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Overplanting in offshore wind power plants in different regulatory regimes

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Abstract—Offshore wind power’s journey towards being competitive with other generation technologies relies on technical innovation and maturation, but also on further optimisation of proven and mature solutions. Capacity optimisation or so-called overplanting is one example of optimisation, which is performed by installing a larger wind power capacity than stipulated in the connection agreement with transmission system operators (TSOs). By developing a discounted cash flow (DCF) model, the paper investigates how both regulatory regimes and geographic characteristics of dedicated offshore wind development areas affect the viability of overplanting. The analysis comprises hypothetical scenarios of the distinctive offshore wind markets of the United Kingdom and Denmark and thereby elucidates the key aspects influencing the value of overplanting. This work’s findings show that the UK regulatory framework results more favourable to overplanting. The results indicate that current conceivable offshore wind power plants in the UK can increase their economic value by around 30 mio-€ when optimising their capacity setup. In Denmark, current regulations are not suitable for overplanting causing loss of value when optimising the capacity design of wind power plants.

I. INTRODUCTION

In the recent years, the development of offshore wind energy has accelerated. The last year alone saw an addition of new offshore wind capacity connected to the grid of more than 3 GW [1]. Along with the rise of installed capacity, capacity factors have increased due to technology maturation as well as a higher installation share of offshore wind power plants further offshore with more favourable wind climates. Yet the duration curves of offshore wind power plants are far from full utilisation of the installed transmission capacity. Overplanting aims to optimise the transmission utilisation by increasing the wind power capacity above the transmission capacity limit. In general the capacity both can be expanded by installing additional wind turbines or by increasing the generator size of the turbines. Fig. 1 visualises the effect of the overplanted capacity on the offshore wind power plant power curve. The extra installed capacity can be used to improve the power curve below rated wind speed and to make up for wind turbine unavailability, whereas the maximum deliverable power is capped so that energy has to be curtailed during high wind and turbine availability. Since wind climates usually show a higher probability of wind speeds below rated power, additional power can be generated during a considerable share of operation time, thereby utilising the transmission capacity more effectively.

Further from shore, the generation time at rated wind power usually increases, whereas turbine availability is challenged by longer travel distances and repair times.

The optimisation of overplanting consequently opposes rising costs linked to the larger installation capacity and growing revenues from the boosted energy generation – since the grid connection setup is not altered, the transmission system cost remains constant.

Capacity optimisation so far has not been a prominent resource of reducing the levelised cost of energy (LCoE) of wind power plants. In fact, the optimal sizing between installed generation capacity and transmission capacity very much depends on the original cost of these two infrastructural components. A high cost share accounting for installation capacity gives lower incentives to overinstall the capacity. The historical development of offshore wind energy with the majority of early projects being placed close to shore resulting in low transmission system costs reflects the lack of consideration of overplanting in the early years of offshore wind development.

The optimisation of the capacity setup came into focus in 2008 with an assessment of optimal reinforcements of the British electricity transmission grid as part of the Round 3 leasing process [2], suggesting an extra capacity of 12% as optimal average setup. In order to prevent regulatory restrictions in Grid Code requirements, Ireland raised their capacity cap by 15 percentage points to 20% above the

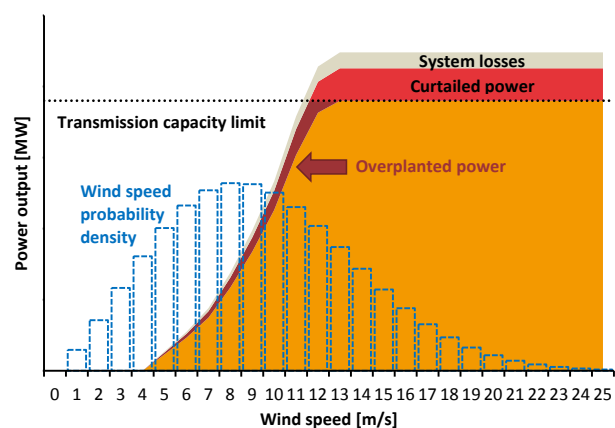


Fig. 1: Illustration of the concept of overplanting

maximum export capacity in order to exploit economic benefits from oversizing generation assets [3]. Likewise, the Dutch Ministry of Economic Affairs allowed an additional installation capacity of up to approximately 8% within the Borssele wind power plant tender in accordance with the development framework of a Dutch offshore grid [4]. Recent studies have estimated the optimal additional installed capacity at 8-20% above the transmission capacity for onshore wind energy in Ireland for varying renewable policy support systems [5] as well as 2-5% for offshore wind power plants in the framework of the United Kingdom [6].

