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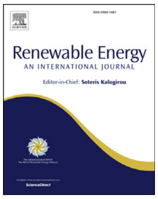

Techno-economic optimisation of offshore wind farms based on life cycle cost analysis on the UK

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ABSTRACT

In order to reduce the cost of energy per MWh in wind energy sector and support investment decisions, an optimisation methodology is developed and applied on Round 3 offshore zones, which are specific sites released by the Crown Estate for offshore wind farm deployments, and for each zone individually in the UK. The 8-objective optimisation problem includes five techno-economic Life Cycle Cost factors that are directly linked to the physical aspects of each location, where three different wind farm layouts and four types of turbines are considered. Optimal trade-offs are revealed by using NSGA II and sensitivity analysis is conducted for deeper insight for both industrial and policy-making purposes. Four optimum solutions were discovered in the range between £1.6 and £1.8 billion; the areas of Seagreen Alpha, East Anglia One and Hornsea Project One. The highly complex nature of the decision variables and their interdependencies were revealed, where the combinations of site-layout and site-turbine size captured above 20% of total Sobol indices in total cost. The proposed framework could also be applied to other sectors in order to increase investment confidence.

1. Introduction

According to the 20-20-20 target on reducing carbon emissions and the Climate Conference in Paris (COP 21) on keeping the global warming temperature below 2 °C, it is important to contribute to the Renewable Energy (RE) investment growth in the UK by making the investments more attractive, information-rich and less risky [1]. The UK technology roadmap highlights that the offshore wind costs need to be reduced to £100 per MWh by 2020 and greater confidence over financial motivations is required [2].

Offshore wind managed to reach 24% of the total installed power in Europe in 2015 compared to the 13% share the previous year [3]. Currently, 1716 offshore turbines are deployed in 32 offshore operational projects of an overall capacity of 6713.520 MW in the UK [4]. However, significant price increases in the overall cost of turbines, their operational and maintenance costs etc. have a direct impact on large-scale wind projects. The location of a wind farm and the type of support structure have great impacts on the overall costs [5–7].

Ensuring a long-term and profitable investment plan for investors and developers can be challenging. In many cases, both pre-consent and post-consent delays cause inconveniences. Considerable actions are mandated, on top of the development plans, for minimising investment, developing the supply chain, securing consents, ensuring economic grid investment and connection, and accessing finance [2,8]. Overall, appropriate studies should be conducted at the early development stages of the project in order to avoid disruptions and minimise the investment risk. A very important decision that appears when starting a new investment is the selection of a suitable offshore location (zone and site) and always requires extended effort from developers. The location of a wind farm and the type of support structure have great impacts on the installation costs. The most important costs in an offshore wind farm can be found in Ref. [9].

In Ref. [10], a study was conducted in order to discuss and compare the results among three state-of-the-art optimisation evolutionary and genetic algorithms (NSGA II, NSGA III and SPEA 2) and then applied to a real-world case of the wind energy sector. A set of optimum locations for a wind farm are suggested by considering only round 3 zones, which are specific sites released by

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Nomenclature

A	Area of the wind turbine (m^2)
C_p	Power coefficient
$C_{P\&C}$	Predevelopment and Consenting cost (£)
$C_{P\&A}$	Production and Acquisition cost (£)
$C_{I\&C}$	Installation and Commissioning cost (£)
$C_{O\&M}$	Operation and Maintenance cost (£)
$C_{D\&D}$	Decommissioning and Disposal Cost (£)
CAPEX	Capital Expenditures (£)
LCC	Life Cycle Cost (£)
NWT	Number of turbines
OPEX	Operational expenditure (£)
P_R	Rated power (W)
u	Mean annual wind speed of each specific site (m/s)
TIC	Total Installed Capacity (W)
ρ	Air density (kg/m^3)

the Crown Estate, where the developers can install and deploy offshore wind farms around the UK. The study considered some of the most important techno-economic Life Cycle Cost (LCC) factors that are directly linked to the physical aspects of each wind farm location such as the wind speed, the distance from the construction ports and the water depth. Optimal solutions were discovered by all three algorithms and such outcomes are expected to reveal the benefits of possible extensions of the Round 3 zones in the future of the UK and will help decision makers for their next cost-efficient investment decision.

