Offshore wind farm optimisation: turbine placement, cable layout and energy storage

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Research questions

What are the potential economic impacts of using a holistic wind farm optimisation tool also considering energy storage to minimise LCOE?

How can wind turbine assets and offshore distributed energy storage be controlled effectively to maximise benefits in terms of the electrical collector network?

CATAPULT Offshore Renewable Energy

Electrical Infrastructure Research Hub
This project is part of a collaboration between the Offshore Renewable Energy Catapult and the Universities of Strathclyde and Manchester.

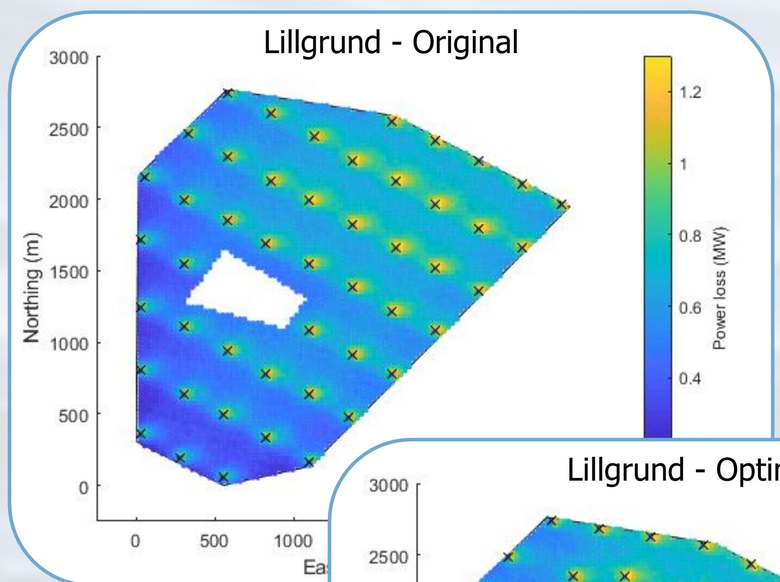
Abstract

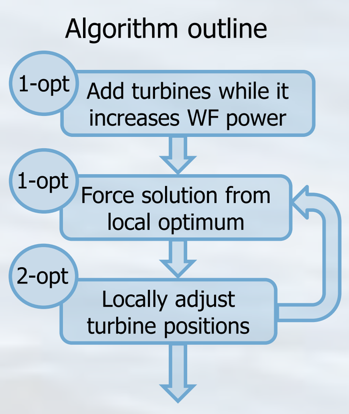
Large scale offshore wind farms (OWFs) are expensive projects costing developers billions of pounds to realise. The electrical infrastructure of such projects contributes around 10-30% of capital expenditure, therefore small design changes can have large financial impacts. The first part of this project aims to develop a practical design tool that is capable of optimising the turbine placement and cable layout of large-scale OWFs. Energy storage systems (ESS) are explored as a means to further improve the levelised cost of energy (LCOE) and future work will be focussed around the control of the distributed ESS and it's effect on individual turbines within the OWF.

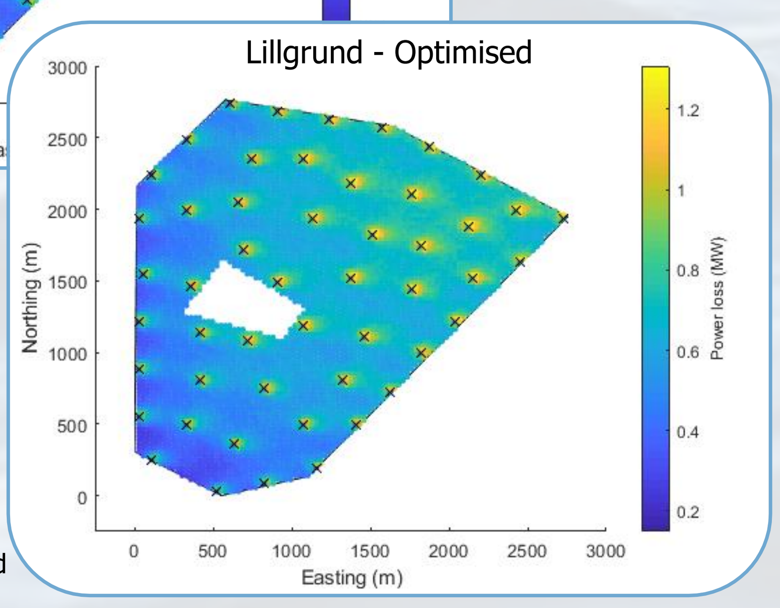
Turbine placement

The aim of a turbine placement optimisation algorithm is to place turbines in the wind farm such that the pair-wise interactions from wake effects is minimised. This increases the annual energy capture and revenue of projects.

