Paper ID 10882 Session 2022

B1 - Insulated Cables

PS 2 / Future functionalities and applications

Optimal energy management of offshore wind farms considering the combination of overplanting and dynamic rating

Ildar DAMINOV[1], Salvy BOURGUET[2],
Didier TRICHET[3], Guillaume WASSELYNCK[4]
Nantes Université
France
[1]Ildar.Daminov@univ-nantes.fr
[2]Salvy.Bourguet@univ-nantes.fr
[3]Didier.Trichet@univ-nantes.fr
[4]Guillaume.Wasselynck@univ-nantes.fr

Anne BLAVETTE*[5],
Hamid BEN AHMED[6]
ENS Rennes
France
[5]anne.blavette@ens-rennes.fr
[6]hamid.benahmed@ens-rennes.fr

Laurent. DUPONT
Univ. Gustave Eiffel
France
laurent.dupont@univ-eiffel.fr

Thomas SOULARD
Ecole Centrale de Nantes
France
thomas.soulard@ec-nantes.fr

Pierre WARLOP
WPD
France
p.warlop@wpd.fr

SUMMARY

The electricity cost from offshore wind turbines has significantly declined over the past decade. However, in the context of energy transition, the further reduction in electricity generation costs remains a forefront subject. One possibility is to enable offshore wind farms to have a greater installed capacity than their transmission infrastructure, known as “overplanting”. This allows increasing their energy generation revenues while requiring some curtailments of their power output during the most energy-rich periods of the year. Also, export cables may have a high thermal inertia, so they can be fully loaded for several days before the cable reaches the maximum permissible temperature (usually 90°C for XLPE cables). Hence, some Transmission System Operators (TSOs) have recently allowed offshore wind farm operators to export more power than the transmission infrastructure may deliver in the steady-state conditions. This is known as the «dynamic thermal rating» (DTR). DTR combined with overplanting can lead to a significant reduction in the Levelized Cost Of Energy (LCOE) of offshore wind farms.

This paper examines the benefits of improving the electricity production commitment strategies against business-as-usual approaches based on the 50% quantile, called P50. In this perspective, a theoretical case is investigated, where the day-ahead and imbalance prices would be known in advance in order to define an optimized power production commitment. This theoretical case intends to define the upper bound on the annual revenue that could be gained by enhanced forecasts on both the production and the day-ahead and real-time energy prices. The study is based on a thermal model of a generic export cable, built per IEC standards 60287 and 60853-2, with data provided by the French TSO. The model was validated against simulation results provided by the French TSO. Historical day-ahead and imbalance prices are considered, as well as forecast and actual measured production profiles from offshore wind farms provided by the Belgian TSO. The source code developed in the project described in this paper, along with relevant data, and a related documentation will soon be provided in open-access repositories available from the project official webpage [1].

KEYWORDS

submarine export cable, dynamic rating, overplanting, imbalance, offshore wind farm

1. INTRODUCTION

The cost of electricity from offshore wind farms (OWF) has decreased over the last decade. Nevertheless, in the context of the energy transition, it is of paramount importance to continue reducing electricity generation costs. One possibility consists in allowing OWF to present a greater power capacity than their transmission infrastructure, which is referred to as "overplanting" [2–11]. This enables to increase the revenues from the boosted energy generation, while requiring curtailment during the most energy-abundant periods of the year. These wind energy curtailments are necessary to keep the OWF output below the limits of its transmission (export) network. The transmission infrastructure may have various bottlenecks: power transformers and/or export cables (in J-tubes, joints, submarine or landfall sections), depending on TSO design choices [12]. In this paper, we focus in particular on the submarine section of export cables. These export cables may present a high thermal inertia (depending on the installation, soil characteristics, burial depth along the cable route and laying configurations of the cable system). Therefore, they could be operated at full power during several days before the cable reaches its maximum allowed temperature (usually 90°C for XLPE cables [13]). Note that OWF produce a full power only few days per year [14] and for such periods, the export cable temperature may be kept below its maximum allowed temperature by taking advantage of its thermal inertia.

Under these conditions, Transmission System Operators (TSOs) in some countries have recently allowed offshore wind farm operators/developers to export more power, on a temporary basis, than the rated power of the export electrical infrastructure which corresponds to steady-state conditions [15–19]. This is referred to as "dynamic thermal rating". The combination of overplanting and dynamic rating may lead to a significant decrease in the offshore wind Levelized Cost Of Energy (LCOE) [18]. Hence, we investigate this topic, and contribute to the necessary cost reduction of offshore wind farms by focusing on potential savings from the electro-thermal management of export cables [1]. In particular, this paper investigates the benefits of improving the electricity production commitment strategies with respect to the business as usual commitment strategy based on the 50% quantile, referred to as the P50. The P50 quantile represents the power level that could be exceeded with 50% chance. In this perspective, a theoretical case is investigated, where the day-ahead and imbalance prices would be known in advance in order to define an optimized power production commitment. This theoretical case intends to define the upper bound on the annual revenue that could be gained by enhanced forecasts on both the production and the day-ahead and real-time energy prices.

