Renewable Energy 101 (2017) 667–679

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Minimizing transportation and installation costs for turbines in offshore wind farms

Bhaba R. Sarker*, Tasnim Ibn Faiz

Department of Mechanical and Industrial Engineering, Louisiana State University, Baton Rouge, LA 70803, United States

ARTICLE INFO

Article history:
Received 1 December 2015
Received in revised form
20 August 2016
Accepted 8 September 2016

Keywords:
Offshore wind farm
Transportation
Installation process
Repair
Maintenance
Cost minimization

ABSTRACT

Building an offshore wind energy facility is an undertaking of large capital investment. The cost of such transportation and installation depends on the time to complete these processes. The cost can be minimized by an optimum selection of variables of transportation and installation operations such as onshore pre-assembly of turbines and their rated power outputs. Other factors such as learning rates for lifting and assembly operation, port-to-farm site distance, vessel deck area and lifting rate of the vessel crane have significant effects on the system cost. A model based on these costs is developed for wind turbine installation and transportation in an offshore wind farm, and the impact of decision variables on total cost of transportation and installation is investigated here. The effects of wind farm and vessel parameters on cost are studied such that an optimal set of system parameters is chosen to minimize the total cost of transportation and installation. A numerical analysis is performed to illustrate the model and to understand the general behavior of different system parameters. The results show that the total cost is significantly impacted by turbine size and pre-assembly method. Also, the scheduled maintenance help reduce the cost significantly that the unscheduled maintenance.

1. Introduction

Wind energy has been considered as one of the most efficient clean energy sources. From the beginning of 1980s, there have been many developments in the field of renewable energy, and many wind energy facilities have been installed and are now operating successfully. At the end of that decade, offshore wind farms started to grow; first in a small scale and then as large offshore projects with over 100 MW energy output. Offshore wind energy is attracting more attention due to the constraints of onshore space and other barriers. Offshore installation ensures better wind potential and abundant space but it also costs more. Nonetheless, European countries such as United Kingdom, Germany, Sweden and Norway have set target to achieve a great percentage of their total energy demands from offshore wind energy. In those countries, large (above 100 MW capacity) offshore wind farms have been commissioned and many more are on the way of becoming operational. China and India are also on the forefront of undertaking of renewable energy generation. In U.S., so far not many offshore facilities have been constructed; but some projects have been approved and few others are waiting to be approved. There is a keen interest for studies in various areas such as capital cost structure, energy output, structural issues, supply networks, maintenance, installation, and transportation pertaining to offshore wind facility.

The most critical stage of commissioning an offshore wind facility is the installation phase. It involves a lengthy period of time, and hence the high capital cost. Installation phase includes transportation of foundation materials from port to farm site, piling and grouting of foundations into places and transportation and installation of turbines. Besides that, relatively smaller steps are substation installation, array cable installation within the farm and between port and the farm. In the present study, transportation and installation of turbines have been brought into discussion.

Very few studies have been conducted on offshore wind energy facility development and installation of wind farms. In these studies, different models which covered diverse problems concerning offshore wind energy (i.e., development potential for wind farm, cost of installation, effect of design of the wind farm, learning effect on cost and so on) have been developed, Menz and Vachon [28] proposed a model for wind energy development index wherein they suggested that development of a wind farm in an area

* Corresponding author.
E-mail addresses: bsarker@lsu.edu (B.R. Sarker), tasnim6603@gmail.com (T.I. Faiz).

http://dx.doi.org/10.1016/j.renene.2016.09.014
0960-1481/

not only depends on the wind potential, but also on different energy policies effective in that area. Their model took wind potential index as the output, and various financial incentives granted by governments in a particular region as the concerned variables. From their model, it is suggested that, mandatory policies set by the authorities lead to increasing wind power development whereas voluntary choices and financial incentives fail to stimulate the development. Their model only considered incentives granted for setting energy prices for the energy providers. Incentive in manufacturing or logistics industries for offshore wind farm components and their effects on the development potential were not considered. Heptonstall et al. [12] developed a levelised cost model for generation of electricity from wind energy. According to their model, cost of energy depends on the major cost drivers, such as investment and operations cost, and fuel costs which indicates a gradual rise in cost of electricity generation. They predicted that financial incentives from governments, scale of production and enhancing the capability of supply chain can encounter this rise in cost. This cost model considered an overall investment cost and maintenance cost, but it did neither consider the installation methods nor its effect on leveled cost. Hong and Moller (2012) gave a levelised cost of electricity generation, in which risk of storm/cyclone was included.

