and the three Scottish-based projects (Seagreen, Seagreen 1A and Moray West). This can be attributed mainly to the geographical spread of grid connection TNUoS charges (shown in Fig. 5), which are significantly higher in Scotland than in the rest of Great Britain. Based on analysis carried out on TNUoS charges [13], the differences in charges accounts for £14.30/MWh of the difference in CfD bid between the Hornsea 3 and Moray West project.

The translation of median bid prices into a probability of being awarded a subsidy can be seen in Fig. 10. It can be seen that Hornsea 3, Inch Cape and East Anglia 3 are predicted to be successful with a reasonable amount of certainty (>70%). On the other hand, Moray West and Seagreen 1A are predicted to win a low amount of certainty (<30%).
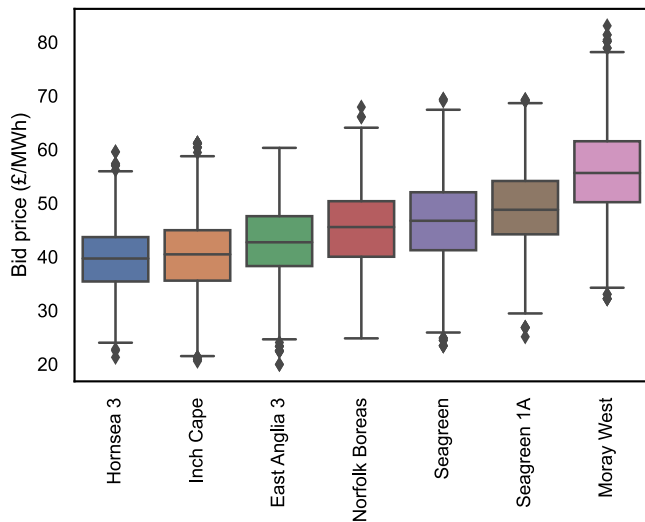
**Fig. 9.** Estimated merit order of projects competing in AR4. The bid spread for different projects due to stochastic cost data is also illustrated.
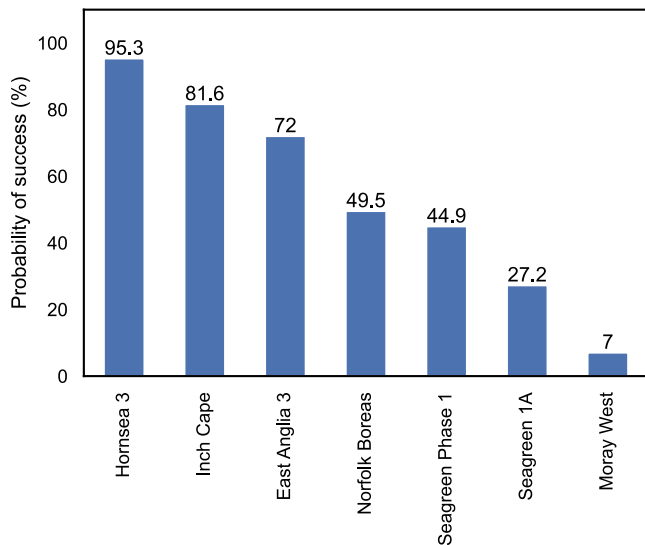


**Fig. 10.** Probability of each project successfully being awarded a subsidy.

### 4.2.3. Game-theoretic bidding behaviour results

The game-theoretic bid shading analysis has quantified the incentive for different developers to deviate from cost and shade their bids. Fig. 11 shows how the optimal bid with respect to the E[X] of auction pay-off and the incentive to engage in bid shading (described in Section 2.2) depends on the developer in the Case Study. The incentive is defined as how high developers can increase their expected E[X] of auction pay-off by increasing their bid beyond the minimum calculated CfD bid price (explained in Section 3.1.1. It can be seen from the results presented in Fig. 11 that the incentive to engage in strategic bidding varies for each player and their project. Results show that Hornsea 3 has the largest incentive to bid shade, as identified by having the largest E[X] peak. This is because the optimum bid price is not only the furthest away from the cost price at a bid price signal deviation of £3.00/MWh but also gives the player the highest E[X] of approximately £2.00/MWh. This is mainly due to its position of having the lowest minimum CfD bid price but also because it has the largest budget impact as it attempts to procure the most capacity from the auctioneer. This result is consistent with auction-theoretic literature, where in uniform price, multi-unit auctions, the incentive to shade depends on the units demanded and the bidders' market power [10]. Inch Cape, which also has a low median bid price (see Fig. 9), is incentivised to bid shade; this is because it can optimise its bid by increasing its bid price by £2.50/MWh and achieve an E[X] of auction pay-off of £1.70/MWh. Developers such as Moray West and Seagreen 1A, defined as unlikely to win by the model, have minimal incentive to engage in bid shading behaviour. Therefore, projects with a high estimated median bid price and, therefore, unlikely to win cannot increase their E[X] of auction pay-off by increasing their bid price further.

