Thermal and economic optimisation of windfarm export cable

J A Pilgrim*, S Kelly †

**University of Southampton,UK, j.a.pilgrim@soton.ac.uk, †Transmission Excellence Ltd, UK, sean.kelly@transmissionexcel.com*

Keywords: windfarm optimisation, over-planting, ratings

Abstract

A method is proposed for the economic optimisation of offshore wind cable connections through utilising the thermal inertia of the cable system. Taking account of expected wind yields, turbine reliability and the dynamic thermal environment, the method determines the economically optimal number of turbines for a given export cable system. Analysis has shown that, providing means to actively curtail generation output so as to thermally protect the cable are in place, it is possible to reduce the cost of energy delivered to shore by up to £1/MWhr through the use of "over-planting", i.e. building a wind farm that is larger than the continuous rating of its export cables.

1 Introduction

In recent years, significant effort has been expended on reducing the Levelised Cost of Energy (LCoE) of Offshore Wind, resulting in record low strike prices in the September 2017 Contract for Difference awards in the UK. As larger wind farms are built further from shore, the relative contribution of the export cable system to the overall LCoE becomes more significant, placing greater emphasis on the optimisation of the cable sizing in order to benefit the overall project economics.

This paper approaches the optimisation of the export cable by bringing together thermal and economic models. Traditionally, power transmission cables have been sized based on the maximum continuous load current which could be supported before the cable reached its operating temperature limit. Offshore wind generation produces a time variant power output, and the thermal time constant of the cable is relatively long, meaning that buried cable sections may not reach a constant temperature until they have been subject to continuous loading for many days. In contrast, many peak generation periods for offshore wind farms do not exceed 100 hours. In practice, this means that the maximum power output of the windfarm can be set higher than the continuous rating of the export cable, provided that distributed temperature sensing systems are used to monitor the cable temperatures and ensure that they do not overheat. If additional turbines can be added to the same size export cable as a result of this, the overall LCoE will reduce.

To take advantage of this, this paper combines transient thermal models of different sections of an export cable route with an economic analysis that determines the export cable contribution to the overall windfarm LCoE. By varying the size of the notional windfarm, it is possible to determine the overplanting factor at which the export cable contribution to the LCoE is minimised. (Overplanting factor means the actual MW capacity of the wind farm divided by the largest capacity that could be accommodated using continuously rated export cables)
The method accounts for the expected variation in generation output, varying environmental temperatures, cable power losses and the impact of turbine or cable outages. To thermally protect the cable, it is occasionally necessary to curtail the output of the turbines; the opportunity cost of this lost generation is also accounted for in the model. The methodology is demonstrated through application to a number of possible export cable scenarios.

2 Modelling Approach

The overall process taken by the model to determine the optimal number of turbines is described by Figures 1 and 2. Further description of the two key components, the economic and cable thermal models, are provided in the following subsections.

2.1 Economic Models

The inputs on the left hand side of Figure 1 overleaf are project specific data, or assumptions which will need to be validated for the case concerned.

2.1.1 Input Assumptions

A number of assumptions are necessary to solve the model; it is recommended that users consider potential sensitivity to these variables, as they are likely to evolve over the life of the installation.

Turbine availability: For these studies we have assumed a turbine availability of 96%, based upon work reported by DONG Energy in [1]. Information published by ORE Catapult shows that the UK's offshore wind fleet currently averages a much lower availability: around 92% [2]. However it also shows that availability tends to climb over time. Assuming that this pattern continues, an availability of 96% does not seem unreasonable for a wind farm during its mature operations phase (c. 5-20 years from commissioning).