The considerable spread between optimal overplanting levels shows the strong dependency between the considered wind farm technology, its geographic location and the regulatory framework it is embedded in. The present comparison of overplanting employed in different countries tries to reveal the main aspects relevant for an optimal capacity setup.

The prospects of overplanting will be evaluated economically by taking the perspective of private investors. In this way, we aim to highlight the effects of regulations set by policy makers on the investment decisions of private wind power plant developers. A DCF analysis model will be developed that estimates the investment cost of conceivable offshore wind power plants for different regulatory and geographic scenarios. Based on the economic analyses of different setups of additionally installed capacity, the optimal capacity setup will be characterised by the setup yielding the highest additional economic value.

The remainder of the paper will be structured as follows. Section II explains the methodology used for the national scenarios and the assumptions behind the wind power plant project investments. Section III successively presents the outcome of the economic analyses, followed by the sensitivity analysis in section IV. Finally, section V concludes the paper with a discussion about policy implications.

II. METHODOLOGY

A. Evaluation parameters

The economic assessment is carried out by two criteria. Firstly, the LCoE as common assessment measure for power generation technologies is used to evaluate the cost reduction potential per generated energy when optimising the capacity setup. LCoE is defined by Eq. (1).

$$LCoE = \frac{I_0 + \sum_{t=1}^T \frac{A_t}{(1+i_{nom})^t}}{\sum_{t=1}^T \frac{E_t}{(1+i_{real})^t}} \quad (1)$$

In this equation I_0 are the upfront investment costs, A the annual costs in the year of operation t up to a total operational time T of 25 years, i the discount factor with which the costs are discounted nominally considering inflation, and E the annual energy generation discounted in real terms. The annual costs comprise O&M cost, balancing costs on national power markets and payable tax from electricity generation revenues. Assumptions on the discount rates follow the suggestion of the national authorities, being 10% in nominal terms in the UK [7] and 4% in real terms in Denmark [8]. The difference between nominal and real terms constitutes a defined inflation rate of 2%. The calculations do not specifically include financing costs and rather follow

the standard approach of the authorities, excluding risk assessments from the present analysis.

The second measure is the internal rate of return (IRR) of the offshore wind power plant or the expected internal growth rate of the project. The IRR derives from the net present value (NPV) of the offshore wind power plant defined by Eq. (2), constituting the discount rate that sets the NPV to zero.

$$NPV = -CF_0 + \sum_{t=1}^T \frac{CF_t}{(1+i_{nom})^t} \quad (2)$$

In this formula CF are all cash flows, i.e. costs and revenues, in the respective year. The IRR therefore fully considers revenues from energy generation and is more apt to account for the different revenue streams of the national scenarios. Likewise, the IRR is independent from assumptions on the discount rate, leading to a more general valuation of profitability throughout different scenarios independent of possible considerations regarding the discount rate as the investor's expected return or risk aversion.

B. Offshore wind power plant scenario choice

A hypothetical offshore wind power plant of 400 MW baseline capacity corresponding to 50 wind turbine generators (WTG) of 8 MW capacity is assumed throughout the economic analyses in order to account for comparability between the different scenarios. Instead of optimising the transmission voltage level to the wind power plant capacity, the different scenarios are modelled with a dedicated transmission voltage level of 220 kV. Although the realistic optimal voltage level can vary depending on the plant location by the length of the installed cable, this estimate seems sufficient for the present analysis. Three offshore wind power plant scenarios are analysed representing currently planned and consented projects in the United Kingdom and Denmark to reflect currently conceivable offshore wind projects. Numbers of water depth and distance to shore of these projects were gathered from an online database [9] and their average values were assumed for the present national scenarios. Wind climates and numbers for average turbine availability were adapted from wind time series of comparable sites and the literature, respectively [10], [11]. While Denmark is an offshore wind forerunner by installing the first offshore wind power plant, Vindeby, in 1991, the United Kingdom has become the leading market of offshore wind energy with 46% of the European installed capacity situated in British waters by the end of 2015 [1]. The United Kingdom is therefore reflected by two different scenarios, the *Conventional British offshore wind power plant* reflecting average characteristics of projects closer than 100 km far from shore, and the *Far offshore British wind power plant* reflecting exceeding distances. The Danish scenario is named *Average Danish offshore wind power plant*. Table I exposes the geographic characteristics of the three hypothetical offshore wind power plants. The higher mean wind speed and slightly lower turbine availability for the *Far offshore British wind power plant* tries to account for the higher wind climate for and longer travel times to sites further offshore.