### 4.2.4. Delivery year rule change results

Fig. 12 demonstrates the effect changing the purpose of delivery years (this rule change is explained in Section 2) has on the auction outcome. The new rules for AR4 drastically reduce the volume of capacity procured and the expected strike price. The median strike price estimated if the old delivery year rules are applied is 4650 MW. This is a 1300 MW increase from what has been predicted using the new rules predicted by AR4. The median strike price predicted by the model is £43.78/MWh, compared to £39.26/MWh, which has been predicted using the new rules.

The results demonstrate that the delivery year rule change is likely to put further downward pressure on CfD bid prices, which will likely impact the profitability of offshore wind developments. Therefore, this rule change can be considered less preferential for developers as it increases the budget impact of projects and reduces the total amount of capacity procured. However, as one strike price is issued for both delivery years, there will be some reduction in the strategic complexity of the auction, as developers will now not need to consider which delivery year it is preferential to bid into.

The difference between estimated results for both rule formats can be explained due to how each bid's budget impact is assessed. As mentioned in Section 3.1.3, a reference price is used to calculate the budget impact of each bid. The reference price corresponds to the first and second delivery years, which are £38.77/MWh and £32.85/MWh, respectively. Applying AR3 rules, bids are assessed against the delivery year in which they are submitted. This means any bid accepted into the second delivery year will have a larger budget impact due to the first term of the Valuation Formula: *Budget Impact = (Strike price − reference price)*. Once there is a budget breach, this delivery year closes; however, bids can still be accepted into the first delivery year. Bids submitted into the first delivery year are then assessed using the higher £38.77/MWh reference price and are accepted until there is a second breach for that delivery year. As a result, far more capacity is procured as the reference price of £38.77/MWh now sets the affordable capacity.

### 4.3. Summary of AR4 results

Table 6 gives an overview of the CfD AR4 Offshore Wind auction results, issued by the UK Government after completion of the CfD auction round. A full list of results for AR4 can be found on the UK government CfD website [18]. The strike price of £37.35/MWh awarded at AR4 is an 8% further reduction in CfD strike price (demonstrated in Fig. 13). A total of 6994.34 MW of offshore wind capacity was procured. It can be seen that five out of seven of the eligible projects were successful in being awarded a contract at a strike price of £37.35/MWh. East Anglia 3, Inch Cape and Moray West, who were unsuccessful in being awarded a contract in AR3, were successful in this auction. SSE's Seagreen projects were the only successful projects and failed to win a subsidy for its 1120 MW of eligible build-out capacity.