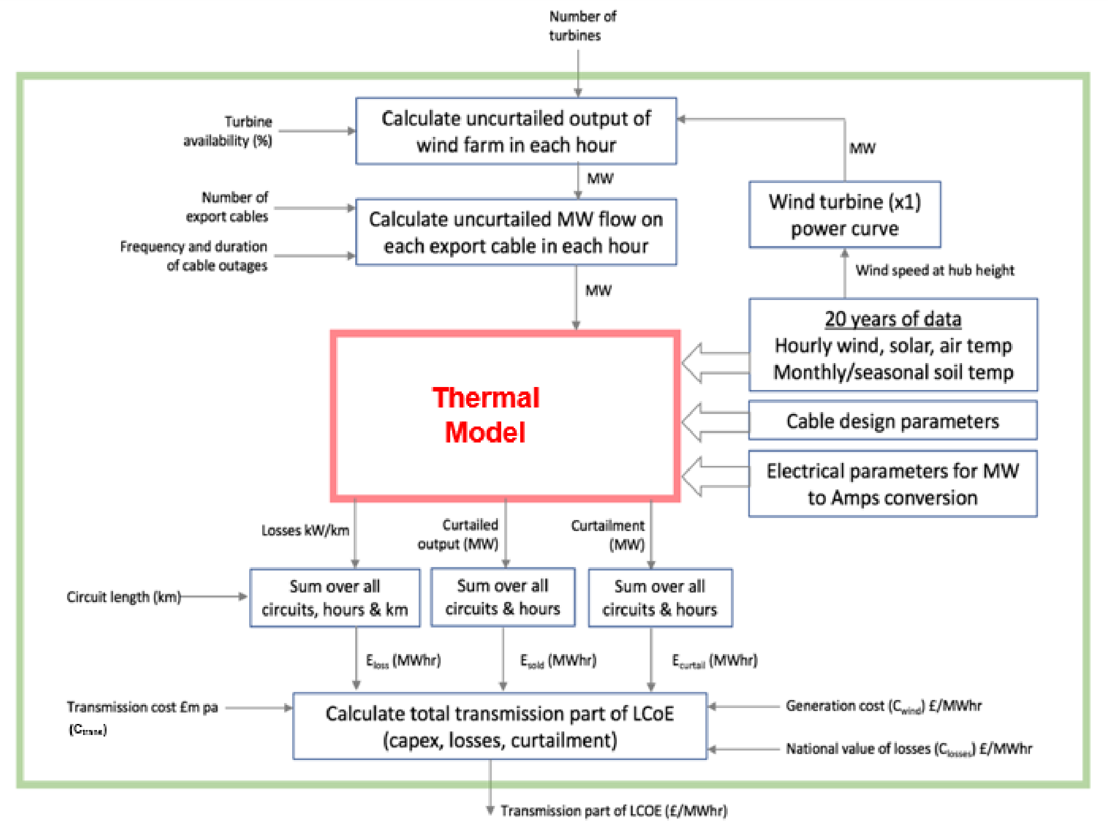

Figure 1: Illustration of overall economic model, the thermal model is described in Figure 2 below and Section 2.2.