TABLE I: Locational characteristics of the scenarios

Offshore wind power plant	Water depth	Distance to shore	Mean wind speed	Turbine availability
<i>British conventional</i>	36 m	29 km	9.5 m/s	95%
<i>British far offshore</i>	29 m	151 km	10 m/s	94%
<i>Danish average</i>	19 m	18 km	9.5 m/s	95%

C. Investment cost assumptions

In order to analyse the economic profitability of the hypothetical offshore wind power plant scenarios, all relevant costs were estimated depending on specific cost drivers in order to allow for changes of geographic locations within the national scenarios. To further account for changes in the scope of investment according to national regulations, costs were expressed in the following cost components, distinguished between costs for the *wind power plant* itself and the *transmission system* cost:

Wind power plant cost components:

- Development expenditure
- Turbines & array cables
- Foundations
- Installation of offshore wind power plant components

Transmission system cost components:

- Offshore substation
- Export cable supply
- Installation of export cable
- Onshore substation

The separation of cost components reflects the diverse legislation of cost allocation of the total offshore wind power plant investment. The common practice of offshore wind power plant developers in the United Kingdom is to construct and bear the cost of all project components. The developer then has to handle the grid connection agreement of the offshore wind power plants separately with the TSO. Developers are required to sell the transmission infrastructure to an offshore transmission owner (OFTO) by a competitive tender, who then owns and operates the asset for a dedicated contract length of 20 years [12]. The OFTO can in turn charge transmission fees to the developer to use the infrastructure, in order for the OFTO to recover his investment [13].

The Danish regulation in contrast requires the TSO to invest into and construct the transmission system infrastructure, thereby limiting the consented offshore wind power plant projects tendered by the government to the offshore wind power plant components [13]. The reduction of the project scope in the Danish case is expected to show a negative effect on the profitability to overplant the offshore wind power plant. Since cost concerning the turbine installation capacity constitutes a higher cost share of the total project when not accounting for the invariant transmission system cost, an increase of turbine capacity will induce higher relative increases in investment and consequently decrease economic benefits.

Project planning cost inclusively other costs as insurance or contingencies, or development expenditure, characterise

fixed planning costs of the investment independent of specific cost drivers. They are assumed to amount to 300 €/kW, which is in the range of several other offshore wind power plant cost analyses [10], [14]. Assumptions for the residual investment cost follow mainly the information given in the analysis of another paper [15], which gives an extract of the confidential data set used within the FLOW (Far and Large Offshore Wind) project by the Dutch Top Consortium for Knowledge and Innovation Offshore Wind [16]. These assumptions were adapted and refined to make them applicable to the characteristics of the considered offshore wind power plant.

Table II lists the cost components that are considered to be solely dependent on the installed capacity of the offshore wind power plant. In reality the turbine supply cost is dependent on further cost drivers like the development of the supply chain, raw material prices and broader macroeconomic conditions, which has been mentioned and partially tried to account for in other articles regarding offshore wind investment cost development [15], [17]. For the present analysis, the presented trend of specific turbine costs within [15] makes it sufficient to define the cost at 1,800 €/kW as a reference for the different investigated scenarios. It is assumed that this price level contains the costs for array cables, which are not defined separately, as they usually represent a minor part of investment cost of offshore wind power plants [18].

The estimated cost for an offshore substation within this paper is also used in other scientific literature [19]. The cost for an onshore substation, which is not part of the public available FLOW model data, was derived to be 25% of the cost for an offshore substation. This lower value with regard to the offshore substation cost is reflected by the dominance of the offshore substation foundation cost over other components within substations such as transformer or switchgear cost and reflects the analysis of other literature [20], [21].