Four out of five successful projects were awarded contracts for over ≥75% of their total build out-capacity. Moreover, three out of five projects were awarded a contract for their total build-out capacity. This demonstrates that hedging against volatile electricity prices through securing a CfD contract is still the preferred route to market for developers.
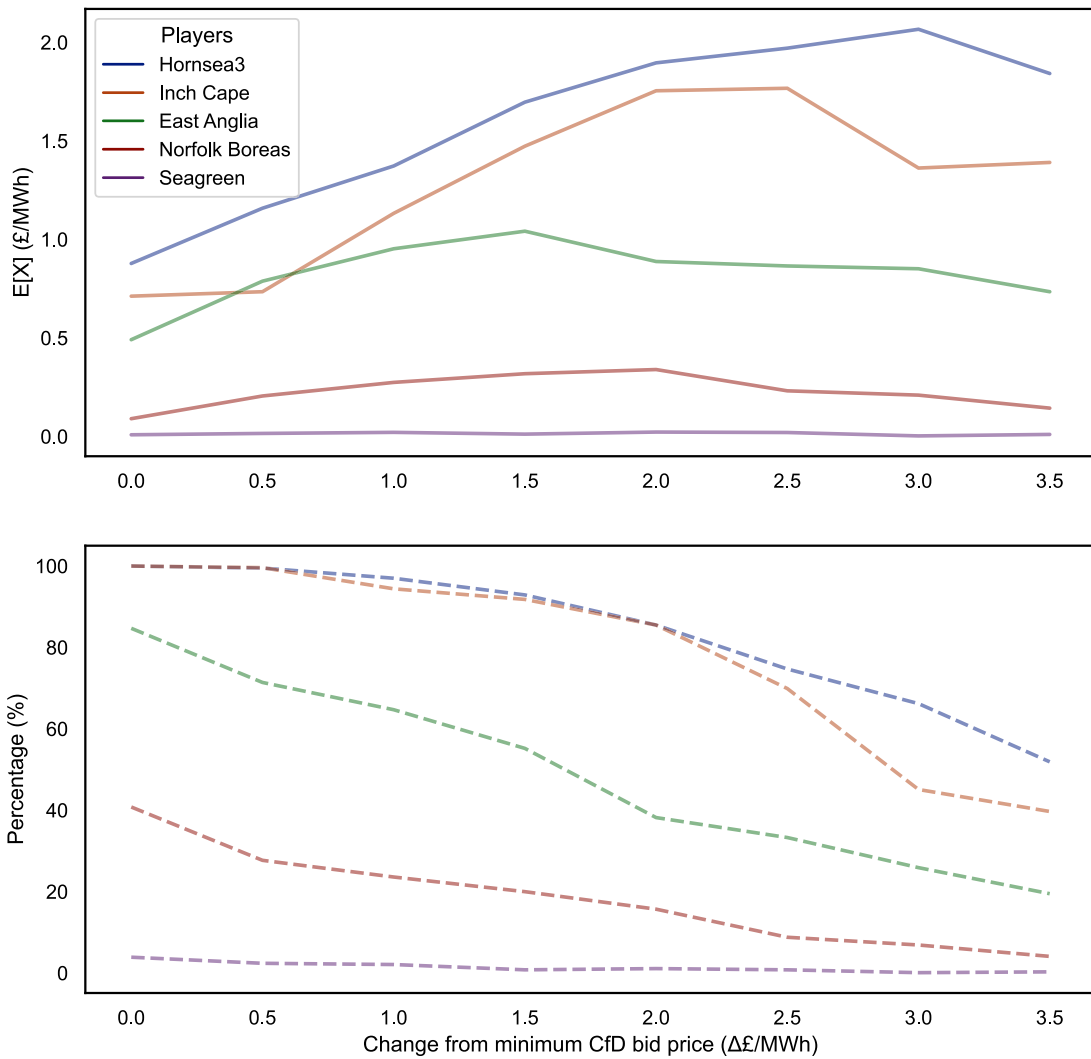
**Fig. 11.** Incentive for different players to engage in bid-shading is highlighted by the change in E[X]. The effect of bid-shading on the probability of winning is also shown.
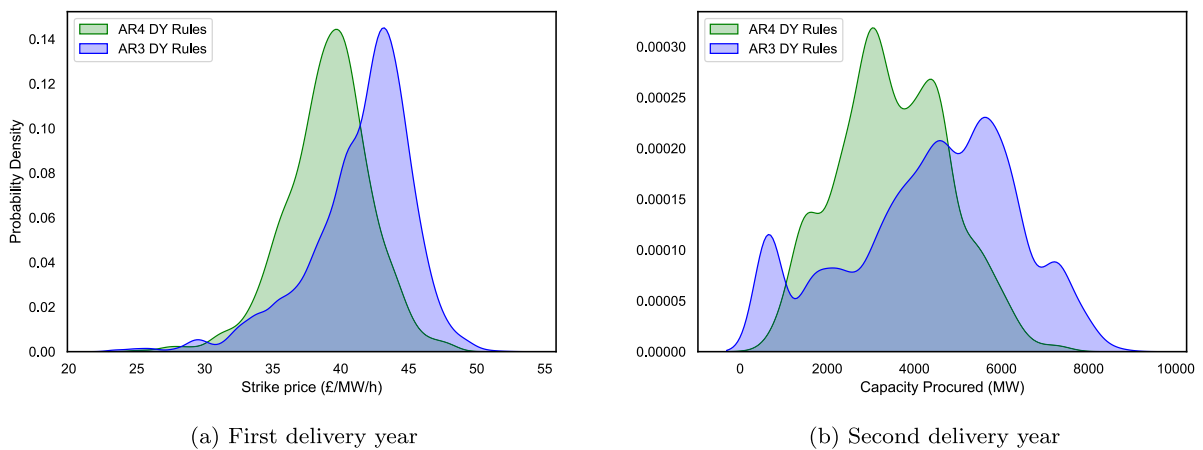