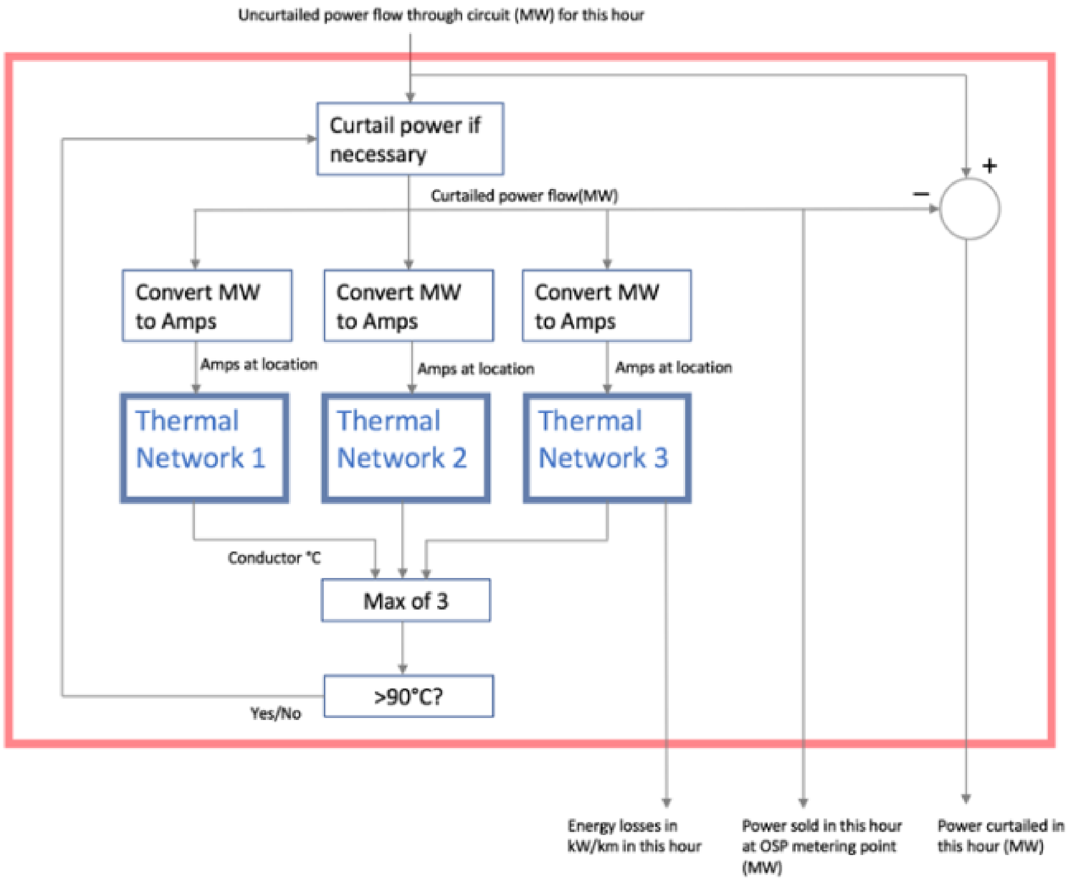

Figure 2: Illustration of overall thermal model

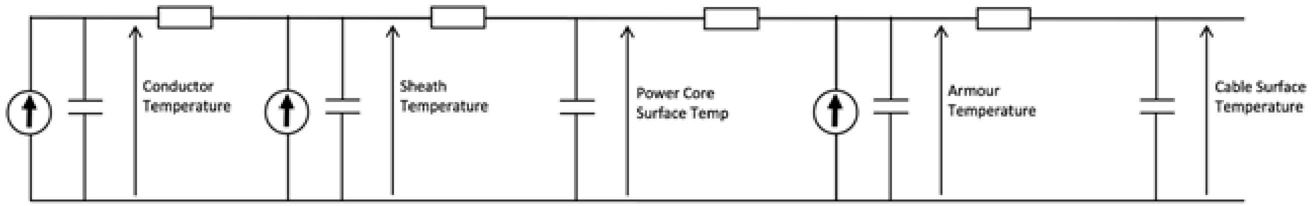

Figure 3: Illustration of cable thermal network.

Cable Outages: Cable outages have a significant impact on curtailed energy. The risk of outage is a function of the cable technology, route length and local conditions (for example, extent of fishing activity) and some mitigation can be achieved, for example through burial protection measures. Our case study assumes a 3 month outage on each export cable, once per decade.

Cost Assumptions: costs are required for the capex associated with the cables, their installation and any associated auxiliaries. The notional cost of losses is taken as £50/MWhr in this study, while the generation cost was taken as £70/MWhr. It should be noted that recent CfD auctions have led to prices around this level for 2021, with even lower prices for subsequent projects.

2.1.2 Generation Data

The model proposed is intended as a tool for use at the initial design stage of the windfarm, meaning that no actual generation data will be available for the specific site in question. We have obtained wind yield data via a NASA database which stores the results of a meteorological reanalysis programme. Reanalysis is an approach where the variables in a model of the entire earth's atmosphere are adjusted repeatedly so that the (relatively few) variables in the model that correspond to actual measurements from weather stations and satellites agree with the measured data as closely as possible, while the model as a whole stays consistent with the laws of physics. When the model has finished being adjusted it will contain a detailed description of the whole atmosphere – including far-offshore locations with no nearby weather-stations. The particular dataset used is generated by a NASA reanalysis programme called MERRA (Modern Era Retrospective-analysis for Research and Applications) [3]. This generates hourly outputs for the entire planet's atmosphere from 1979 to 2015. MERRA was chosen because The Crown Estate have undertaken a validation study in which the offshore wind data from MERRA was compared to actual measured met mast data [4]. The Crown Estate found reasonable good correlation between MERRA and met mast wind speeds, which improved the further offshore the location was: for Dogger Bank the correlation coefficient for hourly wind speeds was around 0.92 and for daily average wind speeds it was 0.97.