A case study of the Lillgrund OWF shows the potential benefits of such an approach. Here a heuristic method is applied to the real-world site. The wind farm is first discretised into many nodes of possible turbine positions, and the pair-wise interactions of every node on every other node is computed. A "k-opt" algorithm then iteratively attempts to find the best combination of nodes on which to build a wind turbine.







The two figures here show the original, real-world, Lillgrund OWF and it's estimated cumulative wake effect across the site, and the heuristically optimised site with the turbine positions and resulting cumulative wake effect. This has been translated from a velocity deficit (as produced by the wake model) into power loss in order to aid the algorithm in maximising wind farm power.

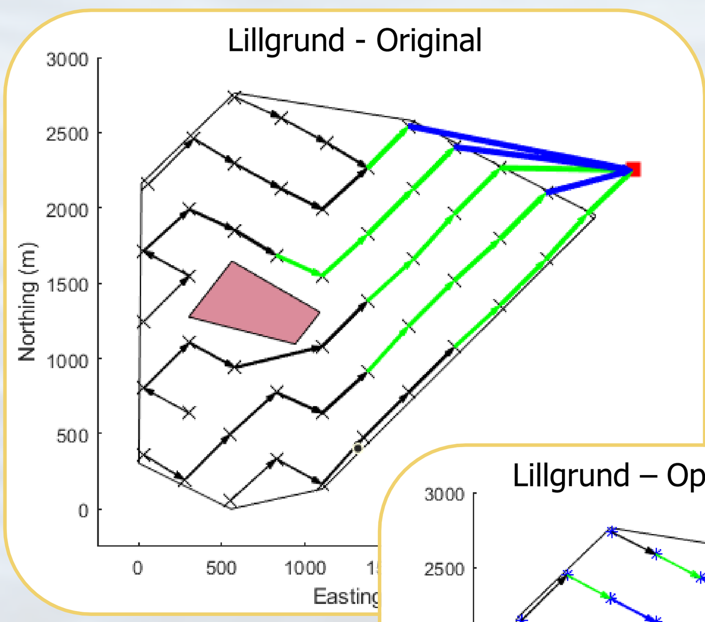
Allowing an unlimited number of turbines to be placed, the algorithm built 50 turbines, two more than the real site increasing the rated power of the wind farm from 110.4MW to 115MW. Because of the meteorological conditions at the site, the expected average wind farm power for the two cases is 59.4MW and 61.9MW respectively. The optimised site has reduced total wake losses from 20.8% of rated power to 18.7% resulting in a net expected wind farm power of 36.4MW and 40.4MW respectively. Approximate capacity factors are also given, not taking into account any O&M considerations.

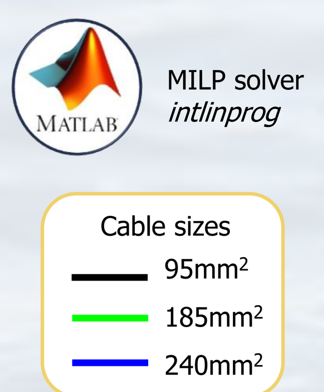
	Original	Optimised
No. turbines	48	50
WF P_{rated} (MW)	110.4	115.0
WF P_{avg} (MW)	59.39	61.87
Wake losses (% P_{rated})	20.82	18.70
WF P_{net} (MW)	36.41	40.36
Capacity factor	32.98	35.10

