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Cost and Uncertainty in Overplanting the Design of Offshore Wind Farms

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Abstract

To date the connection of offshore wind farms is subjected to a Maximum Export Capacity (MEC) set in their connection agreement with the Transmission System Operator (TSO). Generators can export up to their contracted MEC, with any additional generation curtailed by the TSO. However, the share of time an offshore wind farm is generating at its MEC tends to be low. Overplanting the offshore wind farm by installing a higher wind farm capacity compared to the fixed electrical infrastructure can result in better overall economics, but because wind speeds and wind farm component availabilities are uncertain, there are trade-offs between the probability of additional revenue produced by capturing more wind and higher capital costs of over-installation of turbines. Nevertheless, there is enough evidence to suggest that overplanting can lead to further cost reductions in the maturing offshore wind sector. The percentage of time an offshore wind farm operates at its MEC is an indication of the extent to which the asset can profit from higher transmission utilisation rates. This paper provides a framework to assess overplanting when developers, policy-makers or regulatory bodies are confronted with trade-offs between cost and uncertainty. The paper sheds light onto which sites and technology-specific factors make overplanting a viable option. Finally, the findings of the paper are exemplified by an industrial case study where several offshore wind farms configurations are analysed.

Keywords: Overplanting, offshore wind, decision-making under uncertainty, risk aversion

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1 Introduction

The connection of offshore wind farms is subjected to a maximum export capacity (MEC) set in their connection agreement with the Transmission System Operator (TSO). Generators can export up to their contracted MEC, with any additional generation curtailed by the TSO. For this reason, it has been common practice to size the capacity of offshore wind farms to its MEC, even though the majority of the time they are not generating at full power. Little thought has been put into designing offshore wind farms which optimise its farm capacity in regard to the fixed electrical connection capacity. In this paper, overplanting is defined as the process of installing additional wind farm capacity compared to its MEC.

In 2008, while planning the UK Offshore Wind Round 3, it came to the attention of National Grid that installing a higher installed generating capacity than the connection capacity could result in better overall economics for the development of offshore wind farms despite power being constrained at generations peaks [14]. In that report, a high level study was undertaken in Appendix 1 where 12% overplanting was suggested as an optimal setup, which meant that 1200 MW of offshore wind should be built for 1000 MW of grid connection. The report also looked at the sensitivity of ratio of connection costs to installed wind turbine costs, average wind speed and wind turbine availability. The findings of the study showed that (i) as the cost ratio increases there's an asymptotic trend for the optimum size of the wind farm towards 111%, (ii) as the average wind speed increases there is little change in the optimum size, but if the mean wind speed is less than 9 m/s then the optimum size increases in order to maximise the utilisation of the available capacity and (iii) as the percentage of the wind turbine availability decreases, the installed capacity needs to increase to maximise the utilisation of the available capacity. Although this was a high level study and some of the assumptions are a bit conservative at the current state of the offshore wind sector, it opened up further points for analysis.

In 2011, The Irish Commission for Energy Regulation (CER) published a report where generators were allowed to overplant their onshore wind farm capacity up to 5%, value driven by wind farm cabling and transformer losses which would compensate for losses on the generator's side of the grid connection and would allow the developer to export up to its MEC at the connection point [4]. In 2014, CER decided to update the earlier decision in light of potential economic benefits by increasing overplanting to 20% [9].

In 2012, Forewind looked at overplanting by factoring a number of variables: different turbine types, export and inter-array cable losses, wake losses, grid connection downtime and the total cost for wind turbines, including construction, operation and maintenance [5]. In this study it was also shown that adding more wind turbines improves the economics of the project, however further conclusions could not be drawn given the dependence of many site and technology-specific variables. Similar studies have mentioned the economic benefits of overplanting [15].

A clear example of overplanting in the offshore wind industry is given in the Netherlands for the Wind Farm Zone Borssele. The wind farm is divided into 5 sites. Site I, II and IV can accommodate 350 MW plus 30 MW of overplanting, whereas Site III can accommodate 330 MW plus 30 MW of overplanting. This is around 9 % of overplanting for both cases. TenneT, the Dutch TSO, contemplated the option of dynamic loading of the export cables. Namely, in case that Site I, II and IV was producing at full power, which would see a load of 380 MW being transferred through one of the export cables, this electricity could be handled by the cable and sent to the grid [16]. However, the capacity in excess of 350 MW is not always guaranteed by TenneT, but it is subjected to some constraints linked to the final soil resistivity values, temperature of the cable, final design of the cable system and voltage level of the system.

More recently, some authors have attempted to model overplanting for onshore and offshore wind farms [8, 17]. However, the models utilised in assessing overplanting did not capture the complex relationships between offshore wind engineering variables and financing constraints. Whereas the work of McInerney et al [8] sought to emphasize the benefits of overplanting from the economical point of view, it didn't consider technical variables. Conversely, the work of Wolter et al [17] placed more weight on the technical variables but left aside important financing constraints. Nevertheless, there is enough evidence to suggest that overplanting can lead to further cost reductions in the maturing offshore wind sector. However, a tailored techno-economic model that integrates site characteristics, technology specificities and financing constraints is needed to demonstrate the benefits of overplanting. Furthermore, this techno-economic model should be grounded in the framework of uncertainty quantification, where its model inputs are represented by probability distribution functions.

The contribution of the current paper is to provide a framework to assess overplanting under uncertainty in the design of offshore wind farms; allowing developers and regulatory bodies to identify pareto-optimal trade-offs between cost and uncertainty when deploying additional turbines for a given electrical infrastructure. The rest of this paper is structured as follows: Section 2 explains the main factors driving overplanting. Section 3 describes the detailed modelling of overplanting and its main assumptions. Section 4 benchmarks the current model against previous studies on overplanting. Section 5 applies the modelling techniques to different wind farm configurations. Finally, conclusions are drawn in Section 6.

2 Factors Affecting Overplanting

Overplanting is mainly driven by the following factors:

- Ratio of wind turbine expenditure to electrical infrastructure: higher costs of installing an additional turbine for a given electrical infrastructure makes it more difficult for developers to consider this option.
- Wind speed distribution: it describes the variation of wind speeds for a given site. Sites with low mean wind speed mean that the share of time generating at its MEC is low and so is the amount of curtailment; this encourages developers to increase the installation of additional capacity. On the contrary, sites with high mean wind speed mean that the share of time generating at its MEC is high and so is the amount of curtailment; this doesn't favour the installation of additional capacity.
- Wind turbine and inter-array availability: it is defined as the amount of time that the turbine/cable is able to operate over a certain period of time divided by the total time in that period. Farms with high availability values mean that more turbines/cables are operational at a given point in time and therefore it is expected a higher share of curtailment when overplanting. Likewise, low availabilities result in less amount of curtailment and favour overplanting.
- Wake effect: they reduce the wind speed downstream a generating wind turbine. At high wind speeds the farm is able to produce at rated power. However, wake effects need to be taken into consideration for low wind speeds, which is the amount of generation that is not constrained.
- Electrical losses: they take place in transformers, collection wiring, substation and cables. Higher losses will encourage developers to overplant to be able to generate at MEC at the connection point.
- Degradation factor: wind turbine blades are subjected to environmental conditions that result in blade degradation over time, which directly reduces energy production and encourages overplanting.