Having obtained the time series of wind speed data, the turbine power curve in question can then be applied to obtain the maximum available output power from a single turbine over the full time series. This is then input into the analysis; for conservatism, wake effects were not considered, these could be introduced when more is known about a specific site.

2.2 Thermal Models

Although it is beyond the scope of this paper to provide an exhaustive description of the thermal models, including all necessary equations, a summary is provided below. The modelling principle is based upon an extension of the IEC 853-2 transient thermal calculations [5]. The cable is represented using a thermal ladder network of the type shown in Figure 3, consisting of thermal resistances and capacitances, with the cable losses being represented by current sources.

Additional thermal networks to represent the three different installation environments (buried in ducts, buried in the seabed, inside a J-tube) are added to the right-hand side of the cable thermal network. These thermal environments particularly merit consideration as:

- J-tubes may experience high air temperatures and solar radiation during summer, making them potentially more thermally limiting than buried sections at certain times.
- Cable at sea is the bulk of the route length, and for long routes there may be savings from optimising the conductor size separately to the landfall.
- Landfall sections of the cable are often deeply buried, meaning that they have the lowest continuous thermal rating. Our approach can greatly improve the ratings in these sections, and offer significant cost savings.

2.3 Overall Solution Process

Having set up the model for the default number of turbines, the thermal solution shown within the red box of Figure 1, and in more detail in Figure 2, begins. For each given interval in time, the temperature for each of the thermal models is obtained separately. A check is then made to ensure that the temperatures are within allowed ranges. If the temperature exceeds the limiting value, the total farm power output is curtailed by a minimum of 1A, and the solution proceeds until the temperature is within tolerance. All curtailed power is logged, to enable subsequent statistical analysis.

The model is solved over a range of different wind farm sizes (in terms of number of turbines), allowing for variations in the LCoE to be identified as a function of the turbine number. The LCoE is calculated according to:

$$\left(\frac{C_{cable}}{E_{sold}}\right) + \left(\frac{C_{losses}}{E_{sold}}\right) + \left(\frac{C_{wind}}{E_{potential}}\right)\left(\frac{E_{curtailed}}{E_{sold}}\right) \quad (1)$$

where C_{cable} is the lifetime cost of the cable (in £), C_{losses} is the cost of losses on the cable (in £), with losses valued at the market price of electricity, C_{wind} is the lifetime cost (in £) of the wind farm and its associated transmission, but not the cable (already covered by C_{cable}). E_{sold} is the energy in MWhr sold at the tariff metering point over the wind farm lifetime, $E_{potential}$ is energy in MWhr the wind farm could have produced over its life in the absence of cable-related curtailments and $E_{curtailed}$ is the total energy curtailed for cable-related reasons.

This allows the optimal size of the windfarm to be determined to suit a given cable connection. Section 3 presents a case study of the application of this method, demonstrating the extent of benefit derived from over-planting.

3 Case Study

To demonstrate the application of the method, Section 4 of this paper illustrates the results obtained for an example wind farm connection. We describe below the design parameters used, along with the sources of input data for the study.

3.1 Export Cable Design

The notional wind farm is connected by two 220kV export cable circuits. Each of these circuits will comprise a submarine cable part that is 100km along, and an onshore cable of negligible length. The submarine cables will not have intermediate reactive compensation. The wind farm's output will be equally shared between the two cables. This reflects a design where there is a normally closed offshore connection at 220kV between the two export cables. An alternative approach used by many wind farms is to divide the wind farm into two separate groups of turbines with each group normally connecting to only one of the export cables; offshore interconnections between the two export cables exist but are only used if one of the export cables is out of service.

If this alternative approach had been assumed then random variations in the number of in-service wind turbines feeding a cable would have been a more significant effect. Ratings of the onshore cables, transformers and other circuit elements are assumed to not to limit the use of dynamic ratings on the export cables.