The present work assumes that only foundation cost is related to the water depth. Since the foundation cost is linked to the deployed turbine and its size, the foundation cost curves depending on water depth from the FLOW model were adapted to the present wind power plant setup. Power regression curves of the foundation costs over different sizes of WTG for specific given water depths defined the equivalent foundation cost values of the 8 MW WTG for these depths. Fig. 2 shows these data values with the best fit function, with which foundation cost is expressed for other water depths. The data set contains foundation costs for monopiles, comprising 80% of all substructures of the European operating wind power plants, and jacket foundations, which is the leading type of foundations for deeper waters [1]. No further differentiation between other

TABLE II: Specific costs related to the installed capacity

Component	Specific cost
Turbine & array cable cost	1,800 €/kW _{installed}
Offshore substation	210 €/kW _{transmission}
Onshore substation	52.5 €/kW _{transmission}

installable foundation types is therefore considered necessary for the present analysis. The most cost-effective foundation type for different water depths is then taken for the hypothetical offshore wind power plant.

Table III lists the cost components related to the distance to shore, to which the export cable is directly linked. The export cable supply and installation cost deviates from the FLOW model, since the dedicated transmission capacity of 220 kV is not among the public data. Export cable supply costs of 1,500 €/m are presented in [22], while the proportion between cable supply and installation cost for a comprehensive dataset of 220 kV cables, however for smaller power capacities than in the present setup, is presented to be in the ratio 2:1.

The correlation between export cable length and distance to shore is considered separately. The distances of export cable length of the same sets of projects defining the different wind power plant scenarios were compared with the distance to shore and expressed by a multiplication factor, the distance to shore itself being characterised by the factor 1. Average ratios of cable length to distance to shore of 18 UK projects leading to the *Conventional British offshore wind power plant* are at 1.56, while the average ratio of the only two consented Danish offshore projects are close to that value with 1.65. Many projects within the *British far offshore* category lack a specific cable length due to their early planning stage. The present approach assumes a ratio of 1 for this scenario in order to minimise the cable supply costs for these setups, a likely action to prioritise minimal costs for cable routing of far offshore wind power plants.

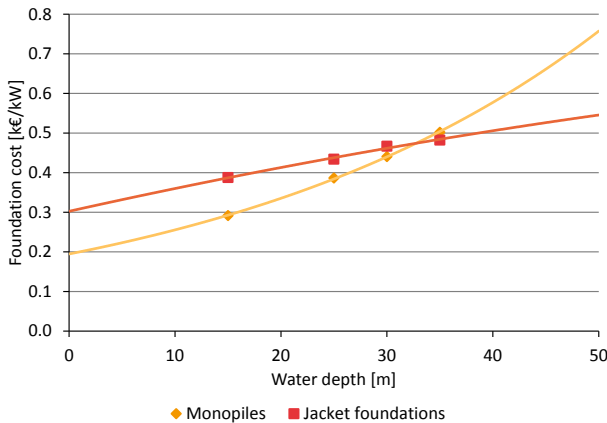


Fig. 2: Monopile and jacket foundation costs for an 8 MW WTG

TABLE III: Specific costs related to the distance to shore

Component	Specific cost
Export cable 220 kV	1,500 €/m _{cable length}
Installation of export cable	750 €/m _{cable length}
Installation of turbines and foundations	4,000 €/km/MW _{installed}

D. Annual cost assumptions

The main component of the annual costs is O&M cost. In general, information regarding O&M cost is hard to obtain. The literature estimates O&M cost to be in a wide range of 15-49 €/MWh [23]. Other scientific sources express the costs as 2.5-4% p.a. in fixed terms as share of CapEx [19], [24]. As the O&M cost strongly depends on the distance to shore (by means of the distance to the nearest maintenance port) [23], the expression in fixed terms can be considered to be suitable to account for this effect. Since investment costs of offshore wind power plants tend to rise with an increasing distance to shore, a fixed percentage of these costs expressing the O&M cost will rise accordingly. Due to the uncertainty of quantifying the O&M cost, a relative share of the detected lower boundary of 2.5% p.a. of CapEx was considered, which is also in the range of numbers suggested by the British and Danish ministries and authorities for energy [7], [11]. This number was adapted throughout all scenarios in order to keep the impact of O&M cost on LCoE small.

In both countries, the offshore wind power plant operator is obliged to pay for occurring balancing costs on the power market. The respective height of balancing costs differ due to the respective production portfolio and the interconnection with the surrounding national electricity systems. Since the UK has a poorer interconnection with the electricity grid of continental Europe, average expectable balancing costs are found to be higher than in Denmark. For the analysis, 3 €/MWh in the UK and 2 €/MWh in Denmark are applied, following respective literature [25], [26].