3 Modelling

The modelling approach to assess overplanting is based around the Offshore Wind Cost Analysis Tool (OWCAT) developed at the EDF Energy R&D UK Centre. Further information regarding its inputs, outputs and interplay between them can be found in Appendix 8. In addition, details on the modelling of overplanting approach can be found in [2]. Modelling Type 2, as referred to in [2], is considered for the rest of the paper in order to take advantage of the full stochastic behaviour of the model inputs despite requiring a higher computational cost.

Stochastic Modelling

The transition from deterministic to stochastic models requires an added level of complexity that can be justified by three of the following features, as suggested in [13]. First, a pre-existing model that captures the relationship between inputs and outputs. Second, a variety of sources of uncertainty affecting the model inputs, which in this case are represented by probability distribution functions and finally, industrial stakes and decision-making circumstances motivating the uncertainty assessment, leading to a better understanding on cost and uncertainty in overplanting the design of offshore wind farms. OWCAT is a numerical model linking inputs (uncertain $\underline{x}$ or fixed variables $\underline{d}$) to outputs $\underline{z}$ (from which decision criteria can be established). This can be formally defined in Equation 1.

$$\underline{x}, \underline{d} \Longrightarrow \underline{z} = OWCAT(\underline{x}, \underline{d}) \tag{1}$$

It is worth noting the difference between these two sets of inputs. Whereas some inputs have uncertainty associated to them, others may be fixed – as they will play another role in the model, those are represented with notation $\underline{d}$. This is the case when: (i) model inputs represent variables under full control: for example the vessel associated with the installation of a monopile foundation, (ii) the uncertainties affecting the model inputs are considered to be negligible and (iii) the decision process conventionally fixes some variables for comparative purposes and time constraints: for example the discount rate may be set by the developer. However, it is important to bear in mind that a distinction between ”uncertain” and ”fixed” variables usually involve an iterative process by means of sensitivity analyses of the model which is out of the scope of this paper. The methodology of quantitative uncertainty management is a staged process. First, the specification of the problem needs to be considered. This is mathematically represented as the OWCAT model. After that, the uncertainty in the inputs is quantified and modelled by probability distributions. Once this is done, the propagation of uncertainty sources to the quantities of interest in the outputs can be carried out via MonteCarlo or other propagation techniques, resulting in a spread of project performance.

Modelling Risk Aversion

Risk aversion is modelled by risk metrics originated in the financial mathematics literature such as the Value at Risk (VaR) and Conditional Value at Risk (CVar). The $\mathbf{VaR}_\alpha$ gives the probability α that a certain outcome is worse than a given threshold. Typically the probability α represents the confidence level and $\mathbf{VaR}_\alpha$ is regarded as the maximum value that will not be exceeded at this given confidence level. Building on $\mathbf{VaR}_\alpha$, $\mathbf{CVaR}_\alpha$ gives the expected outcome given that the value is worse than $\mathbf{VaR}_\alpha$. The concept was first introduced in Rockafellar [12] and further developed by him in [11]. The mathematical formulation for $\mathbf{VaR}_\alpha$ and $\mathbf{CVaR}_\alpha$ for continuous functions is given in Equation 2 and 3, respectively.

$$\mathbf{VaR}_\alpha(LCOE) = min\left(c : P(LCOE \leq c) \geq \alpha\right). \tag{2}$$

$$\mathbf{CVaR}_\alpha[LCOE] = \mathbf{E}[LCOE | LCOE \geq \mathbf{VaR}_\alpha(LCOE)] \tag{3}$$

Where LCOE is the Levelised Cost of Energy, $P(LCOE \leq c)$ is the probability of the LCOE being less or equal than c and $\mathbf{E}$ is the mathematical expectation operator. One of the main shortcomings of the $\mathbf{VaR}_\alpha$ is that it provides no information on the extent to which values might materialise beyond the threshold amount indicated by the $\mathbf{VaR}_\alpha$ itself, whereas $\mathbf{CVaR}_\alpha$ does. In addition, $\mathbf{CVaR}_\alpha$ has superior mathematical properties since this measure is coherent in the sense of Artzner [1]. For this reason, we've selected $\mathbf{CVaR}_\alpha$ as the preferred financial risk metric. In this approach risk aversion is modelled as a weighted average λ of the **Median** and $\mathbf{CVaR}_\alpha$ of the LCOE values. Parameter λ can be varied from 0 (in a risk neutrality setting) to 1 (extreme risk aversion), based on the work of Munoz [10] and displayed in Equation 4.

$$\boldsymbol{\rho}_\alpha[\lambda, LCOE] = \lambda\mathbf{CVaR}_\alpha[LCOE] + (1-\lambda)\mathbf{Median}[LCOE] \tag{4}$$

4 Benchmark against National Grid

National Grid conducted a high level study on the optimal amount of overplanting for the UK Round 3 offshore wind farms [14]. The findings of the study suggested a 12% overplanting. However these findings are based on the following parameters: 5MW wind turbine, 90% wind turbine availability, 1.1GW of total capacity and an average wind speed of 9 m/s, which meant that 1200 MW of offshore wind should be built for 1000 MW of grid connection. Assuming the same base parameters, Figure 1 and 2 were obtained using our cost modelling tool. Figure 1 shows the difference between the unconstrained and constrained yield as a function of overplanting; the amount of constraint is minimum up to 8% overplanting, where the two lines start to diverge. This point is also reflected in Figure 2, suggesting that additional energy produced by the over installation of turbines doesn't outweigh its wind turbine expenditure; a 9% overplanting is considered optimal for this farm. Although the OWCAT modelling provides similar levels of overplanting as National Grid, some of the assumptions are a bit conservative in the current state of the offshore wind sector. For example, the rated capacity of wind turbines has almost double since 2010, moving from 5MW to 10MW wind turbines. Moreover, wind turbine availability rates have also increased from 90 to 95% or above. This suggests that past studies on overplanting based on these assumptions needs to be revisited.

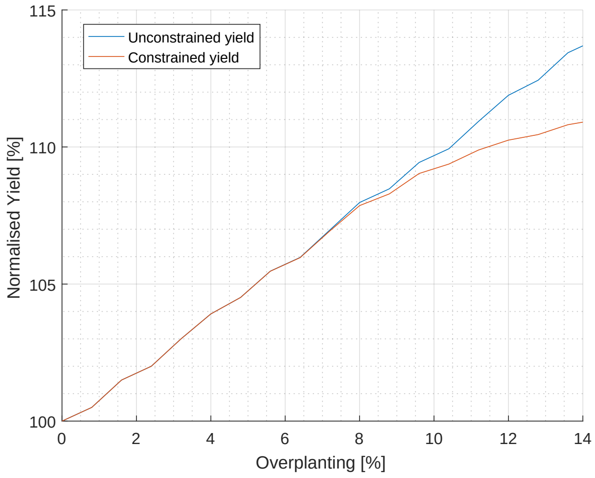

Figure 1: Unconstrained versus constrained normalised yield as a function of overplanting.