Several research works have investigated the overplanting of offshore wind farms, whereas fewer works have focussed on the combination of overplanting and dynamic rating for offshore wind farms (OWFs). For instance, Getreuer et al [17] investigated the thermal overloading of offshore grids, including an oversized OWF (by 4%), which led to a small to negligible curtailment of 0.1% to 1.4%. Pilgrim and Kelly [14] suggested a method to find the optimal number of wind turbines considering the dynamic rating of the export cable (including the J-tube, landfall and submarine sections) while considering the cable reactive power generation. They considered the minimization of the cable contribution to the LCOE, and showed that the LCOE could be reduced by £1/MWh (generation costs of OWF are assumed to be equal as £70/MWh) while increasing the wind farm production by 19%. This is equivalent to reducing the cable CAPEX by 14 %. In [16], authors showed that it is possible to reduce the cross section of an export cable by 25 % without violating the temperature constraints if the actual power profile of the OWF and the cable thermal inertia are considered.

However, most of the works investigating the combination of overplanting and dynamic rating for offshore wind farms considered it in the perspective of the design planning stage. A minority of works have addressed the operational scheduling of overplanted offshore wind farms for which dynamic thermal rating would be allowed. In 2020, Hernandez Colin presented a doctoral thesis on day-ahead (DA) management including probabilistic algorithms considering DTR [18], [5]. This research work considered a revenue based on day-ahead energy prices and including a curtailment strategy. In similar fashion, in 2021, another doctoral thesis by Syed Hamza Kazmi addressed the dynamic rating of an overplanted offshore infrastructure including both cables and transformers [19]. Specifically, the thesis defines the thermal bottlenecks of the OWF infrastructure, and solves the energy management optimization problem, but only for transformers and not for subsea cables. Hence, none of these works considered the costs of imbalance (either as penalties or rewards) between a committed production profile and the actual power profile. However, as forecasts are inherently imperfect, there may be significant mismatches between the expected power profile and the actual one. These discrepancies may be compensated by the TSO through balancing reserves. On a financial level, the Balance Responsible Party (BRP) in charge of a given Balance Perimeter, to which the energy supplier belongs, is therefore either paid by the TSO for an excess of energy compared to the production forecast, or pays the TSO in case of a deficit in energy. This is explained in more detail in Section "Modelling & Methodology".

One of the goals of this paper is therefore to consider the additional revenue/penalties linked with imbalances when considering an optimal DA power commitment strategy in an overplanted OWF where dynamic rating is allowed. A comparative analysis with the business as usual strategy, based on quantiles, and especially on the 50% quantile (P50) will be carried out. In this perspective, an ideal case is investigated, where the day-ahead and imbalance prices would be perfectly known in advance in order to define an optimized power production commitment, while the wind power production is uncertain. These cases are theoretical, as DA prices are known after the market clearing (i.e. after the commitment has been done) while imbalance prices are known a posteriori, but they allow to provide an upper bound on the maximum revenue that could be expected. DA price forecasting has been studied in many research works [20]. It is also worth mentioning that, as renewables are becoming the main cause of imbalances in many power systems, such imbalances may become more and more predictable at different lead times [21]. Research works on imbalance volume and price forecasts are emerging, as there may indeed be some significant benefits for the energy market actors to exploit imbalances, despite the fact that this may be worrying for grid operators [21–24].

2. MODELLING & METHODOLOGY

2.1. Cable thermal model

In our case study, the OWF is connected through one submarine cable to an onshore substation (see Figure 1). It is assumed that other elements (e.g. offshore and onshore power transformers, J-tubes, etc.) are sized at a sufficient rating so that they do not represent a thermal bottleneck for this electrical infrastructure. This design assumption is similar to the one investigated by Dutch TSO [12] for a 350 MW OWF presenting 30 MW of possible overplanting (i.e. thus resulting in a maximum rated capacity of 380 MW) where the J-tubes (having particularly low thermal inertia levels) [8] as well as the transformers [25] are sized for the maximum rated capacity or above [12]. Hence, in this study, the landfall and submarine sections of export cable may represent the bottlenecks of the network infrastructure. In this paper, only the submarine part of the HVAC export cable is considered. Also, at a first stage, the cable joints have not been considered, although they present a lower thermal inertia than the rest of the submarine cable, in the absence of available models on this part.