The last component of the annual costs characterises tax payments of revenues gained from the electricity sales. Respective corporate tax rates are applied to account for these additional costs per energy generation.

E. Revenue assumptions

Table IV shows the main aspects of the national support regulations of governmental tenders of the United Kingdom and Denmark. Both countries have moved to the application of feed-in premiums in order to expose the renewable generators to the electricity market. The British Renewable Obligation scheme, a quota-based support scheme, is currently being phased out, and not part of the analysis.

The support price of tenders in both nations is determined for single projects, for which the total remuneration or strike price is bid by prospective investors. The payments for the consented project to the winning bidder then consist of the hourly electricity price on the respective power market and the sliding difference to the bid price as support payments. While the support payments are granted over 15 years for these projects in the United Kingdom, the total support level in Denmark corresponds to a fixed level of energy generated, often expressed by a specific amount of full-load hours being supported, if not stopped after 20 years

TABLE IV: Overview of support schemes

Country	United Kingdom	Denmark
Support scheme	Contract for Difference (CfD) Feed-in premium	Public Service Obligation (PSO)
Remuneration	Project-specific (tender)	
Market price determination	Hourly average price	
Granted period	15 years	50,000 full-load hours or 20 years

of remuneration. 50,000 full-load hours are equivalent to approximately 11-13 years of support payments for capacity factors of contemporary Danish offshore wind power plants.

Overplanting offshore wind power plants with the effect of a rise in capacity factors will have an influence on the support payment period of Danish projects. While the support payments are completely remunerated at an earlier point in time, which has benefits on the discounting of revenues, the power plant will also face a longer residual operational time in which it only receives lower power market prices for electricity sales. British projects in contrast will receive the same support and market payments per MWh over the lifetime independent of additional capacity installations.

Table V presents the assumptions for strike price and average power market price that are assumed for the feasibility analyses. The price levels are derived from empirical datasets of previously tendered offshore wind projects in both countries, and the recent development of power market prices of the APX Power UK and NordPool Elspot in Denmark. Previous bid support levels of offshore wind power plants in both countries were weighted by the installed capacity of the projects as well as inflated and adjusted for currency exchange. The outcome of the two first governmental tendered offshore projects in the UK [27] and Denmark [28] can be found in the literature. Due to the considerable production of wind power in the Danish power system that totalled a share of 42% on the gross consumption level in 2015 [29], the market prices were adjusted towards an expectable price level for wind power producers. The literature shows that a higher penetration rate of variable renewable energy (VRE) sources has a negative effect on the price that these VRE receive on the electricity market (market value) [30]. Wind power generators in Denmark should therefore expect lower revenues for their provided energy than the average remuneration on the electricity market. The market value of a generator can be calculated by Eq. (3).

$$\bar{p}_W = \frac{\sum_{n=1}^N P_{W,n} \cdot p_n}{\sum_{n=1}^N P_{W,n}} \quad (3)$$

In this equation \bar{p}_W is the average market value or electricity price of wind power generators, P_W the wind power generation in hour n of in total N hours, and p the hourly market price. In fact, the market value of wind power generators being expressed in Table V was determined to be 13.5% lower than the average electricity market price of the investigated time frame. The average market value of offshore wind power plants in the UK was not considered,

TABLE V: Revenue assumptions in scenarios

Country	United Kingdom	Denmark
Strike price	162 €/MWh	114 €/MWh
Power market price ¹	61.9 €/MWh	30.9 €/MWh

¹UK: APX Power, Apr 2011-Sep 2015, DK: NordPool Elspot, 2011-2015, adjusted for wind market value

since British wind power only comprised 12% of the gross electricity consumption in the country in 2015 [31] resulting in a market value close to the average electricity price.

The numbers suggest that the conditions in the United Kingdom are more potent to yield higher returns on the investment for developers if they face comparable levels of specific investment costs in both countries, as the present work assumes. Expectable power market remunerations are approximately twice as high on the British spot market compared to the Danish NordPool price area.

III. COST-BENEFIT ANALYSIS

The results of the present work show the cost estimations for the hypothetical offshore wind power plants, as well as the optimal overplanting level concerning cost reduction potential and economic value gain. While the quantitative addition in economic value of the power plant is reliant on the underlying assumptions of revenues, the optimal capacity addition can be considered unbiased from these considerations, since the relative trend of LCoE and IRR over different levels of overplanted capacity is mainly unaffected from the height of the revenues.