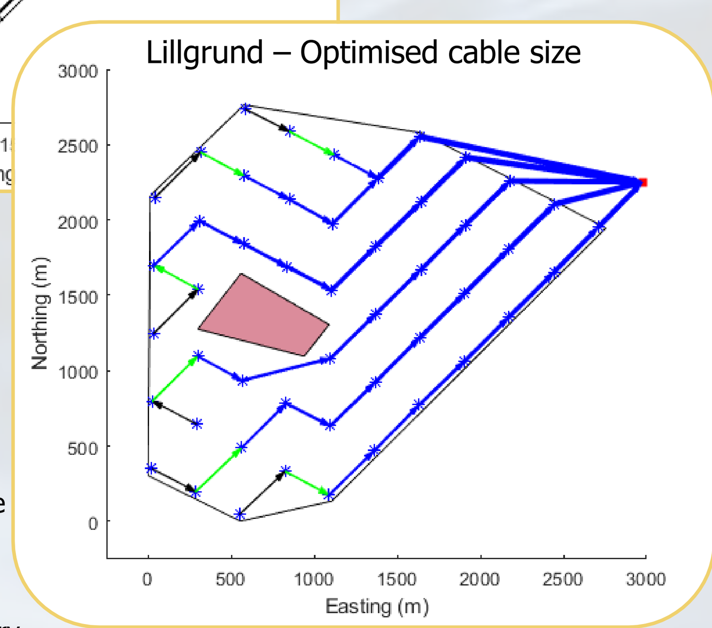
Cable layout & selection

The aim of the cable layout optimisation algorithm is to select the best routes and cable types to connect all turbines in the OWF to the sub-station(s). The objective function of the algorithm attempts to minimise the total associate costs over the lifetime of the project including: cable unit and installation costs and the net present value of electrical losses.

The Lillgrund OWF was again used as a test case on which to run the model. In order to highlight one aspect of the optimisation, the figures below show the changes made by the selection of the cable type with the same cable routing. Three cable sizes are available each incurring different electrical losses due to reducing resistance with increasing cable size. With the combination of *integer variables* describing whether a certain cable size is selected or not, and *continuous variables* to describe the power flow in a given cable section a solver able to deal with mixed-integer problems is required. The solver used here is Matlab's inbuilt *intlinprog* function.







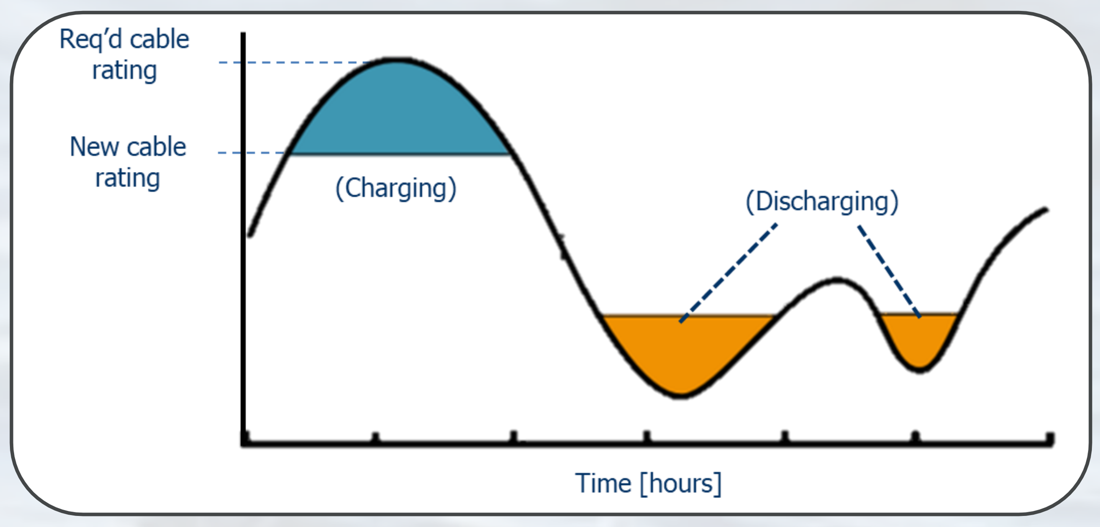
The figures show the real world cable layout used at the Lillgrund OWF and the model result. The selection of the three cable sizes in the new solution can be seen to be very different in each string.

Larger cables than those used in the real site have been selected in every connection except for the very end of the string. The table (below), shows a large increase in capital expenditure because of this increase in cable size, from £11.9M originally to £15.4M. The electrical losses, however, have been greatly reduced from £51.3M to £35.4M. These are calculated using the wind conditions of the site and the cable resistances over an assumed project lifetime of 25 years, with a constant price of energy and discounted into net present value. The overall result is a large reduction in overall cost from £63.1M to £50.8M (↓19.6%).