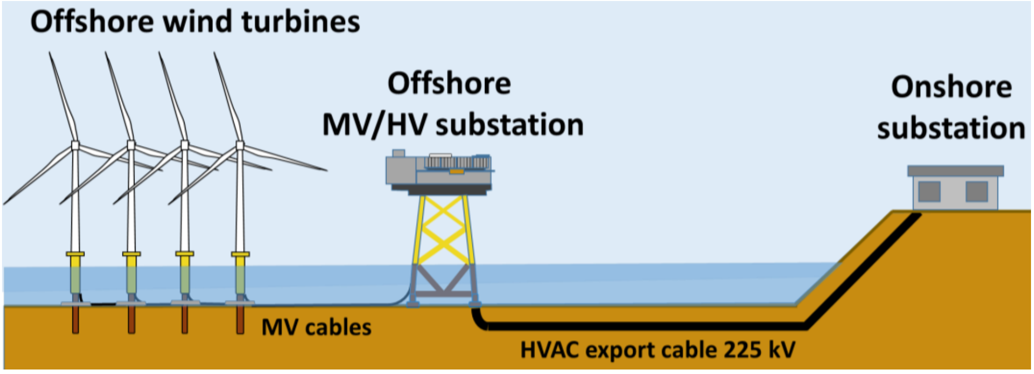

Figure 1 Illustration of the electrical infrastructure of OWF. In our study, only the submarine section of export cable is considered.

In this paper, we use a HVAC 3-core submarine cable of cross-section equal to 1000 mm^2, of rated power equal to 339 MVA, and of rated voltage equal to 225 kV, whose geometry and materials characteristics were provided by the French TSO. Note that through the course of this paper, we always use the same export cable (rated at 339 MVA). In other words, the installed capacity of the OWF may change as a function of the overplanting rate but the export cable capacity remains always the same (339 MVA). At a first stage, we assume a power factor equal to one. It is important to note that cables absorb or provide reactive power, therefore potentially requiring reactive power compensation devices, while energy producers are also legally bound to supply reactive power absorption/supply services. Hence, the transfer of active power through the considered cable can never be equal to the apparent rated power of the cable, which is assumed here and represents a limitation of this study. Future work is intended to consider this aspect. The maximum allowed temperature is equal to 90°C for this type of cable. We assumed that curtailment is applied as soon as the temperature reaches this value. However, temperature monitoring devices may present a coarser precision of few degrees. This may render it necessary to enforce curtailment at few degrees less than 90°C.

The electro-thermal model used in this paper was developed based on IEC standards 60287 [26,27] and 60853-2 [28]. The IEC 60853-2 model is based on a two-cell RC equivalent circuit which is shown in Figure 2. The corresponding numerical parameters of our model are shown in Table 1. As the standards present a sophisticated procedure with some ambiguities, we decided to provide the details of our model in a supplementary material soon to be published on the project webpage [1]. The thermal model was validated against data provided by the French TSO. A temperature difference not exceeding 2°C was observed between the two models, which is deemed sufficient for our studies at this stage.

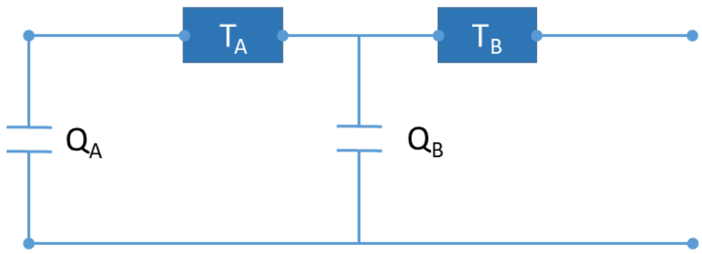

Figure 2 Equivalent thermal circuit with two cells

Table 1 Values of the RC model

Name	Value
T_A	0.1595 K/W
T_B	0.0756 K/W
Q_A	18,008 W·s/K
Q_B	36,333 W·s/K

2.2. *OWF generation forecast and actual production profiles*

To model the OWF power profiles, we used the power measurements of real Belgian OWFs and the corresponding forecasts in the form of quantiles (P90, P50 and P10) provided by the Belgian system operator [29]. These quantiles PX represent the power level that could be exceeded with 100%-X% chance. For instance, the P50 quantile represents a forecasted power level which could be exceeded with 50% chance (100%-50%). Figure 3 shows the actual production of the OWFs connected to the Belgian network, as well as the corresponding forecast quantile profiles in per units.