A. Comparison of investment cost

Fig. 3 shows the investment cost estimations of the three scenarios. The two projects closer to shore need comparable total investment costs of around 3,000 €/MW. The cost for the power plant developer of the Danish project however is around 15% lower than the total project cost, since the cost for the transmission system is borne by the TSO. The investment cost for the British project located far offshore is significantly higher and surging over 4,000 €/MW, mainly due to the rising cost for the transmission system constituting roughly 26% of the total project cost. Since the far offshore sites in the UK constituting the present scenario are characterised by in average lower water depths than sites closer to shore, the distance to shore is the main cost driver in the direct comparison of the British scenarios.

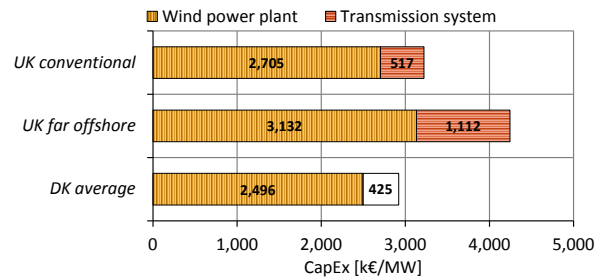


Fig. 3: Investment costs of the scenarios

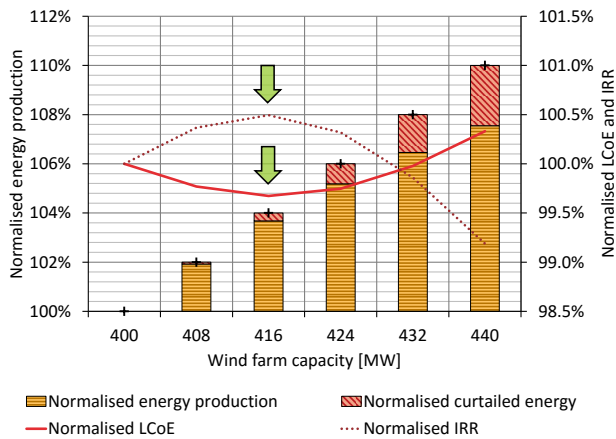


Fig. 4: Business case impact for the *Conventional British offshore wind power plant*

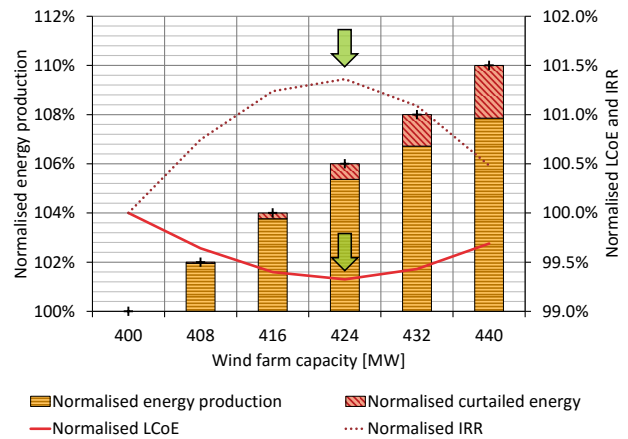


Fig. 5: Business case impact for the *Far offshore British wind power plant*

B. Overplanting in different regulatory regimes

Fig. 4 visualises the impact of overplanting on the *Conventional British offshore wind power plant*. It shows the relative increase in AEP and necessary curtailment over the different setups of additional capacity, along with the relative change of LCoE and IRR with respect to the baseline capacity. In the present setup, an additional capacity of 4% above the baseline capacity characterises the optimal setup considering both LCoE reduction potential and gain in IRR. The corresponding addition of economic value in the optimal design is at +30.2 mio € with an LCoE of 105.91 €/MWh.

Fig. 5 shows the optimal level of overplanting for the *Far offshore British wind power plant*. Most notably the more prominent transmission system cost as part of the total project cost further favours overplanting towards an optimal level of 6%. The LCoE reflects the higher investment costs of projects with an extended distance to shore, being greater than the previous scenario with 124.44 €/MWh in the optimal design. The scenario reveals a higher LCoE reduction potential as well as slightly more economic benefits due to an increased capacity addition: With the same underlying revenue assumptions, also the gain in economic value is still comparable, being at +34 mio € for the optimal design.

