



Evaluating and Improving Logistics Costs During Offshore Wind Turbine Construction

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Abstract: Background: During the whole life cycle of an offshore wind farm, from cradle to grave, logistics is needed. Particularly during wind turbine construction, vessels are intensively used. However, no study has been found to evaluate logistics costs during this particular turbine construction phase. Objective: In order to close this gap, this paper aims to propose an Offshore Logistics Cost (OLC) framework, evaluate OLC impact on total cost and identify recommendations to reduce this impact. Methodology: This study considers two quantitative approaches to evaluate OLC share. First quantitative approach is based on cost information found in twenty related studies from literature. Second quantitative approach was developed in two steps. A first step is a bottom up calculation model. This model performs OLC calculations for each scenario identified. In a second step, OLC results are used as input to two existing calculation models: National Renewable Energy Laboratory (NREL) simplified model and commonly accepted model developed by Megavind. Variance of results are then analyzed to determine a representative range for OLC impact on total cost. Results: Using some related values from literature review, this study assesses wind turbine construction offshore logistics to represent around 1.2% of Levelized Cost of Energy (LCOE). Using bottom up approach, this study evaluates offshore logistics during wind turbine construction with a broader contribution, conservatively from 0.6 to 7.6% of LCOE for offshore wind turbines over 4 MW power rating. It is also demonstrated that the higher the wind turbine size, the lower offshore logistics impact on LCOE. Conclusion: Offshore wind logistics costs during construction phase can represent between 0.6 and 7.6% of LCOE and it appears necessary to optimize these costs to contribute to a competitive LCOE. As main offshore logistics cost drivers have been identified, areas to reduce LCOE impact are suggested: increasing weather limits to reduce waiting on weather costs, minimizing work offshore, improving processes, using economy of scale and optimizing vessel use.

Keywords: Offshore Wind Construction, Offshore Logistics Costs, Cost Optimization

1. Introduction

Offshore wind tends to be part of an increasing number of countries energy plans as onshore availability becomes limited and offshore offers better wind conditions and more space for installation [1]. Offshore wind is still however an immature industry, as reflected by its Levelized Cost of Energy (LCOE). LCOE is used as an indicator for investment options evaluation: it can be considered as a “first order assessment of project viability” [2]. LCOE used to be substantially higher (0.13 \$/kWh median) than the other common energy sources: onshore wind (0.07 \$/kWh median), hydropower (0.06 \$/kWh median), biopower (0.07 \$/kWh median), natural gas combined cycle (0.05 \$/kWh

median), coal (0.06 \$/kWh median), nuclear (0.08 \$/kWh median) [3]. For better acceptance, offshore wind needs to significantly reduce its LCOE in order to be competitive with other energy sources and without government support [4]. The industry is already showing some improvements and latest auction results (in Germany [5] or Belgium [6]) suggest that offshore wind LCOE will decrease to between 0.06 and 0.10 \$/kWh by 2020 [7]. European governments tend also to reduce or even cancel subsidies to offshore wind [8].

Moreover, distance from shore and harsher weather conditions increase logistic challenges during construction

and operations, therefore adding cost pressure on both capital and operating expenditures. Tendency to build larger turbines bring also new logistic difficulties during construction and maintenance [9]. In such context, offshore wind and in particular its logistics is subject to higher challenges. Poulsen and Lema [10] suggest that offshore wind industry depends on transformation and improvement of its logistics. This is in line with Offshore Wind Cost Reduction Task Force [11] which has foreseen installation and logistics as an area where substantial cost-reductions can be achieved through innovation. According to Irena [12], one of the largest cost reduction potential is identified in the construction and installation process (13% of reduction potentials by 2025). Furthermore, wind turbine supply and construction appears to be one of the most cost intensive phase of wind farm life cycle: 28% of capital and operational costs of a typical offshore wind farm according to BVG Associates [13].

Therefore, this paper aims to assess logistics that support installation and construction of offshore wind turbines and to evaluate its cost impact on LCOE. This would then constitute a basis to assess the potential improvements on this particular scope of offshore wind farm life cycle.

Twenty articles or studies have been found relevant for a literature review to evaluate offshore logistics costs during wind farm construction and are presented in Table 1. It has been observed relative balanced origins for the set of articles or studies found. However, it may be argued that academic articles largely point back to industry or government studies. Analyzing more closely the studies and articles, relevant ones have been issued between 2003 and 2017, with higher number after 2013, and more recently dominated by academic. No paper reviewed is clearly providing an indication of the LCOE share for offshore logistics during wind turbine construction.

Table 1. Literature review – offshore logistics costs evaluation.

