Minimization of Transportation and Installation Time for Offshore Wind Turbines

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Abstract

The most challenging aspect of introducing an offshore wind energy facility is high cost of capital for transportation and installation of wind turbines. The cost associated with transportation and installation depends on the required time to complete these processes and the time requirement can be minimized by optimum selection of many variables of transportation and installation operations such as onshore pre-assembly of turbines, rated power output of each turbine and number of turbines in the wind farm. Impact of these decision variables on total time requirement of transportation and installation is investigated in this paper, and a time estimation model for wind turbine installation and transportation is developed. Effect of wind farm and vessel parameters on time requirement is studied. Also a numerical study is performed to illustrate the model. The results show that total time requirement is significantly impacted by turbine size and pre-assembly method.

1. Introduction

Wind energy has been considered as one of the most efficient clean energy source. Offshore wind energy generation facility is attracting more attention due to better wind potential and abundant space but it also costs more. There is a keen interest in studying the prospect of minimization of cost of energy generated from offshore wind energy.

Several studies have investigated offshore wind power development, these studies proposed different models, which discussed the potential for offshore wind energy development, cost reduction prospects, learning effects on cost of wind energy and also cost structure for wind farm installation. Menz and Vachon (2006) proposed a model for wind energy development index. They 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. Heptonstall *et al.* (2012) developed a levelised cost model for electricity generation from wind energy. They predicted that financial incentives from governments, scale of production and enhancing the capability of supply chain can encounter the rise in cost of energy.

Cost of energy generated from offshore wind depends to a great extent on the installation time requirement and costs. A lengthy period of time and therefore high capital cost is associated with the installation phase. Due to wind turbines' size and vessel constraints, transportation and installation of turbines are the tasks that predominates total installation time and costs. Very few studies have been done in developing a relation between turbine installation and cost of energy. Kiranoudis *et al.* (2001) proposed that installation cost is a function of maximum power output, number of turbines and area of offshore farm. Cost coefficients used in their model were developed for that particular study only. Pantaleo *et al.* (2005) 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.

Kaiser and Snyder (2013) developed an installation cost model, where they estimated the time to complete installation procedure and the daily rate of vessel, total cost is estimated from their product. Uraz (2011) studied the effect of pre-assembly of turbines onshore on the installation cost. He studied the effect of different pre-assembly

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methods of turbines and formulated models for estimating the space requirements for transporting turbines and time for installation. These models provided a guideline for estimating transportation installation time for offshore wind farms but did not propose any optimum decision that minimizes the project duration and cost.

In previous works, selection of optimum characteristics of a wind farm and pre-assembly method in minimizing total transportation and installation time requirement is not investigated. Thus, the objective of this paper is to develop a model which estimates the time requirements for transportation and installation of turbines. From the model, optimum solutions for number of turbines, their rated power output and pre-assembly method would be identified which minimize the total installation and transportation time.

2. Model Formulation

Consider a case of launching a new offshore wind energy generation facility. The wind farm would be situated in the open waters and would consist of a number of wind turbines arranged in rows and columns. In the next section, turbines properties related to transportation and installation are discussed briefly.

2.1. CLASSIFICATION OF OFFSHORE WIND TURBINE PRE-ASSEMBLY

Transportation and installation of turbines begins after the foundations are in place at the farm sites. Each turbine is an assembly of several parts, which are pre-assembled onshore following one of five methods prior to transportation. Number of required lifts and deck area required for each turbine on transportation vessel are determined by pre-assembly method. These methods are summarized in Table 1. For each method, sub-assemblies, numbers of sub-assemblies done onshore and offshore are provided in the table.

Table 1. Popular pre-assembly methods for offshore wind turbines.