The submarine export cables use a design which is intended to represent the current (2017) state of the art in 3-core AC export cables. This consists of a 1600mm^2 plain stranded aluminium conductor for the majority of the route, with the exception of the deeply buried section at the landfall where the cable has a copper conductor, with all dimensions remaining consistent. The cable has alternate steel and plastic armour wires for reduced armour losses. In all calculations undertaken for this report it has been assumed the cable losses (heat sources) in the cables' conductor, sheath and armour will be as specified by formulae in the published IEC standards for cable rating. These are known to be quite conservative due to the way in which armour losses are calculated for these cable designs [6].

Component	Material	Outer Diameter [mm]	Thickness [mm]
Conductor	Aluminium / Copper at landfall	49.0	
Conductor Screen	Semiconducting XLPE	52.0	1.5
Insulation	XLPE	92.0	20
Insulation screen	Semiconducting XLPE	95.0	1.5
Swelling Tape	Polymeric	98.0	1.5
Sheath	Lead alloy	102.0	2
Power core oversheath	Semiconducting PE	106.0	2
Filler	Polypropylene yarn		
Binder tape	Fabric	237.0	2
Armour	Steel	248.0	5.5
Outer serving	Polypropylene yarn	257.0	4.5

Table 1: Cable System Design

3.2 Assumed Installation Conditions

Three separate thermal zones are considered in the analysis in this paper (although the number which could be considered is arbitrary). These zones have markedly different thermal responses:

- Landfall: cable in ducted directional drill at 9m depth in soil of thermal resistivity 1.2 K.m.W^{-1} and thermal capacity of 1.5 MJ.m^{-3}.K^{-1}.
- Cable at sea: buried to a depth of 1.5m with a thermal resistivity of 0.7 KmW^{-1} and thermal capacity of 2.5 MJ.m^{-3}.K^{-1}.
- Cable in J-tube, where a 15m section of the tube is air filled and exposed to solar gain.

Air temperatures and wind speeds at the J-tube (which help provide cooling) were based on the MERRA data, with sea-bottom temperatures varying as per typical North Sea conditions. Solar gain on the J-tube was calculated for the given site location on the assumption of cloud-free skies for conservatism.

3.3 Continuous Cable Ratings

Continuous cable ratings were calculated using the thermal models described in Section 2. The charging current of these cables is assumed to be 8.0A per km. If the onshore and offshore substations each take half of the cable's charging current, and each cable is 100km long as previously stated, then the maximum reactive power flow in the cable will be 50km x 8A/km = 400A. For the calculation of losses the reactive current in a "typical" length of cable is assumed to be half this value, or 200A. Accounting for the worst case thermal conditions expected in each of the thermal sections, that which is most limiting is the landfall, which has a continuous rating of 730A. After considering the effects of the charging current, this equates to supporting 58 turbines at a rating of 8MW per turbine.

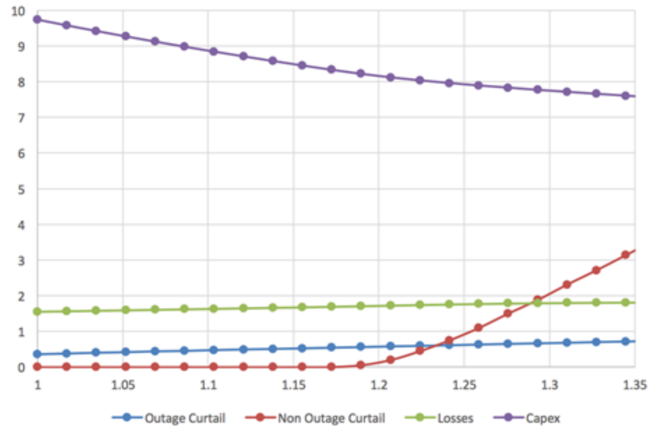

Figure 4: LCoE contribution versus overplanting factor

4 Results Obtained

A number of key trends can be observed in Figure 4, which summarises the economic results. Capital cost is the largest single element and falls steadily as overplanting increases. At very high overplanting factors, however, the rate of reduction falls off because so much energy is being curtailed that eventually adding another wind turbine only leads to half of the increase in MWhr production that it did with limited over-planting: with the MWhr output only growing slowly the capital cost per MWhr falls at a similarly slowed rate.