(a) First delivery year



(b) Second delivery year

**Fig. 12.** Probability density function illustrating the effect of the delivery year rule change on the estimated strike price and capacity procured.

*4.3.1. Coexist price*

The estimated competing capacity used for the pre-auction analysis was estimated from the consenting documents available on the National Planning Inspectorate Website. The consenting documents stipulate the maximum build-out capacity of the wind farms. Typically, developers will build out to this maximum capacity but may differ slightly due

to turbine power ratings and other limitations. As a result, the eligible capacities have been updated in Table 6. As developers typically aim to have a CfD cover the entirety of their site, the auction results represent the best estimate for the actual capacities of each of the consented sites. Additionally, Moray West signed a PPA (power purchase agreement) for 350 MW of its capacity at an undisclosed price [53]. This reduces

**Table 6**
Overview of AR4 Pot 3 auction results [18]. Successful projects are shown with a strike price.

| Project | Owner(s) | Eligible capacity (MW) | Capacity (MW) | Strike price (£/MWh) |
|---------|----------|------------------------|---------------|----------------------|
| Inch Cape | Red rock power | 1080 | 1080.00 | 37.35 |
| East Anglia 3 | Scottish power | 1373.34 | 1373.34 | 37.35 |
| Norfolk Boreas | Vattenfall | 1800 | 1396.00 | 37.35 |
| Hornsea 3 | Ørsted | 2852.00 | 2852.00 | 37.35 |
| Moray West | Ocean winds | 510 | 294.00 | 37.35 |
| Seagreen 1A | SSE | 1075 | – | – |
| Seagreen | SSE | 500 | – | – |
| **Total** | | **8735** | **6994.34** | |
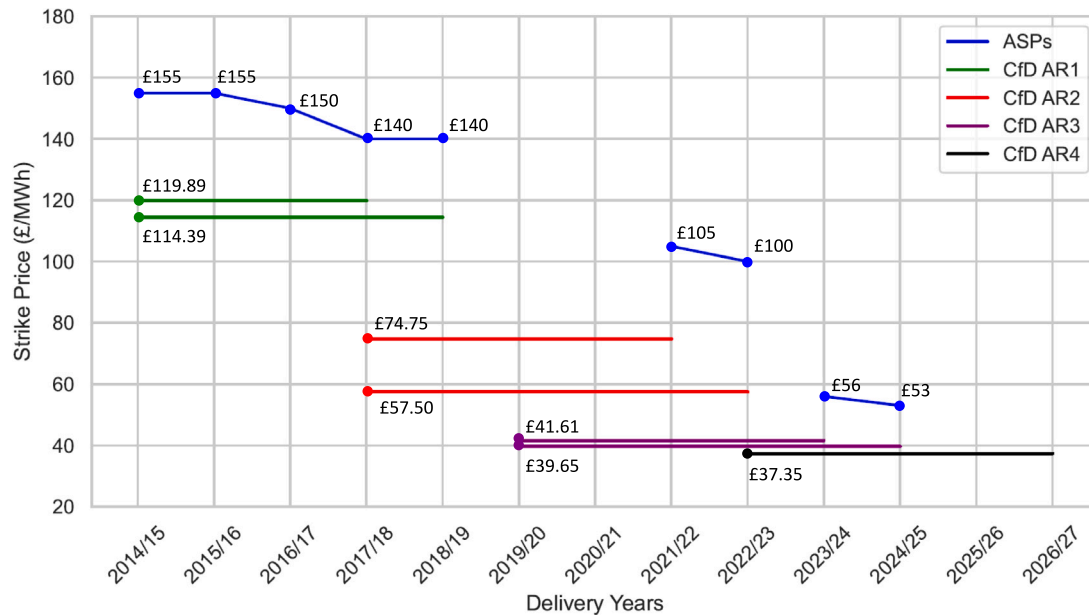


**Fig. 13.** Offshore Wind CfD strike price historical results [15–18], demonstrating sustained CfD strike price reduction.

the amount of capacity Moray West will likely bid from 850 MW to 510 MW. Therefore, the actual eligible capacity for each site has been updated post-auction and can be seen from Table 6.