The aim of this paper is to establish a methodology for the decision-making process at the initial stages of a wind farm investment of Round 3 zones in the UK that reveals the optimum offshore locations by considering a model that combines techno-economic factors of the LCC analysis, layout selection and location-based constraints. The revealed optimum solutions per zone and a reference selection of zones will offer flexibility at the cost budget assignment phase of the wind farm development and is aligned with the reduction of the cost of energy at less than £100 per MWh. It is also expected that the differences among three suggested wind farm layouts will be explored by considering the conflicting nature of the cost elements. The outcomes will provide further insight into wind energy sector for future investments.

The contribution of this work follows. First, as illustrated in Fig. 1, it proves the effectiveness of the developed framework that links the economic modelling of the LCC analysis to an optimisation method, where the solutions comprise of wind farm layouts, offshore Round 3 locations in the UK, number of turbines and turbine size. The interplay between CAPEX and OPEX will be revealed through multi-objective optimisation and quantified based on each decision variable through sensitivity analysis. This study assists project developers and researchers at the first stages of the development of a wind farm in order to select an optimum, economically efficient and viable option.

The remaining structure of the paper consists of a literature review on LCC analysis, turbine layout optimisation, wind farm location selection and cost related frameworks in the offshore wind energy sector. Next, the methodology of the present study will follow. The non-dominated results for all zones and each zone individually will be analysed and discussed. Future avenues will be drawn in the conclusions.

2. Literature review

2.1. Offshore wind farm location selection

The UK has released 3 Rounds of offshore wind farm sites for leasing. The 3 Round divisions appeared because of the administrative licensing process adopted by the UK and reflect the development of offshore power collection and transmission systems. In Round 1, the developments were small (up to 90 MW) and with up to thirty turbines each and near the shore (less than 30 km away from the shore). Round 2 sites were released later and contained larger projects up to 500 MW and a bit further away from the shore (up to 90 km). Finally, Round 3 is currently undergoing planned installations up to 1000 MW and 300 km distance from the shore [11]. When the Crown Estate released the new Round 3 offshore wind site leases, they provided nine new considerably larger zones that include up to 32 GW of power capacity. The new leases encourage larger scale investments and consequently bigger wind turbines. The new zones include locations further away from the shore and in deeper waters which could be more challenging [2,8,12–14].

The Round 3 zones are the following; Moray Firth, Firth of Forth, Dogger Bank, Hornsea, East Anglia (Norfolk Bank), Rampion (Hastings), Navitus Bay (West Isle of Wight), Atlantic Array (Bristol Channel) and Irish Sea (Celtic Array). Every zone consists of various sites and extensions. In this study, the five first zones in the North Sea are investigated. The selected zones provided a group of sites. These groups were selected as a reference case in order to prove the present methodology that provides results for both overall and individual zones.

Each location faces similar challenges; deep waters or high distances from the shore, etc. For example, Dogger Bank offers some advantages because of its shallow waters and high wind speed (above 10 m/s). It also offers economies of scale. However, it faces marine environmental issues and long distance from the shore and thus the ports, which has a costly impact [15]. The Round 3 offshore zones and sites are shown in the following Fig. 2.

In literature, only a few location-selection-focused studies can be found but the findings and the formulation of the problems provided follow a different direction. Goal programming was used in Ref. [16] in order to obtain the optimum offshore location for a wind farm installation. The study involves round 3 locations in the UK and discusses its flexibility to combine decision-making. The work shows the energy production, costs and multi-criteria nature of the problem while considering environmental, social, technical and economic aspects.

A study on offshore locations for a RE platform by using multiple criteria and Geographical Information Systems (GIS) is provided in Ref. [17]. Issues around offshore RE platforms have been reviewed and a combination of criteria has been selected for the Atlantic facing shores in Europe. Potential risks and trade-offs between designing costs and energy production were discovered. Factors such as the lack of construction ports that results in under-exploited sites, access problems and weather window conditions, even during the summer months were provided. The study is mostly focused on environmental, geographical and weather issues.

Similarly, a study for the optimum selection of wind turbines was conducted in Ref. [18] by considering cost-effective criteria and especially the cost of energy and the local wind conditions. The study demonstrates the need for a framework to deal with such challenging problems where a decision is necessary. In Ref. [19], a selection method of the optimum access point for offshore wind farms in China is suggested by using multi-objective optimisation and a comprehensive weight decision-making method, Analytic