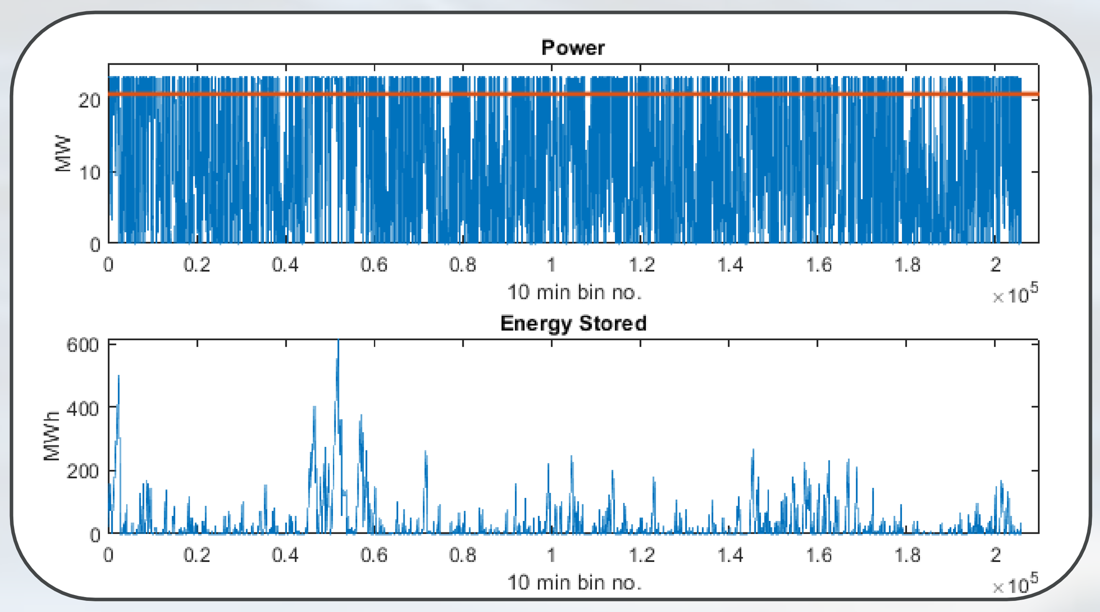
	Original	Optimised
Cable cost (£M)	11.87	15.40
Electrical losses (£M)	51.26	35.35
Total cost (£M)	63.13	50.75

Energy storage

Given an optimised cable layout solution it may be possible to further reduce the total cost by utilising energy storage. The figure below shows how an ESS may be charged and discharged in order to reduce the peak power seen by a cable and thus reduce the required cable rating. As the electrical losses have been shown to be a far more significant cost, this same charging strategy is applied but with the intention of reducing the peak power in order to reduce electrical losses rather than cable type/size.



The storage systems are placed in the turbine immediately before the section of cable under consideration. The figure below shows a representative time series of power in a section of cable supporting 10 turbines (23MW). The level to which the storage is trying to 'peak shave' the power is shown by the red line, at 9 turbines rated power (20.7MW). Integrating about this de-rated power level – without allowing the result to drop below 0 – gives the energy storage requirement over time, and can be seen in the bottom plot.



It can be seen that, for the vast majority of the time, the required storage size is relatively low. Peaks of much higher values are seen but for a smaller proportion of the time. With the storage being sited in an offshore turbine, space is at a premium and so the solution must be constrained to a relatively small capacity. In doing so, the ESS is limited in being able to provide a peak-shaving service to a small amount of time. This reduces the cost saving benefits of the storage system.

For any value of de-rating, and any ESS size this approach is unable to find a profitable solution to this stand-alone mode of operation. Secondary revenue stream must be provided in conjunction to find possible feasible solutions.

Conclusions and future work

There are significant benefits to be made in terms annual energy production, through the improvement of turbine placement and the reduction in electrical losses in the collector network. Additionally, secondary benefits may be found in the reduction of turbulent loads on turbine structures. Optimising the collector network to minimise total lifetime costs increases the CAPEX due to larger cable sizes being installed, however, reductions in electrical losses far offset this cost resulting in large overall savings. Energy storage as a means to peak shave the power seen by a cable and thus reduce the cable size and/or losses is not a profitable stand-alone mode of operation. Secondary revenue streams must be included if ESSs are to be considered.

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