Pre-assembly method, j	**Sub assemblies**	**Sub assemblies done onshore,** m_j	**Lifts for each turbine,** N_{L_j}
Method 1	(Nacelle+hub+2 blades)+tower in 1 piece+3rd blade	4	3
Method 2	(Nacelle+hub+2 blades)+tower in 2 pieces+3rd blade	3	4
Method 3	(Hub+3 blades)+tower in 2 piece+nacelle	3	4
Method 4	(Nacelle+hub)+ tower in 1 piece+3 blades	2	5
Method 5	(Nacelle+hub)+ tower in 2 pieces+3 blades	1	6

2.2. ASSUMPTIONS AND NOTATIONS

Transportation and installation of wind turbines are complex tasks requiring a combination of various sub tasks. To reduce the complexity of analysis of installation process for an offshore wind farm, several assumptions are taken into account during the model formulation.

Assumptions:

In order to formulate the model in a simple way, following assumptions are made:

1. All the vessel(s) and turbines are identical (same geometrical properties).
2. For all turbines in a single wind farm, same pre-assembly method is used.
3. Vessel(s) are available throughout the transportation and installation period.
4. Weight concentration on the deck of a vessel does not exceed the limit.
5. Crane on the vessel(s) is the only available option for performing lifting operation.
6. Crane capacity is sufficient to lift the components of turbines.
7. All assembly operations are identical in terms of time requirement.

Notation:

The following notations for system parameters and decision variables are used in the paper:

N_i : Number of turbines in the farm (unit),

P_i : Rated power output of one turbine (megawatt),

C : Rated capacity of the wind farm (megawatt),

D : Distance from port to farm site (meter),

d : Distance between two turbines sites (meter),

V_N : Number of vessel used (unit),

A : Deck area available for transporting foundation (square meter),

i : Index for type of turbine class used,

j : Index for type of turbine preassembly used,

A_{T_j} : Deck area required for one turbine during transport (square meter),

H_{H_i} : Turbine hub height (meter),

H_{JU} : Jack up height (meter),

R_L : Rate of lifting (meter/hour),

R_A : Rate of assembly (assembly/hour),

t_{PL} : Pre-loading time at the port (hour),

t_{FS} : Pre-loading time at turbine site (hour),

N_{L_j} : Number of lifts for each turbine during loading or installation (unit),

m_j : Number of sub assemblies done onshore (unit),

L_R : Learning rate for the crane operation

2.3. TRANSPORTATION AND INSTALLATION TIME ESTIMATION

The rated power capacity of the wind farm is C · The number of wind turbines in the farm is N_i , each with rated power output P_i ; That is, $C = N_i P_i$. To estimate the total time requirement for transportation and installation of N_i turbines, the process is divided into operation segments and time requirements of each segment is estimated. In the following section, time requirement for each segment is expressed in terms of controlling variables.

(a) Travel/transportation time:

During transportation, deck area occupied by one turbine occupies is a function of rated power output and pre-assembly method and can be expressed as $A_{T_j} e^{q_1(P_i-2)}$ m^2, where, q_1 is a constant coefficient and A_{T_j} is average deck area required for a turbine with nominal rated power output (2 megawatt) following pre-assembly method j . If V_N (for now V_N is assumed to be 1) number of vessels each with deck area A m^2 are available, number of required trip is $\left(N_i A_{T_j} e^{q_1(P_i-2)} / V_N A \right)$. If the distance between port and farm site is D and distance between two turbine sites is d , preparation and pre-loading time for each trip as t_{PL} at the port and t_{FS} at each turbine site, total travel time for transporting turbines is:

$$T_v = \frac{N_i}{V_N V_S} \left[\left(2D - d + t_{PL} V_S \right) \left(\frac{A_{T_j} e^{q_1(P_i-2)}}{A} \right) + 2V_N d + t_{FS} V_N V_S \right] \tag{1}$$

(b) Installation and vessel loading time:

Vessel loading and installation process involves several activities, and time requirements for them need to be estimated. Time requirements of these tasks can be described as following:

1. Assembly operation time (prior to vessel loading and during installation).
2. Lifting operation time (during loading on the vessel and during installation).
3. Vessel jacking up operation time