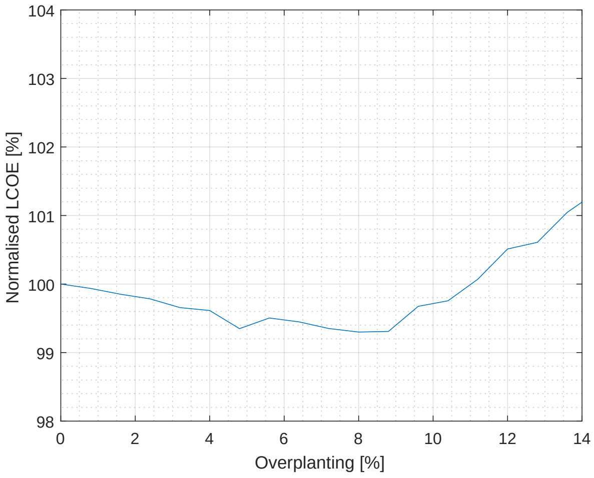

Figure 2: Reference case LCOE values for National Grid as a function of overplanting

5 Case Study

Several offshore wind farm configurations are analysed in terms of its suitability to overplanting; its project specifications are shown in Table 1. It is assumed, for the sake of simplicity, that the export cable length, construction and operational port distances are equal to the distance from shore. The MEC is 400MW, 1GW and 2GW and offshore wind farm capacities are varied from 0% to 14% in overplanting. The estimated mean wind speed is represented by a normal distribution with mean (μ) and standard deviation (σ) as $\mathcal{N}(\mu, \sigma^2)$[1]. Likewise, availabilities are represented by uniform distributions with lower(a) and upper(b) bounds as $\mathcal{U}(a, b)$.

Table 1: Offshore wind farm project specifications.

Characteristic	Value	Uncertainty
Water Depth [m]	25	None
Distance from shore [km]	25	None
Mean Wind Speed @ 100m [m/s]	9	$\mathcal{N}(9, 0.1^2)$
Wind Turbine Availability [%]	95	$\mathcal{U}(90, 97)$
Inter-Array Cable Availability [%]	99	$\mathcal{U}(97, 99)$
Foundation Type [-]	Monopile	None
Electrical Infrastructure [-]	HVAC	None
Wind Turbine Type [-]	164-8 MW	None
Wake effect [%]	10	None
Degradation Factor [%]	0.05	None

The reference case is calculated through a Monte Carlo simulation with input parameters from Table 1 (without uncertainties). Figure 3 shows the difference between the unconstrained and constrained yield as a function of overplanting; the amount of constraint is minimum up to 2% overplanting, where the two lines start to diverge. This point is also reflected in Figure 4, suggesting that additional energy produced by the over installation of turbines doesn't outweigh its wind turbine expenditure; a 2% overplanting is considered optimal for this farm. This is considerably lower compared to National Grid. As shown in Borras [2], several technology-specific factors were investigated in terms of its suitability to overplanting: wind speed, wake effects and wind turbine and inter-array cable availability. It was shown that the most sensitive parameter to overplanting is the wind turbine availability, which has been fixed to 95% for the local sensitivity in this study. The purpose of this paper is to expand this study to examine parameters such as wind farm capacity, wind turbine size, average water depth and average distance from shore, in order to provide some insight on how overplanting is influenced by larger turbines and sites located further from shore. In order to do so, the following number of combinatorial configurations (81), displayed in Table 2, have been examined.

Figure 5 shows the optimal amount of overplanting as a function of the wind farm total capacity and distance from shore. For a 25km distance from shore, overplanting the farm results in overall economic benefits. As the wind farm size increases so does the optimal amount of overplanting, moving from 2% to 4%. On the contrary, for 50 and 75km distance from shore, the optimal amount of overplanting remains at %2 for 400 MW while higher capacities lead to a negative overplanting effect; to the extend that for a 75km from distance any amount of overplanting results in a negative effect. For a given

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[1] 0.1 m/s is a representative value combined from independent uncertainties, individually determined by normal distributions as seen in [7, 6, 18]

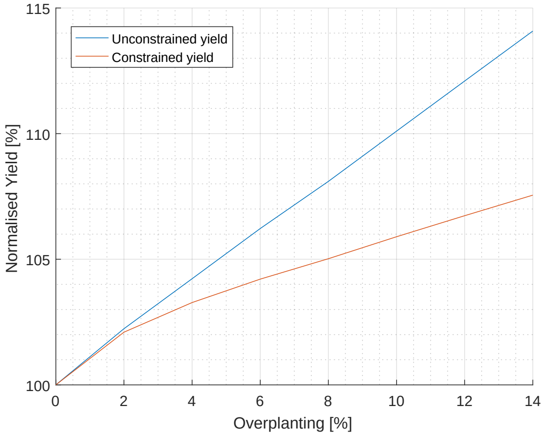

Figure 3: Unconstrained versus constrained normalised yield as a function of overplanting.

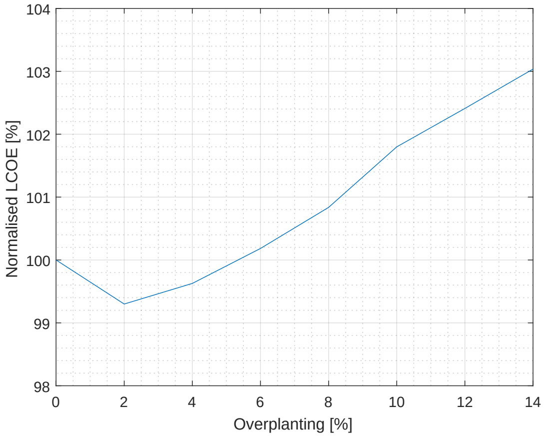

Figure 4: Reference case LCOE values as a function of overplanting.

Table 2: Wind farm configurations.

OWF Capacity[MW]	WTG Size[MW]	Distance Shore[km]	Water Depth[m]
400	4	25	25
1000	8	50	40
2000	12	75	60

site, the further from shore, the higher are the installation costs of the wind turbines. Given that the wind resource remains constant for all cases (at 9m/s mean wind speed), increasing the distance from shore, reduces the amount of optimal overplanting. In addition, the increase in wind farm size acts as a catalyst, increasing the effects of overplanting - derived from its economies of scale. Figure 6 takes advantage of the same data as Figure 5; however these are display holding wind farm capacity constant for every subplot. Figure 7 shows the optimal amount of overplanting as a function of the number of wind turbines for several wind farm sizes. Although the amount of overplanting changes depending on the size of the wind turbines, this effect is reduced as the the size of the farm grows. Figure 8 shows the optimal amount of overplanting as a function of the water depth and distance from shore in a 400 MW farm, whereas Figure 9 represents the same data but for a 2000 MW farm. Both figures suggest that the water depth has a neglegible effect on the optimal amount of overplanting.

The probability distribution function of the LCOE is obtained by 20,000 model evaluations of an outer Monte Carlo loop with parameters displayed in Table 1. It is worth bearing in mind that, for each model evaluation, an inner Monte Carlo simulation propagates the wind speed and availabilities with another 10,000 model evaluations within the Annual Energy Production module; this process is repeated for several degrees of overplanting. The risk metrics given by the expression $\lambda \mathbf{CVaR}_{\alpha=0.05}[LCOE] + (1-\lambda)\mathbf{Median}[LCOE]$ are normalised with respect to the values obtained when no overplanting is applied, as displayed in Figure 10. Overplanting the farm from 2% to 8% results in risk metrics (in a risk neutrality setting) that improve the economics of the farm. However, the optimal design is found at 4% of overplanting regardless of the risk appetite. Figure 11 includes the case when a 0.05 m/s mean wind speed uncertainty is given - the optimal amount of overplanting remains constant.