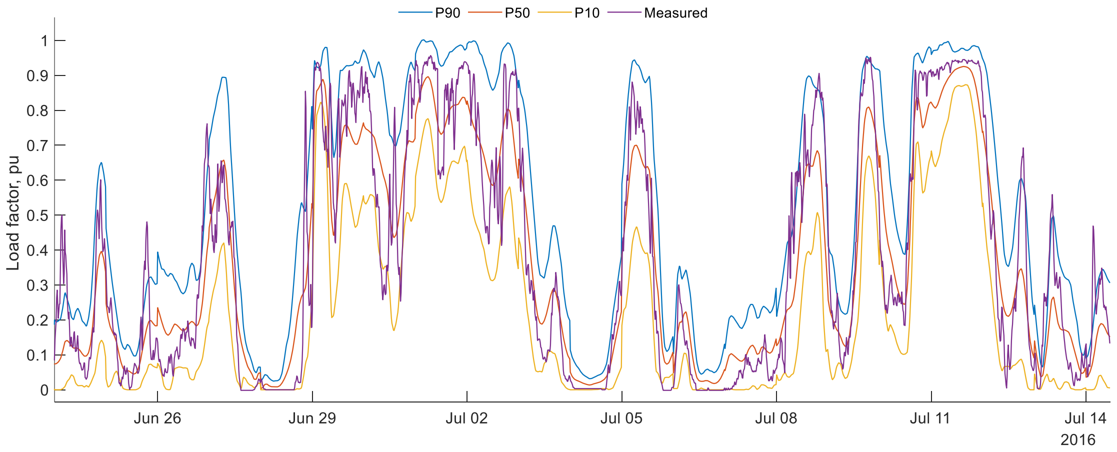

Figure 3 Power generation forecasts and actual measurements of the OWFs connected to Belgian network

To generate a power profile in MW (for both the measured and the forecast data) for the given overplanting rate, their initial power profile in pu is multiplied by the targeted installed capacity: from

339 MW up to 679 MW. Note that this proportional method is approximate, as it does not consider any change in the power profile shape due to upscaling/downscaling (e.g. no increased power smoothing due to the aggregation effect in a larger farm, wake losses variation, etc.). However, this was deemed sufficient for the purpose of the considered study.

In this paper, it is assumed that the mismatches between the commitment and the actual production of the OWF are purchased/remunerated at the imbalance prices, defined in France by the TSO. The impact of such a strategy on the power system stability is not covered in this paper. We used the datasets of both energy prices (both DA and imbalances) for the period of January 13, 2018 – January 12, 2019 in France [30](see Figure 4).

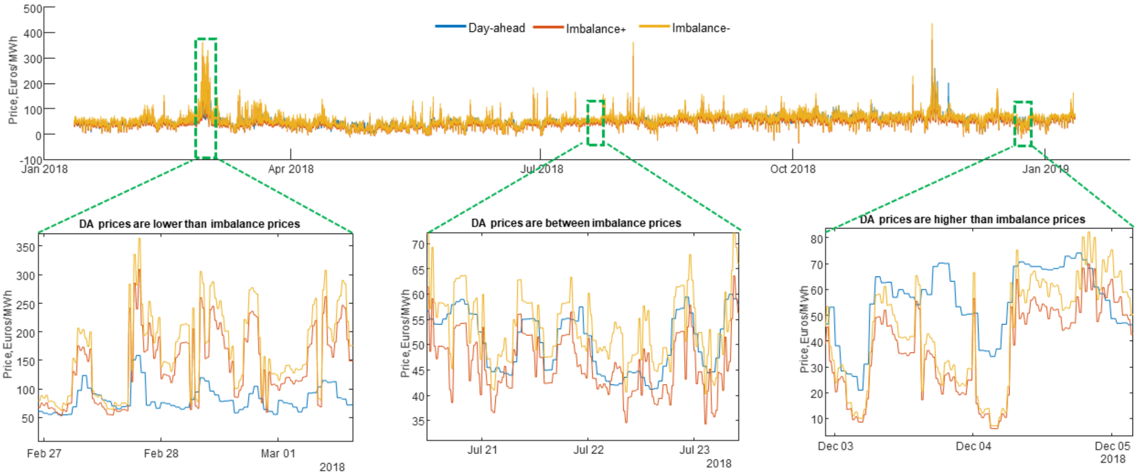

Figure 4 Market prices in France and different situations where the DA price may be greater, in-between or less than the imbalance prices.

It is interesting to note that DA prices may be greater or less than the imbalance prices, as shown in Figure 4. This means that selling energy as an imbalance, rather than on the DA market, may sometimes be more beneficial in terms of revenue.

2.3. *Problem mathematical formulation*

The goal of our problem consists in maximizing the annual revenue obtained from the OWF. It is important to note that we consider only the revenue, and not the CAPEX and OPEX costs. In the case of an optimal commitment strategy, this translates into solving a daily optimization problem whose objective function is as follows:

$$\max_{P_{plan}(t)} C_E(d) = \Delta t \cdot \sum_{t=0}^{t=23h45} [P_{plan}(t)] \cdot c_{D-1}(t) - [\max(0, P_{plan}(t) - P_{actual}(t))] \cdot c_{B^-}(t) + [\max(0, P_{actual}(t) - P_{plan}(t))] \cdot c_{B^+}(t) \qquad (1)$$

where $C_E(d)$ is the OWF revenue for the day d, $P_{plan}(t)$ and $P_{actual}(t)$ are the OWF committed and actual power output at time t, $c_{D-1}(t)$ is the DA price at time t, $c_{B^-}(t)$ is the imbalance price for under-production, $c_{B^+}(t)$ is the imbalance price for over-production regulation.