Cable losses are the second-largest element, but they change relatively little over the range of over-planting factors studied. This is because the high levels of curtailment that occur with heavy over-planting mean that increases in cable currents (and in particular increases in current at times of high wind, which is where losses are concentrated) are limited. At an overplanting factor of 1.0 (i.e. keeping to within the continuous rating), our simulation shows 3.1% of the energy generated by the wind farm being lost in the export cables as heat. This 3.1% loss equates to an average loss on the "typical" 1600mm^2 Al cable of 40W/m, while the peak loss on this cable is 70W/m.

At low overplanting factors curtailment relates solely to the situation during cable repair outages. As the overplanting factor increases, the level of curtailment during repair outages rises steadily, but remains small compared to the capital cost or losses element. At low overplanting factors the level of curtailment at times when both circuits are in service is zero. In the case illustrated in this figure, non-outage curtailment first appears at an overplanting factor of 1.17, but it is too small to even be visible in the graph above. Above a critical level of overplanting (1.19 in this case), however, the cost of constraints increases rapidly and it quickly becomes the dominant factor in terms of the marginal change in transmission costs with each additional turbine.

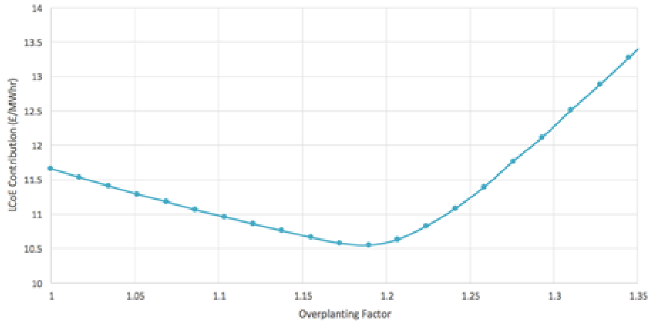

Figure 5: LCoE contribution as a function of overplanting factor (optimum value of 1.19).

Adding together all four of the elements shown in Figure 4 yields Figure 5, which shows the cable's total contribution to the wind farm's LCoE as a function of the overplanting factor.

5 Conclusions and Implications

This paper presents a method by which the LCoE contribution of the export cable system can be minimised, through taking advantage of the nature of the generation profile typical of wind farms, along with the thermal inertia of the export cable system. It was found that optimising the size of the wind farm in this way can give significant financial benefits. In the case presented here the optimum overplanting reduced the levelised cost of energy by £1.1/MWhr, with this optimum cost reduction being achieved by an overplanting factor of 1.19 (i.e. the maximum output of the windfarm was 19% higher than the cable continuous rating). This is equivalent to reducing the export cable capex by 14%.

Such savings are highly attractive in the context of improving the investment case for future, large scale offshore wind farms. However, it must be recognised that the use of such approaches does remove some of the traditional conservatism associated with the thermal design of the cable system. Additional reliance is placed upon the temperature monitoring systems, and operators must be willing to take swift action to protect the cable from thermal damage.

Acknowledgements

The work described in this paper was funded by and developed during the Carbon Trust Offshore Wind Accelerator (OWA) 'Dynamic Thermal Ratings' project, and is published with the permission of the OWA.

References

[1] "Low-hanging Fruit for Reducing the Cost of Energy - Optimising the Electrical Export Capacity", presented by DONG Energy and DNV-GL at EWEA 2015.

[2] Crown Estate, "SPARTA: System performance, availability and reliability trend analysis", 2016.

[3] https://gmao.gsfc.nasa.gov/reanalysis/MERRA/

[4] "UK MERRA Validation with Offshore Meteorological Data", The Crown Estate, October 2014.

[5] "Calculation of the cyclic and emergency current rating of cables. Part 2: Cyclic rating of cables greater than 18/30 (36) kV and emergency ratings for cables of all voltages", International Electrotechnical Commssion standard IEC 853-2.

[6] K. F. Goddard, J. A. Pilgrim, R. D. Chippendale, P. L. Lewin. "Induced Losses in Three-core SL-type High Voltage Cables", *IEEE Transactions on Power Delivery*, **30** (3), pp 1505-1513, (2015).