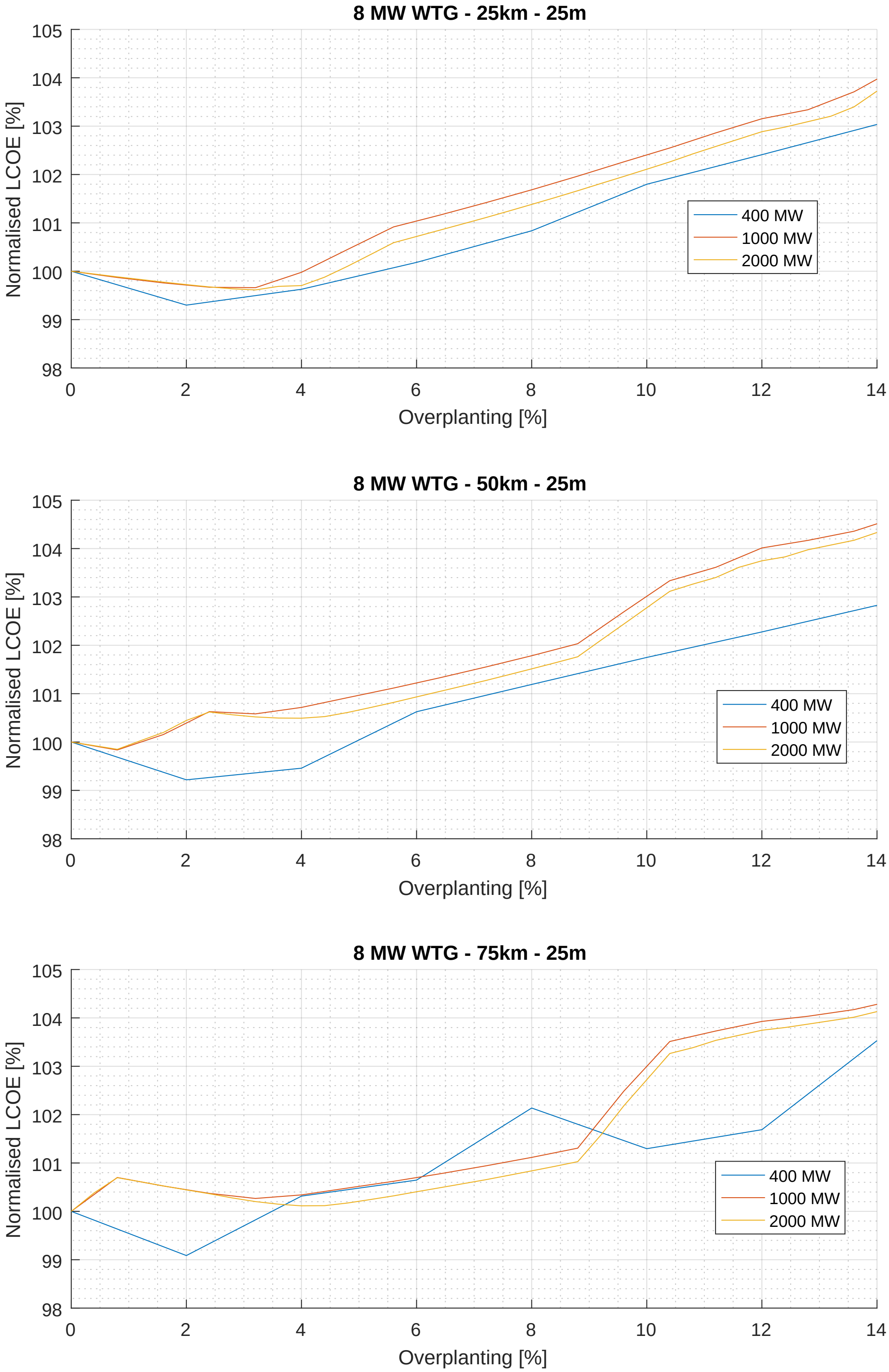

Figure 5: Influence of wind farm capacity and distance from shore to the optimal amount of overplanting.