Among above listed, time requirements for the first two tasks depend on turbine properties as well as operator's efficiency. Rates of performing lifting and assembly are affected significantly by learning rate. A learning rate of 90% indicates time to performing a operation decreases 10% each time the number of operation is doubled. Cumulative averages of rates of lifting and assembly are calculated from the initial rates of performing these operations, turbine's rated power output and number of operations as follows:

$$R'_L = \frac{R_L}{e^{q_2(P_i-2))} {N_{O_L}}^b} \quad \text{and} \quad R'_A = \frac{R_A}{e^{q_2(P_i-2))} {N_{O_A}}^b} \tag{2}$$

where $b = \frac{\log(L_R)}{\log 2}$, $L_R < 1$, $b < 0$, q_2 denotes a constant, L_R denotes the learning rate, N_{O_L}, N_{O_A} are the number of lifting and assembly operations respectively and R_L, R_A are the initial rates of lifting and assembly operation for turbines with nominal rated power output (2 megawatt) respectively. Time requirement for each task is also a function of task specific parameters. Calculation of time requirements is given in detail in the following section.

(c) Lifting operation time:

Each turbine requires N_{L_j} number of lifts by the crane on the vessel during both loading at the port and unloading at the farm site. Lifting time is proportional to the lifting height. During loading at the port, lifting height is equal to jacking up height H_{JU} and at the installation site, lifting height is equal to turbine hub height, H_{H_i}. Total lifting time of turbines, therefore is a function of lifting height and average rate of lifting R'_L, and is calculated as:

$$T_l = N_i \frac{N_{L_j}}{R'_L} \left(H_{H_i} + H_{JU} \right) \tag{3}$$

Hub height of the turbine H_{H_i} is a function of turbine's rated power output P_i, and can be written as $H_{H_i} = a_1 P_i^2 + b_1 P_i + c_1$, where a_1, b_1, c_1 are constant coefficients. Also, considering equation (2), equation (3) can be rewritten as:

$$T_L = \frac{2^b \left(N N_{L_j}\right)^{1+b} e^{q_2(P_i-2)}}{R_L} \left[a_1 P_i^2 + b_1 P_i + c_1 + H_{JU} \right] \tag{4}$$

(d) Assembly operation time:

Each turbine is consisted of M parts, so a total of M assembly operations need to be done to install the turbine . If number of onshore assembly is m_j, then for complete installation of a turbine, $(M - m_j)$ number of offshore assembly must be done. Taking into consideration offshore wind and wave, a multiplication factor W is incorporated for estimating offshore assembly time requirement. Total time required for assembly operation is calculated as:

$$T_A = N \left[\frac{m_j}{R'_A} + \frac{W\left(M - m_j\right)}{R'_A} \right] \tag{5}$$

where R'_A is the cumulative average rate of performing the assembly operation. From table 1, it is known that $m_j + N_{L_j} = M$. So, number of assembly operations done onshore and offshore are $N_i\left(M - N_{L_j}\right)$ and $N_i N_{L_j}$ respectively. From equations (2) and (5), time requirement for assembly operation can be written as following:

$$T_A = \frac{N_i^{1+b} e^{q_2(P_i-2)}}{R_A}\left[\left(M - N_{L_j}\right)^{1+b} + WN_{L_j}^{1+b}\right] \tag{6}$$

(e) Jacking up operation time:

Jacking up operation is performed at port and at each installation site. For jacking up, vessel's legs are reached and protruded to the ground below sea, and the vessel gradually lifts itself up to the required height. During each trip, the vessel performs jack up operation at the port. The vessel also has to perform two operations (raising the platform up and down) at every installation site. Total time required for jacking up operation can be written as:

$$T_{JU} = \frac{N_i H_{JU}}{V_{JU}}\left[\frac{A_{T_j} e^{q_1(P_i-2)}}{A} + 4\right] \tag{7}$$

where V_{JU} is the jack up speed and H_{JU} is the jack up height (fixed for a vessel).