The optimal commitment strategy allows committing to any power profile on the DA market, while not exceeding the OWF installed capacity. However, this strategy is assumed not to consider possible violations of the cable thermal limits. In the case where dynamic thermal rating is allowed, this represents the likely case where the thermal model of the cable is not shared by the TSO (potentially for commercial confidentiality purposes). Under these conditions, the cable thermal behavior is not considered during the commitment optimization phase. However, it is considered that curtailment is enforced by the TSO at the delivery time if the temperature exceeds 90°C. The resulting energy deficit would be paid as an imbalance. This strategy generates the highest theoretical revenue assuming perfect forecasts on wind power production and energy prices. Again, this problem is deterministic as we do not try to propose the best strategy under uncertainty, our goal being to quantify the upper bound for revenue from the OWF. The curtailment algorithm, simulating this TSO behavior, is described below:

```
1. Input: OWF daily current profile (15-min resolution):
   $I_{cable}(t)$ where t =1 : 96

2. If a current limit $I_{nom}$ is applied (static thermal rating case)
      Check if $I_{cable}(t) > I_{nom}$:

         while $I_{cable}(t) > I_{nom}$
            (a) Find the instants when the current exceeds its limit:
                   idx_current =find($I_{cable}(t) > I_{nom}$)
            (b) Reduce $I_{cable}$ when it exceeds its limit for the first time:
                   $I_{cable}$(idx_current)= $I_{nom}$
         end

3. If a temperature limit $T_{cmax}$ is applied (dynamic thermal rating case)
     Calculate the daily temperature profile $T_{cable}$ of the export cable:
        [$T_{cable}(t)$]= f ($I_{cable}$ (t0, …, t))

      Checking if $T_{cable}(t) > T_{cmax}$:

         while $T_{cable}(t) > T_{cmax}$
            (a) Find the instants when the temperature exceeds its limit:
                   idx_temperature =find($T_{cable}(t) > T_{cmax}$);
            (b) Reduce $I_{cable}$ when T exceeds its limit for the first time:
                   $I_{cable}$(idx_temperature (1))= $I_{cable}$(idx_temperature (1)) × (1-$\Delta$)
            (c) Calculate the daily temperature profile of the export cable after the curtailment
                   [$T_{cable}(t)$]=f ($I_{cable}(t)$)
         end

4. Return the current profile, respecting the cable current or temperature constraint
```

where *f* represents the electrothermal model based on IEC standards 60287 and 60853-2. In this paper, I_{nom} is equal to 871 A, T_{cmax} is equal to 90°C and Δ=0.01.

3. RESULTS

3.1. Impact of overplanting and dynamic rating on the annual revenue

This subsection shows how the annual revenue of a given OWF changes as a function of the overplanting rate. In this section, only the business as usual strategy P50 is considered. An overplanting rate of 100% of the rated steady state capacity (i.e. without overplanting) is considered as the reference case (see Figure 5). In this case, the farm rated capacity is equal to 339 MW. Case 2 shows the revenue if overplanting is used together with a Static Thermal Rating (STR, i.e. current constraints are considered). Case 3 shows also the revenue as a function of the overplanting rate in the case where DTR (dynamic thermal rating) is considered as opposed to STR (i.e. temperature constraints are considered). For facilitating the comparison, revenues in both cases are given in percent with respect to the reference case (shown in grey).

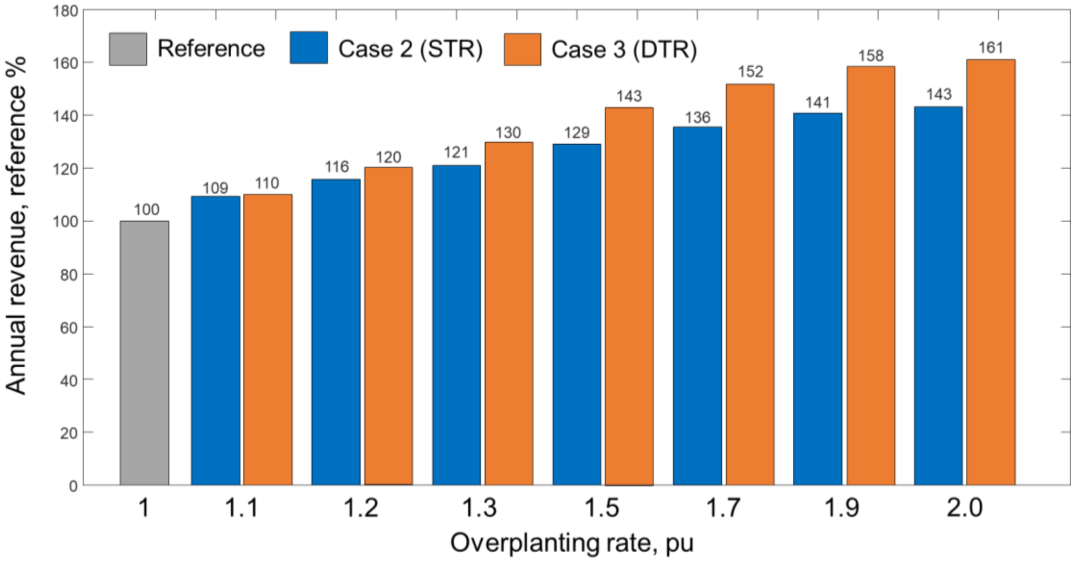

Figure 5 Annual revenue as a function of the overplanting rate for the STR and DTR cases. In all cases, the P50 strategy is used as the commitment strategy