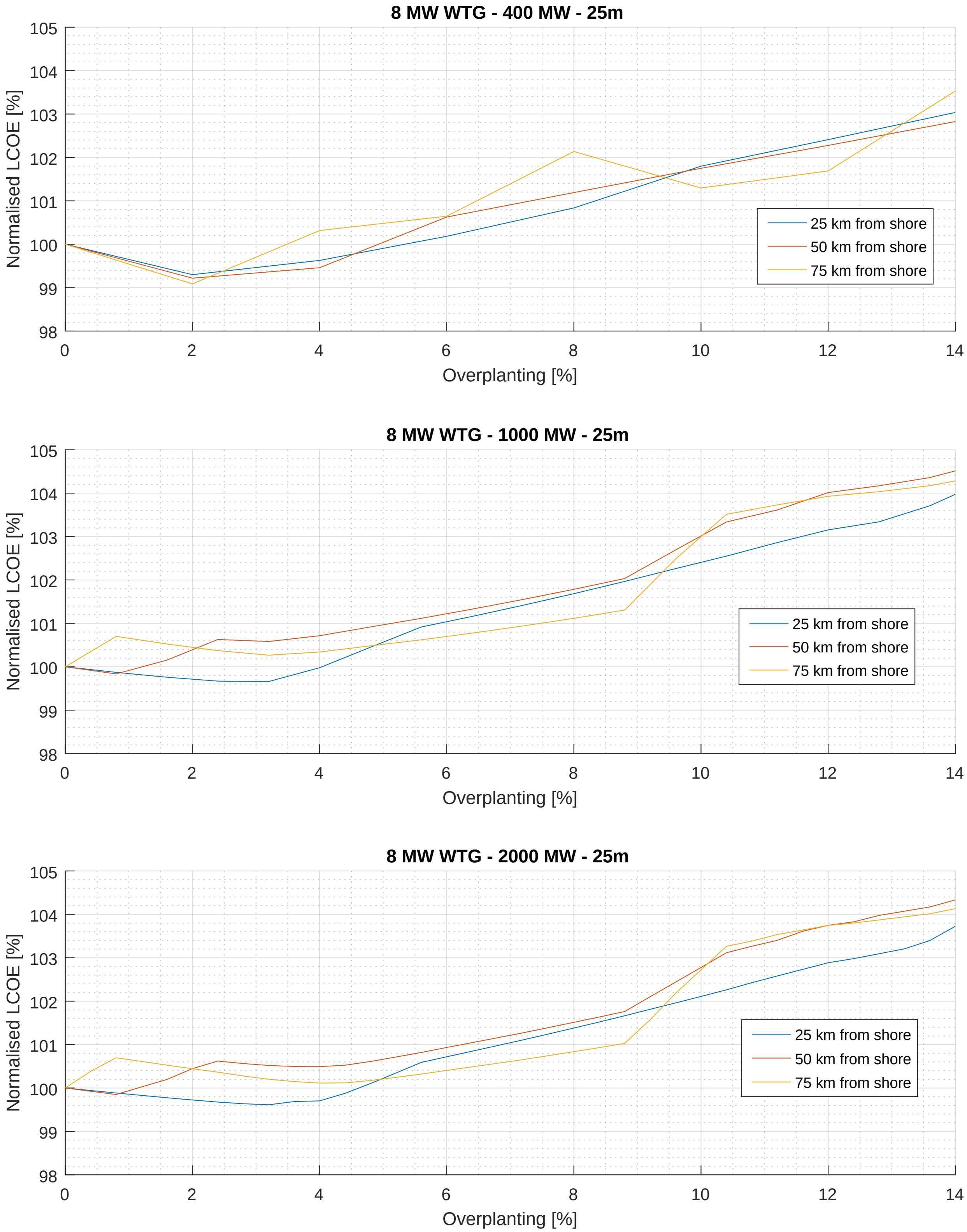

Figure 6: Influence of wind farm capacity and distance from shore to the optimal amount of overplanting.

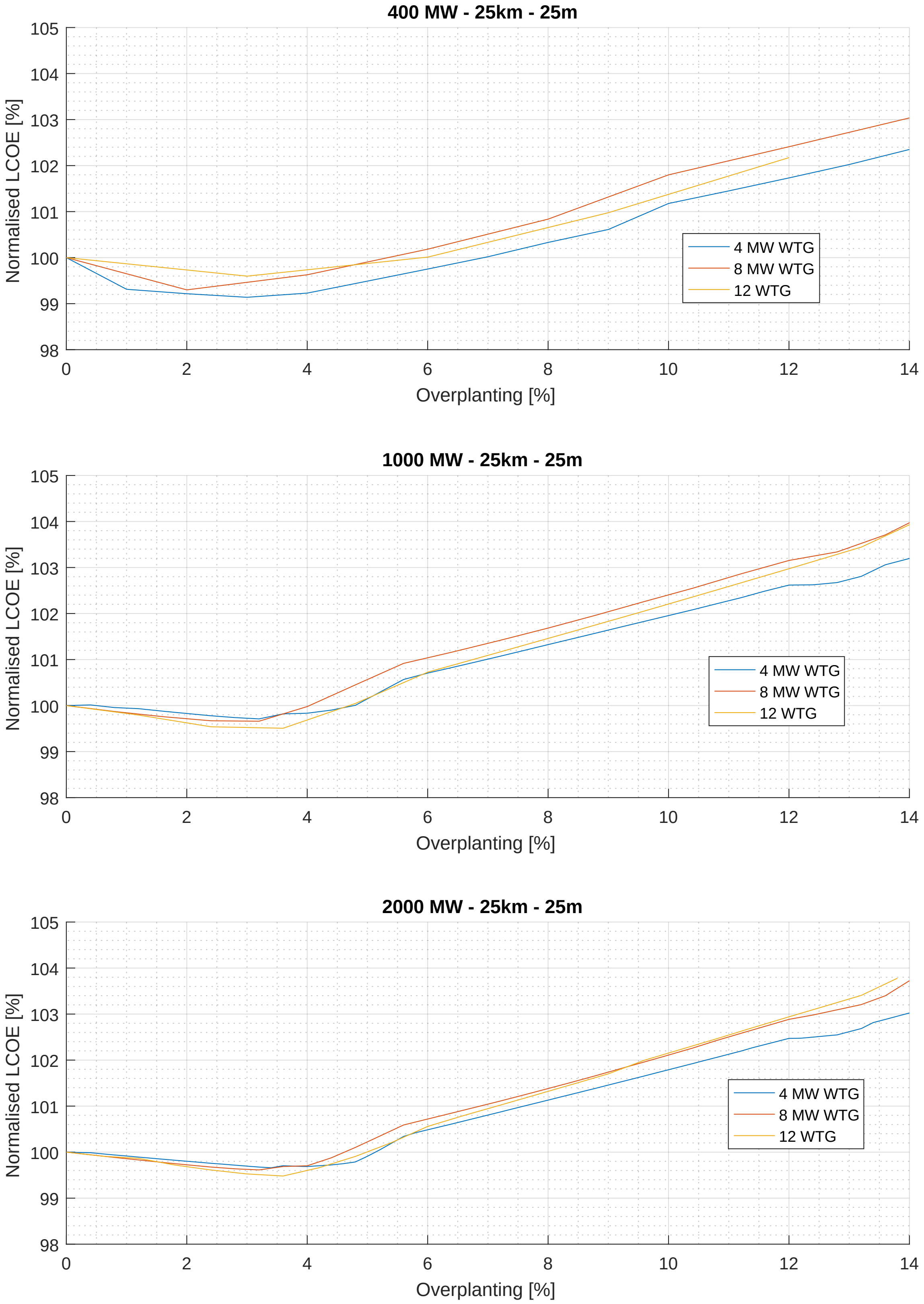

Figure 7: Influence of wind turbine size to the optimal amount of overplanting.