2.4. TOTAL TIME REQUIREMENT:

Total time required for transport and install foundations and turbines is the sum of time requirements for travel, lifting operation, assembly operation, and jacking up operation. The expression for total time requirement for transportation and installation is obtained by summing equations (1), (4), (6) and (7), and dividing it by V_N to take into account simultaneous operations performed by vessels.

$$\begin{aligned} T_{ij} = {} & \frac{N_i}{V_N^2 V_S}\left[\left(2D - d + t_{PL}V_S\right)\left(\frac{A_{T_j} e^{q_1(P_i-2)}}{A}\right) + 2V_N d + t_{FS}V_N V_S\right] + \frac{N_i H_{JU}}{V_N V_{JU}}\left[\frac{A_{T_j} e^{q_1(P_i-2)}}{A} + 4\right] \\ & + \frac{N_i^{1+b} e^{q_2(P_i-2)}}{V_N}\left[\frac{2^b N_{L_j}^{1+b}\left(a_1 P_i^2 + b_1 P_i + c_1 + H_{JU}\right)}{R_L} + \frac{\left(M - N_{L_j}\right)^{1+b} + WN_{L_j}^{1+b}}{R_A}\right] \end{aligned} \tag{8}$$

Replacing N_i by (C / P_i) the expression becomes as follows:

$$\begin{aligned} T_{ij} = {} & \frac{CA_{T_j} e^{q_1(P_i-2)}}{P_i V_N^2 A}\left[\left(\frac{2D-d}{V_S}\right) + \frac{H_{JU}}{V_{JU}} + t_{PL}\right] + \frac{C}{V_N P_i}\left[\frac{2d}{V_S} + \frac{4H_{JU}}{V_{JU}} + t_{FS}\right] \\ & + \frac{e^{q_2(P_i-2)}}{V_N}\left(\frac{C}{P_i}\right)^{1+b}\left[\frac{2^b N_{L_j}^{1+b}\left(a_1 P_i^2 + b_1 P_i + c_1 + H_{JU}\right)}{R_L} + \frac{\left(M - N_{L_j}\right)^{1+b} + WN_{L_j}^{1+b}}{R_A}\right] \end{aligned} \tag{9}$$

Area required for one turbine of nominal rated power output (2 MW) on the vessel deck, A_T and number of lifts required for each turbine, N_L both are functions of pre-assembly method. Thus, total time requirement can be expressed as a function of turbine's rated power output and number of lifts required for each turbine during loading at the port or installation at the farm site. Equation (9) can be rewritten as following:

$$T\left(C, P, N_L\right) = \left(\alpha + \beta A_T e^{q_1(P-2)}\right)\frac{C}{P} + \left[\delta\left(\frac{M - N_L}{P}\right)^{1+b} + \left(\frac{\gamma}{P} + \lambda P + \sigma\right)\frac{N_L^{1+b}}{P^b}\right]C^{1+b} e^{q_2(P-2)} \tag{10}$$

where, $\alpha = \frac{1}{V_N}\left[\frac{2d}{V_S} + \frac{4H_{JU}}{V_{JU}} + t_{FS}\right]$, $\beta = \frac{1}{AV_N^2}\left[\frac{2D-d}{V_S} + \frac{H_{JU}}{V_{JU}} + t_{PL}\right]$, $\delta = \frac{1}{V_N R_A}$, $\gamma = \frac{1}{V_N}\left(\frac{2^b\left(c_1 + H_{JU}\right)}{R_L} + \frac{W}{R_A}\right)$,

$\lambda = \dfrac{2^b a_1}{V_N R_L}$, and $\sigma = \dfrac{2^b b_1}{V_N R_L}$.

The model gives the expression for time requirement in hours for turbine transportation and installation for an offshore wind farm with rated capacity C and each turbine's rated output power P following one of five pre-assembly methods. From this model, optimum rated power P of each turbine and optimum pre-assembly method can be determined which would result in minimal time to complete transportation and operation.