In Case 2 (blue), the annual revenue can be increased from 9 % to 43% as a function of overplanting rate if STR is applied. If DTR is applied, it is possible to extend the range of additional revenue per year from 10 % up to 61%. It is important to mention that increased CAPEX and OPEX costs due to higher overplanting rates are not considered in this study which focusses only on the revenue increase. Hence, these annual revenues have to be put in perspective with these increased costs to determine the optimal overplanting rate, which will be done in future work. However, in Figure 5, we can see that in Case 3 (DTR), the revenue grows in similar proportion to the overplanting rate up to 1.3 pu of overplanting, i.e. the revenue increases by 30% for an overplanting rate of 130%. This leads to think that no curtailment occurs in case DTR is considered up to this overplanting rate. This is confirmed in Figure 6 which shows that curtailment is applied from 1.5 pu of overplanting.

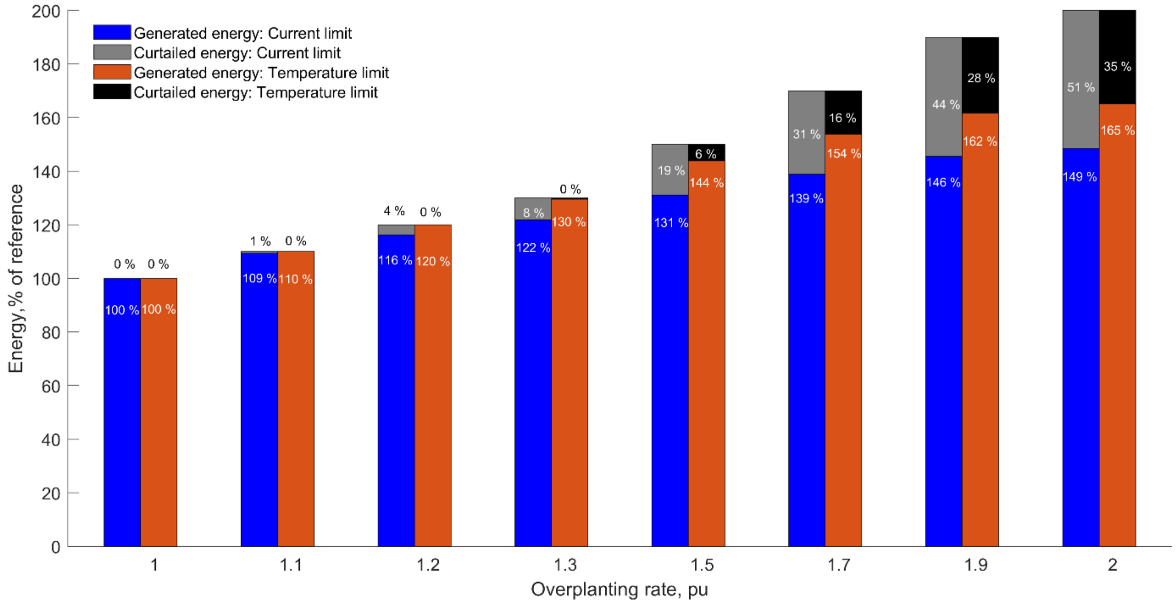

Figure 6 Annual generated and curtailed energy (normalized to the annual generated energy of a non-overplanted OWF) a function of the overplanting rate (with both STR and DTR cable limits)

Hence, in our case, overplanting, when combined with DTR, can be considered as economically profitable up to at least 130%, given that no curtailment is applied. This is limited to 100% when overplanting is not combined with DTR. Future works considering more detailed models (including the cable reactive power generation, other bottlenecks, etc.), as well as considering the CAPEX and OPEX will allow to determine the optimal overplanting rate.

3.2. Impact of the optimal commitment strategy on the annual revenue

In this section, the business as usual strategy (P50) is compared with the optimal commitment strategy. Results in Table 2 show that with the optimal commitment strategy, a significant revenue increase may appear in comparison with the P50 strategy. For the no-overplanting case (i.e. 1 pu overplanting), 21% more revenue can be obtained compared to the P50 strategy. When the overplanting rate is equal to 2 pu, this difference is equal to 44% (i.e. 187%-143%) when STR is applied, and equal to 43% (i.e. 204%-161%) when DTR is applied. In this theoretical case, such better results are due to a full exploitation of the DA and imbalance prices. This in turn becomes possible because it is assumed that the optimal commitment strategy does not have any restrictions on the shape of power commitment profile, except that it cannot exceed the maximum rated power of the farm.