Fig. 6 shows the outcome for the *Average Danish offshore wind power plant*. The two evaluation parameters diverge and reveal the negative effect of the support scheme regulations on the viability of overplanting. An LCoE reduction potential is still apparent even without the transmission system in consideration, since static costs for project planning as well as an increase in the capacity factor continue to promote overplanting. An increase in AEP of 3.7% can be achieved in the optimal design, lifting the energy generation by 1.8 percentage points to a capacity factor of 49.5% with respect to the fixed transmission capacity. Yet the remuneration of the wind power plant based on a fixed level of energy generation causes the additional generated energy per overplanted wind turbine to be less valuable for the developer. The slightly earlier remuneration does not make up for more earnings only gained on the power market, which reimburses the generated energy for lower prices.

IV. SENSITIVITY ANALYSIS

The sensitivity analysis presents the influence of the wind climate and turbine availability on the prospects of overplanting by using the *Conventional British offshore wind power plant* scenario as example. Financial sensitivities have shown only little effect on the relative change of the evaluation parameters, since the different capacity setups of the wind power plants are equally affected by varying support revenues and power market prices. Even for the Danish regulations, in which the relation between support level and market price can play a role on the optimal rate of return, the implications of the analysis remains unchanged when considering reasonable alterations in these variables.

A. Wind climate

Fig. 7 shows the effect of a change in the wind climate on the optimal design of the offshore wind power plant. With a lower mean wind speed the time generating at rated power also decreases, reducing the amount of necessary curtailment and favouring the installation of additional capacity. A higher mean wind speed in contrast counteracts overplanting due to a longer generation time at rated power. Although the

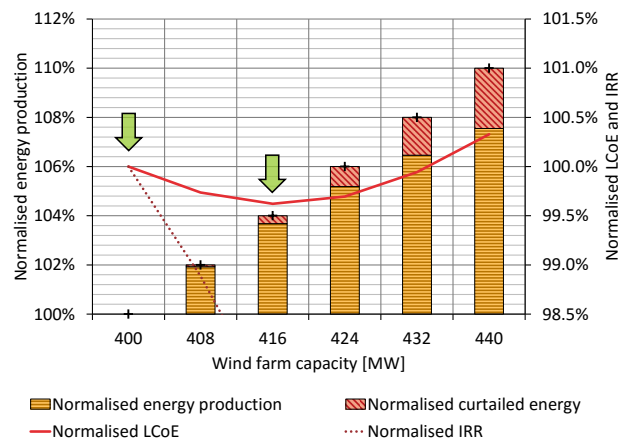


Fig. 6: Business case impact for the *Average Danish offshore wind power plant*

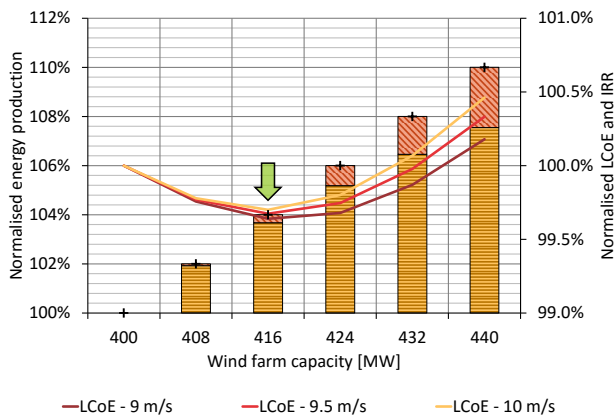


Fig. 7: Sensitivity of wind potential

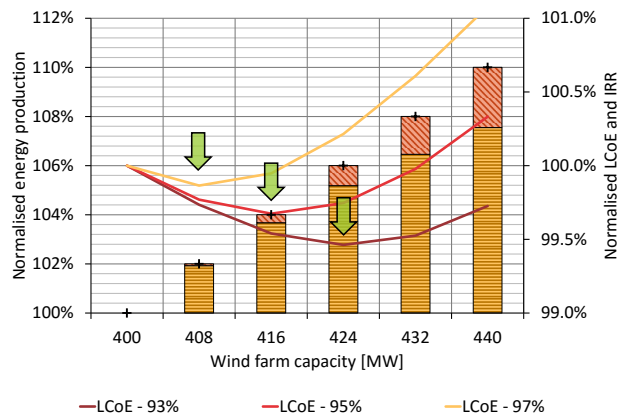


Fig. 8: Sensitivity of turbine availability

LCoE ranges from approximately 101-112 €/MWh in the analysis, the wind climate shows little effect on the LCoE reduction potential for the low additions of capacity in which an optimal overplanting level is found for contemporary offshore wind power plants. The optimal design remains unaffected at 4% above the baseline capacity for all cases.