Using the same methodology outlined in Section 3.2.1, the new coexist price is £37.23/MWh. As the coexist price is a function of total eligible capacity, developers can raise this price by reducing the total capacity submitted in their bid. For example, Moray West submitted a bid of 294 MW instead of the total 510 MW that they were eligible to submit. This means Moray West's view on total submitted capacity is reduced by 216 MW to 8520.34 MW. The new coexist price for this calculated amount of eligible capacity is £37.35/MWh, the same price as the auction results.

The budget impact of all successful bids is £172 million; approximately £38 million of additional subsidy budget was unused. This unused budget represents an extra £0.63/MWh possible increase in strike price, or a further 1524 MW of total capacity subsidised. The inefficient use of budget by developers is a disadvantage of adopting a risk-averse bidding strategy, such as bidding at the coexist price. This *optimum* price was not achieved as winning developers would have factored in Seagreen and Seagreen 1A bidding into the auction when calculating the coexist price. In reality, Seagreen and Seagreen 1A, the only unsuccessful projects, either did not adopt the coexist strategy or did not submit bids into the CfD auction. As the auction is sealed-bid, the successful developers would not have known the bid price of either Seagreen or Seagreen 1A (see Fig. 14).

The coexist analysis shows that developers are highly likely to have followed a risk-averse auction strategy and bid at a price which guarantee's them a CfD contract. The stochastic analysis has indicated that each project's median bid price (Fig. 9) is likely to be higher
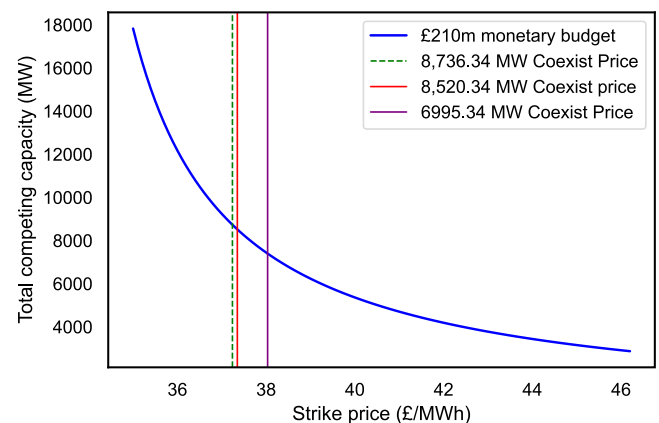


**Fig. 14.** Post-auction analysis of affordable capacity results and identification of coexist price.

than the coexist price obtained of £37.35/MWh. One possibility is that projects may have adjusted hurdle rates to ensure a CfD bid price at the coexist price and therefore accept a reduction in profitability of their developments. Results demonstrate that the CfD is still primarily the preferred route to market for large-scale offshore wind developments (as explained in Section 4.3). Risk-averse bidding in CfD auctions can be attributed partly to additional costs incurred by developers due to missing out on a CfD contract and delaying construction for a year as projects wait for the next CfD auction. From a policy standpoint, the

auction is well designed and ensures allocation efficiency. The auction rules ensure competitiveness and, in light of increasing supply chain pressures, have resulted in further CfD cost reductions. However, the low prices are likely to increase the probability of developers experiencing the winner's curse, resulting in the non-realisation of projects [42]. Under continual pressure to accept decreasing CfD prices, developers may look at alternative route-to-markets, particularly in light of the maturation of the corporate PPA market [5].

### 4.4. Comparison of auction results and prediction

There is currently no published literature which has analysed using simulation the described Case Study. For this reason, a comparison with previously available work is not possible. Therefore, a direct comparison between the auction results and the simulation allows for the analysis of the methodology and the identification of any limitations.