Table 2 Annual revenue (in %) as a function of overplanting rate for the two commitment strategies with STR and DTR

Cable limit	**Commitment strategy**	**Overplanting rate (pu)**							
		1	**1.1**	**1.2**	**1.3**	**1.5**	**1.7**	**1.9**	**2**
STR	P50	100	109	116	121	129	136	141	143
	$P_{OptimProfile}$	121	132	141	148	161	172	182	187
DTR	P50	100	110	120	130	143	152	156	161
	$P_{OptimProfile}$	121	133	145	157	175	188	199	204

It is interesting to observe the overplanting rate above which the revenue loss linked to the energy curtailment is no longer compensated by the exploitation of the energy prices variability (imbalance and DA). This can be observed by comparing the increase of revenue (e.g. 157% for the optimal strategy) to the corresponding overplanting rate (130%) in the DTR case. When the optimum profile strategy is used, it can be observed that the increase in revenue is always greater than the overplanting rate. This increase ranges between 21% when an overplanting rate of 100% is considered, grows up to 27% for an overplanting rate of 130%, and then decreases slowly to 4% when an overplanting rate of 200% is considered. However, it remains positive which means that, despite an increasing level of curtailment, which may go up to 35 % when DTR is used, the revenue decrease linked to energy curtailment is more than compensated by exploiting the energy prices variability. When the P50 strategy is used, overplanting may be deemed economically viable up to 130% while further studies involving the increased CAPEX and OPEX costs are necessary to define the optimal overplanting rate. The same observation can be done in the STR case where overplanting may be deemed economically viable up to 170% when the optimal commitment strategy is used, while cases where the overplanting rates are greater than 100% require further studies to determine the optimal one when the P50 strategy is used. Hence, this shows the importance of the commitment strategies on the value of the optimal overplanting rate, as well as the significant influence of the type of rating (static or dynamic) applied on the export cable on this optimal rate.

4. CONCLUSION

This paper presented a techno-economic analysis on the combination of overplanting with dynamic rating of an OWF while comparing an ideal optimal commitment strategy with the business as usual one. This is intended to estimate the margin for improvement in terms of commitment strategies. It was observed that the revenue increased in the same proportion as the overplanting rate up to 130% of overplanting, in case the business as usual strategy (P50) strategy is used and that dynamic rating is applied. This means that no curtailment is done in this case which can be deemed as economically viable. If the optimal strategy is used, the revenue increase is always greater than the overplanting rate, therefore suggesting also an economically viable case. However, as mentioned earlier, some simple modelling assumptions were made at this stage and future work will consider more detailed models (reactive power generation from the cable, other bottlenecks, etc.), as well as necessary aspects such as the CAPEX and OPEX costs corresponding to each overplanting level of the offshore farm. The important influence of the commitment strategies and type of rating (STR or DTR) applied to the export cable on the value of the optimal overplanting rate was also demonstrated. In addition, it was shown that there exists a large margin for improvement regarding commitment strategies, provided that forecast tools may be become sufficient to exploit the events when the variations of imbalances prices compared to the day-ahead price may lead to small costs for a deficit of energy / high rewards for an excess of energy. Hence, this shows that enhancing the forecasting quality on day-ahead and imbalance energy prices, in complement to having good production forecasts, could result in significant benefits. As mentioned in the paper, these cases are theoretical as energy prices are considered as known in advance, but it suggests that a sufficient knowledge on these prices may have an important influence on the selection of an optimal overplanting rate. Future work may investigate the level of forecast quality above which this knowledge would play a significant role in the annual revenue increase.

ACKNOWLEDGMENT

This research work was conducted as part of "CELT4Wind" project carried out within the framework of the WEAMEC, West Atlantic Marine Energy Community, and with funding from the CARENE and the Pays de la Loire Region. All these organizations are gratefully acknowledged. We wish to thank Alexandre Godard with French TSO for his technical assistance. We also highly appreciated the help from specialists at Belgian system operator Guillaume Rovai and Victor Le Maire with the Belgian OWFs forecast and measured data.

BIBLIOGRAPHY

[1] WEAMEC. CELT4Wind Cable Electrothermal Management for Offshore Wind Farms 2021. https://www.weamec.fr/en/projects/celt4wind/ (accessed December 24, 2021).

[2] McInerney C, Bunn DW. Optimal over installation of wind generation facilities. Energy Econ 2017;61:87–96. https://doi.org/10.1016/j.eneco.2016.10.022.

[3] Mora EB, Spelling J, van der Weijde AH, Berthelot M. Cost and Uncertainty in Overplanting the Design of Offshore Wind Farms. IAEE Int. Conf. 2019 - Local Energy, Glob. Mark., 2019, p. 18.