2.5. SOLUTION PROCEDURE:

Step 1: Initialize parameters $\alpha, \beta, \delta, \gamma, \lambda, \sigma$ and C .
Step 2: Construct the sets of possible values for turbine's rated power output,
$P = \{P_i,\ i = 1, 2, ..., K\}$, number of lifts for each turbine, $N_L = \{N_{L_i}, j = 1, 2, ..., Z\}$ and required deck area for each turbine, $A_T = \{A_{T_i},\ j = 1, 2, ...Z\}$ for each of the corresponding controlling variables P, N_L and A_T.
Step 3: Finding the minimum time requirement, T^*
For $i = 1, 2, ..., K$
For $j = 1, 2, ..., Z$
(a) Calculate time requirement, T_{ij} using equation (10).
(b) Find $T^* = Minimum\ \{T_{ij}\}$.
(c) Identify P_i^*, $N_{L_i}^*$ and $A_{T_i}^*$, corresponding to T^*, obtained in Step 3(b).
Step 4: Stop

3. A CASE STUDY

In this section for a farm with fixed rated capacity, a numerical study is performed that provides insights as to what combination of turbine's rated power output and pre-assembly method minimizes the time to transport and installation of turbines.

Table 2 provides the values for wind farm and vessel parameters used in calculating the model parameters. These parameters Total transportation and installation times are calculated for an offshore wind farm with rated capacity 300 megawatt (MW). Decision variables are turbine's rated power output pre-assembly method. Both of these variables are chosen from the sets of their available values, e.g. turbine's rated power is chosen from 2.0, 2.3, 3.0, 3.6, 4.0 and 5.0 megawatt classes and pre-assembly method is selected from five available ones.

Table 2. Wind farm and vessel Parameters used in the model and their values.

Parameter	Description	Value	Parameter	Description	Value
D	Distance from farm site to port	200000 meters	V_n	Number of vessel	1
d	Distance between two turbine sites	1000 meters	H_J	Jack up height	35 meters
A	Deck area of the vessel	2000 m^2	V_J	Jacking up speed	30 meters/hour
V_S	Vessel speed	15000 meter/hour	q_1	Constant	0.1019
C	Wind farm's rated power output	300 megawatt	q_2	Constant	0.3214
M	Number of parts in each turbine	7	a_1	Constant	0.5714
R_L	Lifting rate	40 meters/hour	b_1	Constant	0.7714
R_A	Initial assembly operation rate	1 every 2 hours	c_1	Constant	77.12

t_p	Pre-loading time at port	5 hour	LR	Learning rate	0.95
t_S	Pre-loading time at turbine site	1 hour	b	$\log(LR)/\log 2$	-0.074
W	Multiplier for offshore assembly	2			

In Table 3, time requirements for transportation and installation of turbines for a 300 MW capacity wind farm for five pre-assembly methods and five turbine classes are summarized. Learning rate is assumed as 95%.

Table 3. Time requirements for transport and install turbines for a wind farm of 300 MW.

Turbine's rated power output (Number of turbines)	**Time requirement for different pre-assembly methods (days)**				
	Method 1	Method 2	Method 3	Method 4	Method 5
2 MW (150 turbines)	211	225	207	210	233
2.3 MW (131 turbines)	194	208	208	197	218
3 MW (100 turbines)	170	206	182	177	208
3.6 MW (84 turbines)	162	195	175	179	202
5 MW (60 turbines)	175	192	192	187	210

In general, with increasing rated power of turbines, time requirement decreases and reaches the minimum and then increases again. When learning rate is 95%, installing turbines with 3.6 MW rated power following pre-assembly method 1 is found to be optimum choice. It takes 161.522 days to complete transportation and installation of 84 turbines, each with 3.6 MW rated power output.

4. SENSITIVITY ANALYSIS:

Transportation and installation time requirement is significantly impacted by wind farm and transporting vessel parameters, for example, distance from operating port to farm site D, available vessel deck area A and learning rate. In this section the effects of these parameters have been discussed.