B. Turbine availability

Fig. 8 shows a reasonable change in average turbine availability and the effect on optimal overplanting. A decreased average turbine availability reduces the time that the wind power plant utilises the full capacity of the transmission system and favours overplanted installation capacity and its ability to compensate for lost power. High average turbine availabilities contrarily reduce the need for this compensation. The analysis shows that a change in availability highly influences the optimal design level, even though the LCoE over all cases stay at a close level with 105-107 €/MWh.

Since the magnitude of LCoE is comparable over the different sensitivities, it is worth considering to use overplanting as a measure to hedge against risk of the project. Lower availability can also stem from unexpectedly low energy generation of the power plant or missing returns that were budgeted in the project. It is apparent from the analysis that with lower mean turbine availabilities the cost reduction trend becomes more flat around the optimal level. This allows for choosing to install a slightly higher additional generation capacity than the analysis suggests, thereby accounting for uncertainties in the estimation of AEP. Risk averse investors could therefore consider to use overplanting as a means to secure the project against unforeseen bad operation performance.

V. DISCUSSION AND CONCLUSION

The aim of this paper was to quantify the impact of regulatory regimes and geographical characteristics on the viability of the so-called capacity optimisation of overplanting. The distinctive regulatory regimes of the United Kingdom, the leading market of offshore wind energy in Europe, and Denmark, the originating country of offshore wind energy, were contrasted and their aptness towards overplanting were examined. Three scenarios of offshore wind power plants

were established that represent a broad range of possible prospective offshore wind projects in both countries. The key differences in the regulatory regimes decisive for the economic viability of overplanting are the remuneration of support payments, the allocation of development responsibilities of the total offshore wind investment project as well as the general prospects of remuneration levels on the national power markets.

It was found that a basic cost reduction potential per generated energy and thereby optimisation of the utilisation of transmission capacity can be achieved in both countries despite different cost allocation regulations. The increase in AEP and linked rise of capacity factors as well as static project planning costs not affected by rising levels of installed capacity contribute to an observable benefit in LCoE when applying overplanting. Static transmission system costs play a more significant role first for considerably long distances to shore, which are not found within the contemporary planned offshore wind projects in Denmark, therefore not raising the question (yet) whether a change in regulations should be considered to make more use of an optimisation of the wind power plant capacity setup.

The crucial drawback of the Danish regulations were determined to be the energy-based remuneration of support prices. Fixing support payments to a certain amount of generated energy counteracts the installation of additional capacity, since the increased energy output reduces the time span, in which the offshore wind power plant is remunerated by the tendered support price. The LCoE reduction potential can therefore not be exploited by an investor, since rather the return on the investment is decisive for the project evaluation. In order to make it worth installing a higher generation capacity, the energy generation of this capacity has to be remunerated equally as the generation of the baseline capacity over the lifetime of the offshore wind power plant. This is guaranteed by a time-based remuneration of support prices that is independent of the actual energy generation level of the plant, as is it present in the United Kingdom. We find that the demonstrated cost reduction potential of overplanting can justify a reconsideration of the reference of support payments in the Danish regulations.

The present work focused on a capacity optimisation

independent of other impacts of planning considerations of offshore wind power plants. Besides, overplanting can further be embedded into other areas of optimisation for offshore wind power plants. Constraints or pareto-optima could be found when linking the capacity optimisation with the park layout optimisation, and with that the related array cable routing as well as the optimisation of estimated AEP considering wake effects between the turbines. These impacts however are considered to be small due to the comparatively little change in costs and AEP, respectively, that these aspects can induce. Further benefits expected to show greater positive effects can be achieved when considering overplanting together with dynamic cable rating and temporal loadings of the export cable over the nominal transmission level, thereby reducing the amount of curtailment and further increasing the additional energy generation. Overplanting thus is expected to also be able to show greater benefits than presented in this paper.

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