[25] had planned and developed a decision support system for maritime logistics concepts for offshore wind farms and subsequently [30] optimized marine energy installation of operations [27]. showed how to control multi-indenture repairable inventory of multiple aircraft parts and [26] developed optimization models for critical spare parts inventories from the perspective of reliability [9]. performed a model-based prognosis strategy for prediction of remaining useful life of Ball-Grid-Array interconnections [21]. did a case study on a hybrid analytical-simulation approach for maintenance optimization of deteriorating equipment in wind turbines [4]. found a set-valued approach to FDI (fault-detection and isolation) and FTC (fault-tolerant control) of wind turbines and [39] organized current progress and future perspectives of maintenance logistics for offshore wind energy [2]. developed a planar open vehicle routing in an offshore wind farm array cable layout problem.

[33] determined the cost of an electro-mechanical equipment of a small hydro-plant [47]. calculated the hosting forces of the wind turbine rotor based on wind condition [29], evaluated offshore wind resources by scale of development, and [11] described the role of grouping in the development of an overall maintenance optimization framework for offshore wind turbines. A series of research on optimization of integrated systems was performed in the subsequent years. For example [48], performed a motion analysis on integrated transportation technique for offshore wind turbines, Francois et al. (2013) developed a model for the optimization of the maintenance support organization for offshore wind, and [32] did a framework for data integration of offshore wind farms. Recently Castro-Santos and Dian-Casas [5] analyzed the life-cycle of floating wind farms to classify different cost structure and some technical aspects.

[46] levelized costs and avoided cost of new generation resources in the annual energy outlook [24]. presented many models on the economics of wind energy in the context of European wind energy generation. While [15] analyzed the renewable energy cost for wind power [43], reviewed the cost of wind energy from the US perspective in contrast of her other counterparts. The current study focused on the development of cost models that incorporate the transportation of the components from offshore to the turbine installation sites and the maintenance schedule of the components that contributes significantly to the installation and maintenance costs of such components. The current models recommends the scheduled maintenance over the preventive maintenance as it is done in many such offshore distant locations.

On the issue of installation of wind turbine [7], and [41] optimized layouts of offshore wind energy systems while [36] optimized a risk-based inspection planning of offshore wind turbines, and [40] did a design optimization of an offshore vertical axis wind turbine.

While [6] determined the optimum capacity of stand-alone hybrid generation systems considering cost and reliability [13], reviewed different technical issues on the development of wind farms [16]. analyzed the effect of wind farm location on people's lives and discussed how wind farms can be integrated with the landscape and local environment.

The most critical stage for offshore wind energy facility is the *installation* of foundations and turbines [23]. proposed that an installation cost is a function of maximum power output, number of wind turbines and the area of offshore farm. Their model was developed for a particular region; empirical relations and cost coefficients used in the model is valid only for that particular study [22]. developed a model to determine which the optimum wind power system configuration would minimize the installation cost over a long period. Pantaleo et al. [35] developed a cost model where they defined the cost of installation as a function of water depth at the farm site and turbine hub height. The authors compared cost of energy at various offshore sites in a region using different turbine models. They developed a method for selecting optimum offshore site and a turbine model depending on a specific region.

[17] performed an offshore wind energy installation and decommissioning cost estimation on the U.S. outer continental shelf and subsequently in 2012 they (Kaiser and Snyder) published a book on the modelling offshore wind energy cost for installation and decommissioning [19,20]. developed models for offshore wind installation vessel day-rates in the United States and for offshore wind installation costs on the US outer continental shelf. The most detailed study for offshore wind turbine transportation and installation was conducted by Refs. [19,20]. In their model cost of installation is a function of wind farm nameplate capacity, wind turbine capacity and distance from port to farm site. The authors formulated the cost model as a product of time to complete installation and daily cost of installation. The model did not provide insights whether there is any effect of installation method on installation cost [[8]].

[14] considered the effect of installation method of wind turbines on in his installation cost model. He also considered the effect of delay in operation due to bad weather. The effect of turbine model and its size was not considered in the model [45]. also studied the effect of installation method of turbines on the installation cost. Both of these works proposed a number of pre assembly type operations and formulated the time and space requirements for transport and installation. These models provided estimations of installation time and cost of offshore wind farms but did not propose any optimum decision that would minimize the installation time and cost.

Very few studies ventured in developing cost models for wind turbine transportation and installation. In these studies, cost models developed considered only a few of the impacting factors. Cost of transportation and installation is significantly affected by the wind farm properties, primarily by rated power output of wind turbines. Another important factor to be considered is the installation procedure followed for wind turbines. These cost determining factors have not been included altogether in previous studies. Also, effects of various parameters of offshore wind farm, installation vessel and learning capability on cost need to be analyzed. Formulating a model that presents the relationship