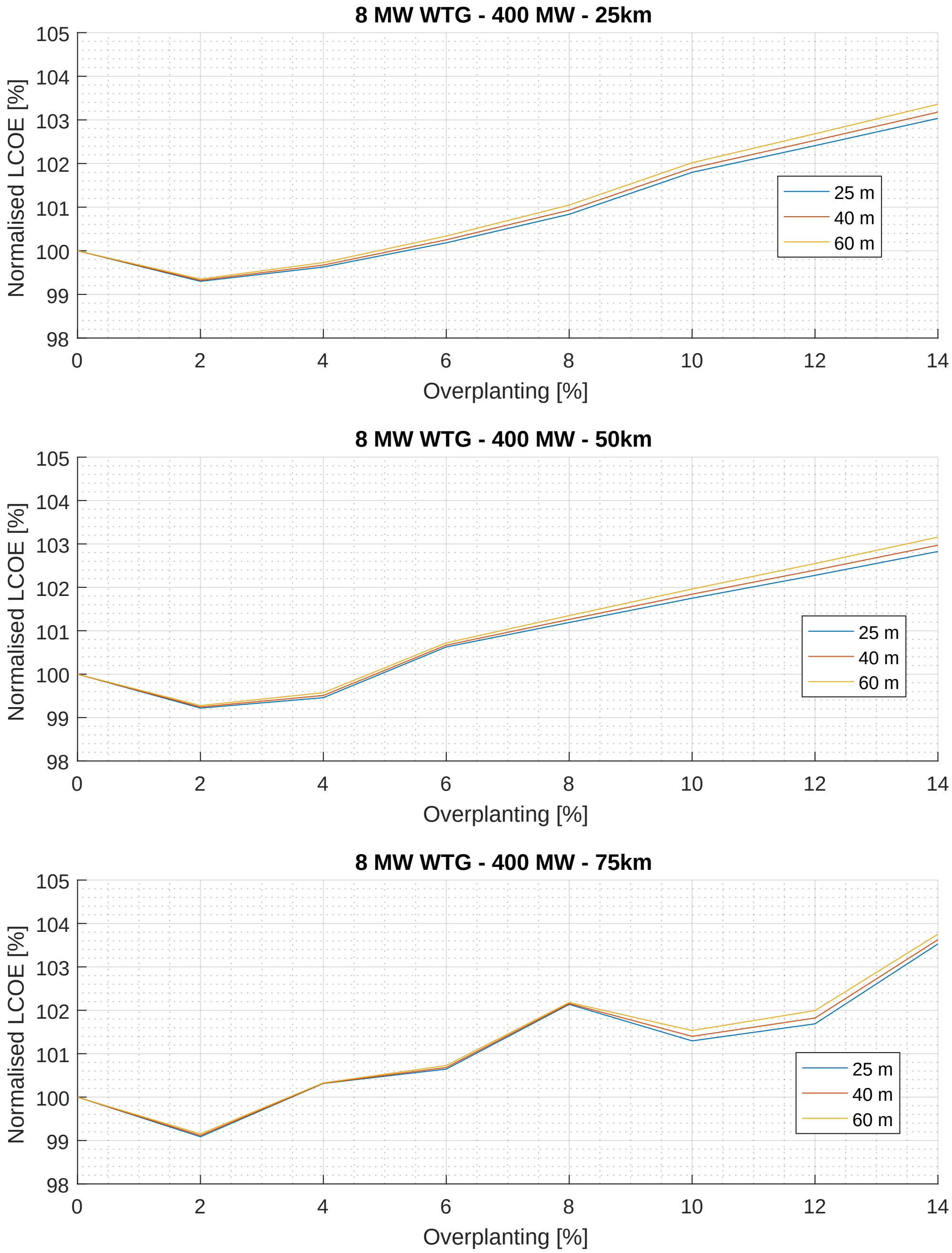

Figure 8: Influence of water depth to the optimal amount of overplanting in 400 MW farm.

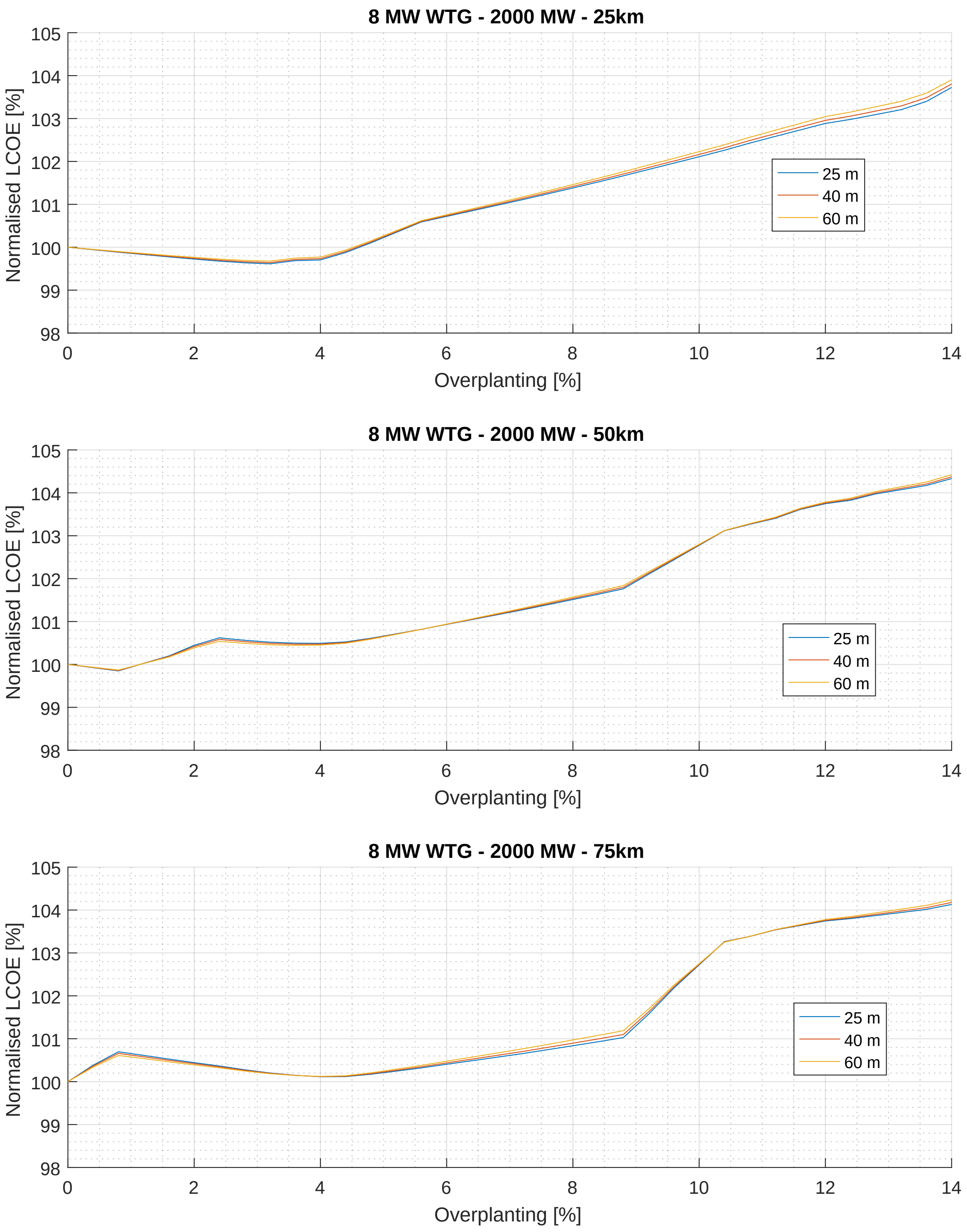

Figure 9: Influence of water depth to the optimal amount of overplanting in 2000 MW farm.

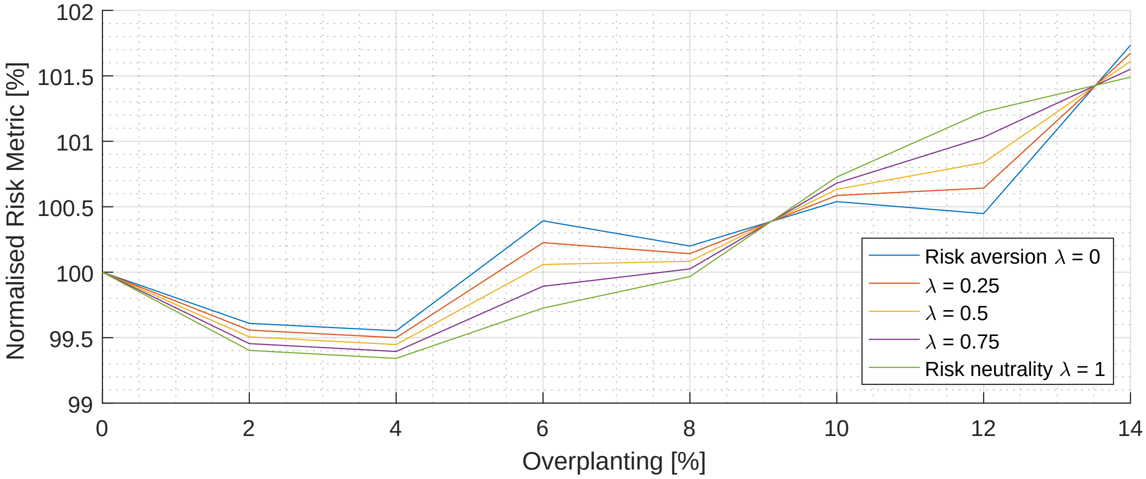

Figure 10: Risk aversion represented by $\boldsymbol{\rho}_\alpha[\lambda, overplanting]$ - 0.1 m/s mean wind speed uncertainty.