The award of subsidy largely follows the estimated merit order of projects as shown in Fig. 9. The four cheapest projects, Hornsea 3, Inch Cape, East Anglia 3 and Norfolk Boreas, as predicted from the stochastic simulations, were all awarded a CfD contract. The three projects Hornsea 3, Inch Cape and East Anglia, which won a contract to cover the entirety of their build-out capacity, are the three projects estimated to win with the highest certainty (as demonstrated in Fig. 10). This demonstrates that the actual auction results well replicate the pre-auction prediction of the likely winners (demonstrated in Table 6. However, Moray West, which is predicted by the simulations to have a very low chance of winning, was awarded a contract. This can be explained in parts due to the project's hybrid financing approach. As the PPA price is unknown, it is difficult to model the CfD bid price required by the project. This introduces more uncertainty and further complexity associated with estimating auction outcomes.

The strike price AR4 result achieved of £37.35/MWh is 5% lower than the most likely estimate from the stochastic simulations. The AR4 result is obtained in approximately 11% of auction simulations. There are several possible explanations for this, owing to the limitations of the model. Firstly, the model relies on inputs from a cost assessment tool, which is used to generate cost data for each site. As the outputs from the auction simulation depend on the cost assessment tool, any inaccuracy in cost estimation for the offshore wind farms would lead to incorrect auction predictions. Secondly, the case study uses the same wholesale electricity price forecast for all developers. In reality, developers may use more or less optimistic forecasts than the one used in the simulation. Therefore, the simulation does not capture the effect of using different wholesale electricity price forecasts. Thirdly, developers bid according to their cost bid price in the stochastic simulations. In CfD auctions, developers can strategically bid lower than their estimated minimum CfD bid price to guarantee themselves an award of a contract. One form of strategic bidding is to vary the required IRR of the development to bid at the coexist price. This work does not consider lowering the bid price below the minimum CfD bid price.

## 5. Conclusion

This paper has introduced a novel methodology for developers and policymakers to analyse CfD auctions. The analysis is useful for developers to prepare a dominant bidding strategy, which mitigates the winner's curse and so reduces the risk of non-realisation, and is valuable for policymakers to test allocation efficiency. A previously validated stochastic cost modelling tool, which utilises the publicly available site and project-specific data, is used to generate stochastic cost estimates for the different competing projects in a Case Study. The Case Study replicates AR4 with information only available to developers before the auction. Cash flow analysis over the lifetime of the projects is used to estimate a distribution of CfD bid prices for each player. The auction is simulated thousands of times using the different estimates of CfD bids, which produce stochastic auction outputs, which characterise the

significant uncertainty experienced by developers. Developers can use the outputs to determine a bid strategy in the context of the given probabilities. The paper has demonstrated how each developer's incentive to deviate from cost differs. The incentive to deviate from cost is achieved through identifying a bid price which maximises the expected value of auction pay-off for each player. Finally, the effect of a rule change on this auction has been investigated. This rule change simplifies the role of delivery years and is analysed by modelling the auction using AR3 rules and then comparing it to the results of the AR4 simulation. This gives developers and policymakers a deeper understanding of what effect this change will have on auction dynamics. Finally, the actual AR4 results are compared to the stochastic pre-auction simulations.

The simulation of this CfD auction has demonstrated that the most likely strike price, as predicted by the analysis, is £39.26/MW, 5% lower than the actual auction results. Post-auction analysis has demonstrated that the strike price was largely determined by a risk-averse coexist strategy, with projects bidding at a price which would ensure the award of a CfD. The analysis successfully identified the most likely winners of the auction. Estimated merit orders are useful to assess their projects' competitiveness and align their bidding strategy accordingly. The results of the game-theoretic simulations have found that player have an incentive engage in bid shading, where the level of incentive varies between projects. The projects lower down on the merit order (i.e. cheapest projects) have a larger incentive to deviate from cost in an attempt to increase pay-off. Shading ones bid decreases the allocation efficiency, and should be mitigated against policy makers, such as through the introduction of stringent pre-qualification criteria which result in significant sunken costs. Finally, an analysis of the delivery year rule changes demonstrates that it makes the auction more competitive for developers and puts further downward pressure on CfD bid prices. Excessive downward pressure on awarded CfD bid prices increases the risk of the non-realisation of projects. Therefore, policymakers face a trade-off between increased risk of non-realisation and minimising subsidy payments (i.e. minimising cost to tax-payer).

Interesting expansions of this work could be to increase the *smart* capabilities of all players in the game-theoretic analysis to investigate what effect it would have on the expected value if all players are attempting to optimise at once.

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