4.1. EFFECT OF LEARNING RATE:

Learning rate significantly affects time to perform lifting and assembly operation therefore total time requirement for installation of turbines. Higher learning rate results in completion of installation in less time across all pre-assembly methods and all turbine classes. Table 4 shows the change in time requirement due to change in learning rate for two turbine classes and five pre-assembly methods. Learning rate affects the choice of pre-assembly method. For example, if turbine class of 3.0 MW is used, method 1 results in least time when there is no learning and/or when learning rate is 95%; but method 4 results in least time when learning rate is 90% or 85%. Time to complete an operation decreases 15% each time the number of operation is doubled when learning rate is 85%.

Table 4. Effect of learning rate on time requirement.

Turbine's rated power output (No of turbines)	**Learning rate**	**Time requirement for different pre-assembly methods (days)**				
		Method 1	Method 2	Method 3	Method 4	Method 5
3 MW (100 turbines)	No learning	223	269	246	251	292
	95%	170	206	183	177	208
	90%	134	164	141	130	154
	85%	110	137	114	100	121
3.6 MW (84 turbines)	No learning	216	258	239	254	287
	95%	162	195	175	179	202
	90%	125	152	133	131	147
	85%	101	124	105	100	112

4.2. EFFECT OF DISTANCE FROM PORT TO FARM SITE:

Transportation and installation time increases with increasing distance between the port and farm site, D . This effect is the minimum for method 4 and highest for method 2, for which, each turbine occupies the largest and smallest area on the vessel deck respectively. In Table 5, effect of distance between port and farm site on time requirement is summarized. It is observed that, when distance between port and farm site is small e.g. 25 kilometers, time requirements for different pre-assembly methods differ less compared to that when the distance is large e.g. 200 kilometers. Also, difference in time requirement across turbine classes is less when the distance is small.

Table 5. Effect of distance between port and farm site on time requirement.

Turbine's rated power output (No of turbines)	**Distance from port to farm site (Kilometer)**	**Time requirement for different pre-assembly methods (days)**				
		Method 1	Method 2	Method 3	Method 4	Method 5
3 MW (100 turbines)	25	145	163	157	163	179
	50	149	170	161	165	183
	100	159	184	171	171	193
	200	177	212	189	182	211
3.6 MW (84 turbines)	25	139	157	152	161	175
	50	143	163	156	164	179
	100	151	175	163	170	186
	200	167	198	179	182	202

4.3. EFFECT OF AVAILABLE VESSEL DECK AREA:

Transportation time decreases as the vessel deck area capacity A increases. Table 6 summarizes this effect of vessel deck area capacity on time requirement. It is evident that, when vessel deck area is large, difference in time requirements decreases across both pre-assembly method and turbine's rated power output.

Table 6. Effect of available deck area on time requirement.

Turbine's rated power output (Number of turbines)	**Vessel capacity (m^2)**	**Time requirement for different pre-assembly methods (days)**				
		Method 1	Method 2	Method 3	Method 4	Method 5
3 MW (100 turbines)	1500	200	212	212	200	234
	2000	177	212	189	182	211
	2500	166	189	178	178	200
	3000	159	178	171	174	193
3.6 MW (84 turbines)	1500	186	255	198	191	221
	2000	167	198	179	181	202
	2500	167	179	169	175	192
	3000	157	179	164	169	187

5. CONCLUSION:

In this paper a time estimation model for transportation and installation of offshore wind turbines is developed. In this model, wind farm's rated capacity, turbine's rated power output and pre-assembly method are regarded as decision variables and solution procedure for optimum values is proffered. A case study is presented to illustrate how the selection of optimal pre-assembly method and turbine's rated power output results in minimum transportation and installation time for an offshore wind farm. Variation in time requirement due to change in learning rate, distance between port and farm site and vessel deck area capacity is also investigated.

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