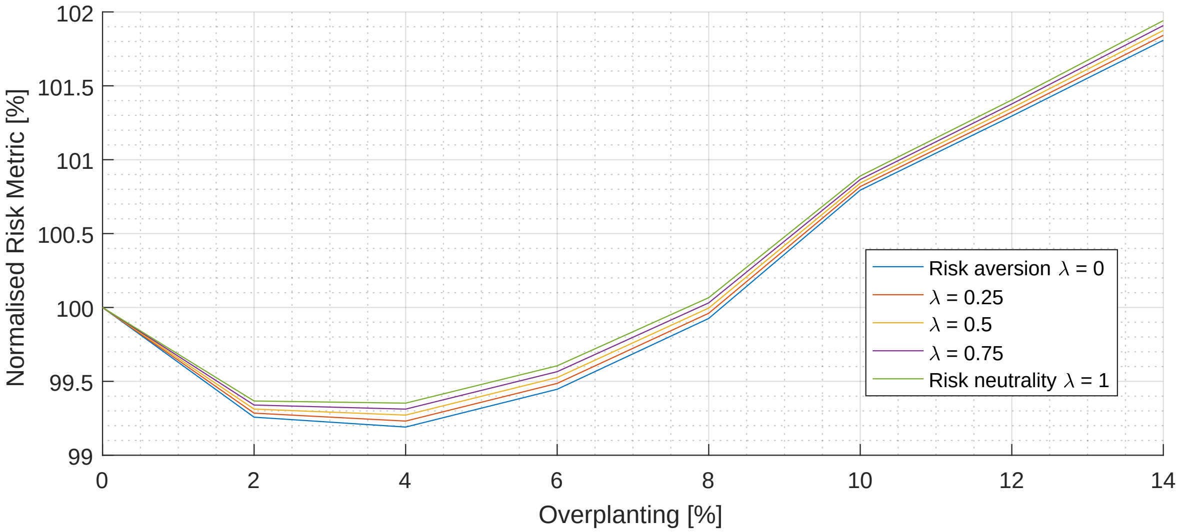

Figure 11: Risk aversion represented by $\boldsymbol{\rho}_\alpha[\lambda, overplanting]$ - 0.05 m/s mean wind speed uncertainty.

6 Conclusions

This paper has presented the development of a novel framework to assess overplanting in the design of offshore wind farms when the underlying variables, such as the wind speed and availability rates, among others, are uncertain. As seen by a benchmark with National Grid, as the wind turbine availability increases, overplanting becomes less valuable. This suggests that previous studies on overplanting, which were based on low wind turbine availabilities rates from UK Round 1 offshore wind farms (in the order of 90%), need to be revisited.

A local sensitivity analysis has revealed that wind farm capacities, turbine sizes and distances from shore are sensitive parameters to overplanting, whereas water depths play a secondary role. For a given site, wind farm sizes act as a catalyst for overplanting - increasing the positive or negative effects depending on the wind farm configuration. In addition, bigger wind turbine sizes reduce the effect of overplanting. Finally, the further the distance from shore, the higher installation costs of the wind turbines are and when holding wind resource constant, it reduces the amount of optimal overplanting. As a consequence, it is expected that sites located further from shore, with bigger wind turbines and less units for a given wind farm capacity will most likely have small benefits from overplanting.

Without considering the uncertainties in the different parameters represented by the outer Monte Carlo loop, it appears that the optimal amount of overplanting is 2% for our reference offshore wind farm. Generally speaking, the role of determining the optimal setup comes down to the risk appetite of the developer, which in this case is represented by a linear combination of the risk aversion and risk neutrality setting, governed by the λ parameter. However, when conducting the double loop Monte Carlo simulation, the optimal setup is found at 4% regardless of the risk appetite considered. Furthermore, overplanting the farm by any value from 2% to 8% gives a better result than with no overplanting for a risk neutral setting, meaning that overplanting can be used as a hedging instrument. Sensitivities on wind speed uncertainty do not change the optimal amount of overplanting.

Future work will take advantage of the framework developed in this paper to quantify how risk aversion influences the investment decision for the local sensitivity analysis carried out in this study. Also, the degradation factor has been taken into account after the constraint, but we would expect greater amounts of overplanting if this was taken before the constraint.

7 Acknowledgements

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8 Appendix A - Offshore Wind Cost Modelling Tool

The Offshore Wind Cost Analysis Tool (OWCAT) developed at the EDF Energy R&D UK Centre has been used in the past for comparative evaluation of multiple sites, detailed evaluation of specific project layouts and sensitivity studies on both design/technology choices and cost variations [3]. The tool has been validated against cost data from the Navitus Bay, Courseulles-sur-Mer and Neart na Gaoithe projects and shown to be accurate within ± 15% for these cases.

The cost modelling tool consists of four main modules: a wind farm design module, a cost calculation module, a financial module and an overarching stochastic module which allows inputs to be represented by probability distribution functions. The first stage of the module concerns the wind farm design. In order to evaluate the costs of the project, it is necessary to have information about the number and type of wind turbines, foundations, inter-array cabling and the export system. In other words, the wind farm itself must be modelled. Designing an offshore wind farm requires interaction between teams from different disciplines; for example, the wind turbine team will have to interact with the foundation team to make sure that the loads of the turbine are correctly passed onto the foundation, and the foundation team will need to make sure that the electrical connections are correctly secured within the foundation. As such, a cost model must capture the same interactions as the design process and cannot be a simple accumulation of models from separate disciplines.

The design outputs of the first module are fed as inputs into the second module, which calculates the costs of the different offshore wind farm components. The cost module can be divided into Development Expenditure (DEVEX), Capital Expenditure (CAPEX), Operational Expenditure (OPEX) and Decommissioning Expenditure (DECEX). DEVEX covers the costs of all the processes up to the financial close or placing firm orders to proceed with the construction. CAPEX calculates the supply and installation costs of the wind farm, including wind turbines, foundations, inter-array cables, offshore substations, export cables and onshore substations. Indirect costs such as Engineering, Procurement, and Construction Management (EPCM) costs and insurance are also included in the CAPEX breakdown. OPEX includes direct costs for the operation and maintenance of the wind farm, as well as transmission charges, insurance, taxes and royalties. DECEX accounts for the decommissioning of the wind turbines, foundations and offshore substations.

The cost outputs of the second module are passed into the third module, which is the financial model of the wind farm project. The financial model takes into consideration the different cash flows throughout the life of the wind farm, as well as the financing structure put in place to supply the initial capital investment. Based on the resulting free cash flows and financing costs, the LCOE can be determined, together with other financial performance indicators. The financial module allows for corporate and project financing modelling.