[4] Tennet. Position paper. Overplanting. 2015.

[5] Colin MAH, Pilgrim JA. Cable Thermal Risk Estimation for Overplanted Wind Farms. IEEE Trans Power Deliv 2020;35:609–17. https://doi.org/10.1109/TPWRD.2019.2917789.

[6] Wolter C, Klinge Jacobsen H, Zeni L, Rogdakis G, Cutululis NA. Overplanting in offshore wind power plants in different regulatory regimes. WIREs Energy Environ 2020;9:1–16. https://doi.org/10.1002/wene.371.

[7] Mora EB, Spelling J, van der Weijde AH. How does risk aversion shape overplanting in the design of offshore wind farms? J Phys Conf Ser 2019;1356:012026. https://doi.org/10.1088/1742-6596/1356/1/012026.

[8] TenneT. TSO Overplanting-version: Hollandse Kust (zuid) v2. 2018.

[9] Henderson A, Baldock N, Yendole H, Parker G, Greig GP. Money does grow on turbines – overplanting offshore wind farms. Proc. Glob. Offshore Wind Conf., Glasgow: 2014, p. 11–2.

[10] Chen P, Thiringer T. Analysis of Energy Curtailment and Capacity Overinstallation to Maximize Wind Turbine Profit Considering Electricity Price–Wind Correlation. IEEE Trans Sustain Energy 2017;8:1406–14. https://doi.org/10.1109/TSTE.2017.2682820.

[11] McInerney CM, Bunn DW. Optimal Oversizing of Wind Generation Facilities. SSRN Electron J 2015:41. https://doi.org/10.2139/ssrn.2576307.

[12] TenneT TSO Overplanting-version: Hollandse Kust (noord) 2019. https://offshore-

documents.tennet.eu/fileadmin/offshore_document_uploads/Tender_documents/3._Technical_papers/1a_Memo_Overplanting_version_Hollandse_Kust_noord (accessed January 14, 2022).

[13] Cigre. TB640 A guide for rating calculations of insulated power cables. 2015.

[14] Pilgrim J, Kelly S. Thermal and economic optimisation of windfarm export cable. J Eng 2019;2019:4991–5. https://doi.org/10.1049/joe.2018.9272.

[15] Vree D, Vink S, Van Doeland JW, De Vries FSW. Ampacity calculation method for deeply buried wind farm AC submarine export cables. CIGRE Sess., 2018, p. 10.

[16] Kvarts T, Arana I, Olsen R, Mortensen P. Systematic description of dynamic load for cables for offshore wind farms. Method and experience. CIGRE Sess., 2016, p. 12.

[17] Getreuer R. Preferred offshore power grids for wind energy. Delft university, 2015.

[18] Hernandez Colin MA. Probabilistic dynamic cable rating algorithms. University of Southampton, 2020.

[19] Kazmi SHH. Dynamic Rating based Design and Operation of Offshore Windfarm Export Systems. DTU, 2021.

[20] Lago J, Marcjasz G, De Schutter B, Weron R. Forecasting day-ahead electricity prices: A review of state-of-the-art algorithms, best practices and an open-access benchmark. Appl Energy 2021;293:21. https://doi.org/10.1016/j.apenergy.2021.116983.

[21] Jónsson T, Pinson P, Nielsen H, Madsen H. Exponential Smoothing Approaches for Prediction in Real-Time Electricity Markets. Energies 2014;7:3710–32. https://doi.org/10.3390/en7063710.

[22] Avis P, Lee J. Evaluating System Imbalance Forecasting Models for the United Kingdom Electricity Market 2021. https://www.cefims.ac.uk/research/papers/DP163/dp163.pdf (accessed December 19, 2021).

[23] Contreras C. System imbalance forecasting and short-term bidding strategy to minimize imbalance costs of transacting in the spanish electricity market. Universidad Pontificia Comillas, 2016.

[24] Salem TS, Kathuria K, Ramampiaro H, Langseth H. Forecasting Intra-Hour Imbalances in Electric Power Systems. Proc AAAI Conf Artif Intell 2019;33:9595–600. https://doi.org/10.1609/aaai.v33i01.33019595.

[25] TenneT. Requirements reactive power. 2015.

[26] IEC. 60287-1-1 Electric cables – Calculation of the current rating – Part 1-1: Current rating equations (100 % load factor) and calculation of losses. Geneva: 2006.

[27] IEC. 60287-2-1 Electric cables – Calculation of the current rating – Part 2-1: Thermal resistance – Calculation of thermal resistance. 2006.

[28] IEC. 60853-2 Calculation of the cyclic and emergency current rating of cables. 1989.

[29] Elia. Wind-power generation 2021. https://www.elia.be/en/grid-data/power-generation/wind-power-generation (accessed December 13, 2021).

[30] ENTSO-E. Transparency Platform 2021. https://transparency.entsoe.eu/ (accessed January 14, 2022).