The OWCAT structure is shown in Figure 12. This information has been divided into:

- (i) Project Specifications
- (ii) Technical Specifications
- (iii) Economic and Financial Specifications
- (iv) Vessel Specifications
- (v) Structural Masses and Electrical Components Database

(i) refers to the project offshore wind farm characteristics such as the capacity of the farm, the wind speed at a given referenced height, the average water depth, the soil conditions, the distance from shore, the wind turbine model, foundation type and export system specifications among others. Since no two projects will have the same characteristics, project specifications attempt to model each particular site.(ii) addresses the details of the offshore wind technology, representing wind turbine, foundation, inter-array cable, export system and grid parameters. For example, as far as the wind turbine is concerned, parameters such as the wind turbine availability, the installation vessel associated with the wind turbine, the average loading, installation and commissioning times are accounted for. In addition, a decommissioning factor is used for all offshore wind farm components to account for a reduction in time from the installation phase.(iii) concerns the reference year for real prices, the risk-free rate and cost of debt, insurance and insurance premium tax rates, contingency requirements, corporation taxes, depreciation, seabed rent, exchange rates and inflation.(iv) involves the different vessel characteristics used in the installation and decommissioning of the offshore wind farms. As an example, heavy-lift jack-up vessel parameters comprise the day rate, vessel transit speed, vessel positioning time, vessel mobilisation time, operational weather window and carrying capacities in regard to different components.(v) consists of the data used to establish the foundation mass correlations, which are the basis for the CAPEX estimation in the foundation procurement. It also considers the correlations used to estimate the cost of different electrical components.

The final design contains not only the design of the offshore wind farm, where the foundations masses, inter-array and export system are sized, but also the procurement, vessel charter model and the Annual Energy Production (AEP) as displayed in Figure 12. Procurement stores all the information concerning wind turbines, foundations and the electrical system, in terms of the type, number of elements and size (also length if required), giving rise to a procurement catalogue which forms the basis for the cost module. The vessel charter model is based on the work of Kaiser [**Kaiser2012**], whereas the AEPs is built upon industry's best practices assuming respectively either a logarithmic- or power-law wind profile in conjunction with a Rayleigh or Weibull probability distribution to model the wind speed. Wake losses and electrical losses are also accounted for in the AEP submodule.

As far as the financial module is concerned, the calculation itself entails not only one but a twofold iterative process. The external loop consists of determining the value of λ that makes Equation 5 equal to 0.

$$LCOE = \lambda | \sum_{t=1}^{n} \frac{FCF_t(t)}{(1+MARR)^t} = 0; \tag{5}$$

Where FCF are the free cash flows, $MARR$ is the desired Minimum Acceptable Rate of Return (MARR) and λ_0 is the intial guess obtained from a simplified financial model. The LCOE financial metric is calculated as the constant inflation-linked real electricity price required to meet the desired MARR. The internal loop is used in the project finance setting and concerns the debt sizing or sculpting, which determines the maximum amount of project finance debt that the offshore wind farm can sustain based on the bank's requirements. Project lenders usually specify the borrowing capacity on the basis of debt service ratio and convenants. As such, parameters such as the Debt Service Coverage Ratio (DSCR), the maximum leverage and the Cash Flow Available for Debt Service (CFADS) have been considered.

Lastly, the stochastic module (depicted in orange in Figure 12) allows the model to be embedded in the framework of uncertainty quantification.

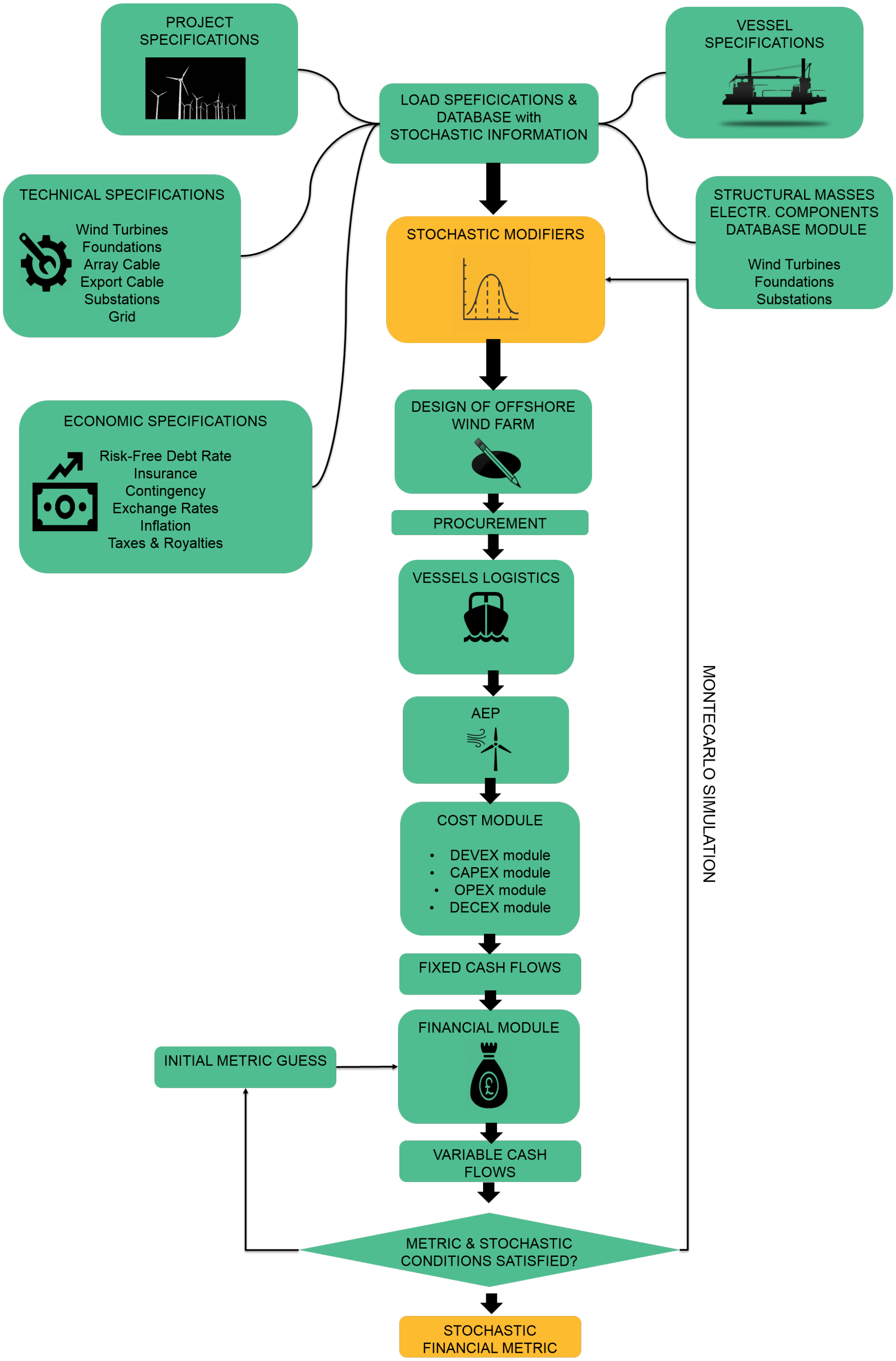

Figure 12: Stochastic OWCAT Structure

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