#	Author	Year	Ref.	Relevant extract
1	Henderson et al.	2003	[14]	From example breakdown of initial capital costs for an offshore wind farm, installation represents 7% of capital costs.
2	Krohn et al.	2005	[15]	Installation costs can account for approximately 30% of the overall project cost and it is anticipated in this area further cost saving potential.
3	Offshore Design Engineering Limited	2007	[16]	WTG installation: 2% of CAPEX. Testing and commissioning: 2% of CAPEX. Installation and commissioning: 26% (6% labor, 2% material, 18% other) of CAPEX.
4	BVG Associates	2010	[17]	Turbine installation: 9% of installation and commissioning (2.8% labor, 0.5% material, 6% other).
5	Kaiser and Snyder	2010	[18]	Turbine transportation and installation costs make up almost 30% of total installation costs.
6	Greenacre et al.	2010	[19]	Foundation, turbine, and cable installation together comprise approximately 15 to 20% of overall CAPEX. Installation is a major cost, currently accounting for 18 to 21% of CAPEX (or 11-13% of LCOE) for projects with FID in 2011.
7	The Crown Estate	2012	[20]	Breakdown of installation capital costs, 4MW-Class Turbine FID 2011; Turbine: 17%, which represents 1.9 and 2.2% of LCOE for turbine installation.
8	Kaiser and Snyder	2012	[21]	Installation costs make up on the order of 20% of capital expenditures in European wind farms.
9	Prognos & Fichtner Group	2013	[22]	Installation: 12% of overall cost.
10	Navigant Consulting, Inc	2013	[23]	Installation: 10% of overall cost and 19% of capital cost installation operations. It includes transportation and installation of turbine components, foundation components and electric cables.
11	Maples et al.	2013	[24]	The baseline installation strategy resulted in a total installation cost of \$633 million dollars for the 500MW project. Roughly 12% of the baseline LCOE is attributable to operation and maintenance and 20% to installation activities (installation vessels + ports and staging).
12	Wagner	2013	[25]	LCOE shares of typical 2013 German project. Turbine installation: 2% overall cost.
13	BVG Associates	2014	[13]	Installation Ports: 0.5% overall cost. Installation other: 3% overall cost.
14	Myhr et al.	2014	[26]	Depending on type of bottom-fixed turbines considered, installation of wind turbine could represent between 7 and 8% of LCOE cost breakdown over life cycle.
15	Faiz	2014	[27]	Wind turbine transportation and installation contributes almost 5% of total capital costs.
16	IRENA II	2016	[28]	Contribution of each wind farm element to LCOE: 8 to 9% of installation.
17	Poulsen and Hasager	2016	[4]	Logistics may conservatively amount to 18% of the LCOE for offshore wind farms.
18	Tekle Muhable et al.	2016	[29]	The transport and installation cost of an offshore wind farm could range between 5% and 30% of the total cost of the investment.
19	IRENA I	2016	[12]	Installation is a major cost component, accounting for around 19% of total installed costs.
20	Poulsen et al.	2017	[30]	Scenarios displaying fluctuations in operating expenditure share of total costs. CAPEX value between 43 and 85% of total costs.

Consequently, the following research questions are studied:

[Q1] What is offshore logistics cost impact on LCOE during wind turbine construction?

[Q2] Are there some preliminary recommendations to

reduce this impact?

In chapter 2, methodology adopted in this study is presented. In chapter 3, offshore logistics wind turbine construction cost is assessed using information from existing literature and with a bottom up evaluation of offshore

logistics during wind turbine construction. Results from bottom up evaluation are then applied on two existing LCOE calculation models in order to quantify offshore logistics cost impact. Results are then discussed in chapter 4 and based on assessments of main cost drivers, some recommendations from existing literature are classified and presented to reduce offshore logistics costs impact on LCOE. Finally, the study outcome is discussed, evaluated in terms of its contribution and further research areas are raised.

2. Methodology

A research framework is defined based on existing LCOE breakdown. Intention is to clarify where in LCOE cost structure are allocated offshore logistics costs during wind turbine construction. In Figure 1, Gaeta and Rao [31] propose a LCOE cost structure for offshore wind plants.

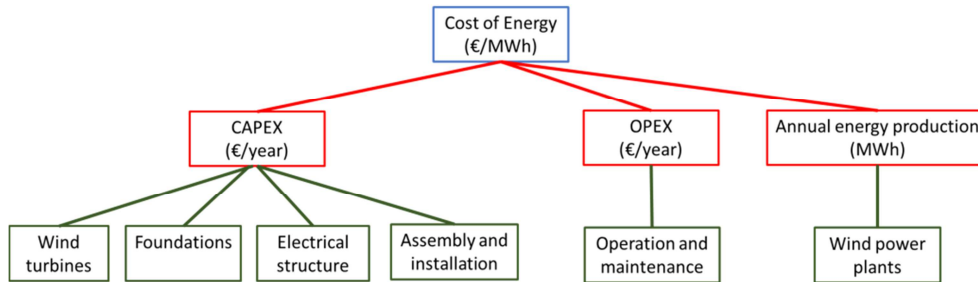


Figure 1. LCOE structure for offshore wind power plants. Source: adapted from Gaeta and Rao [31].

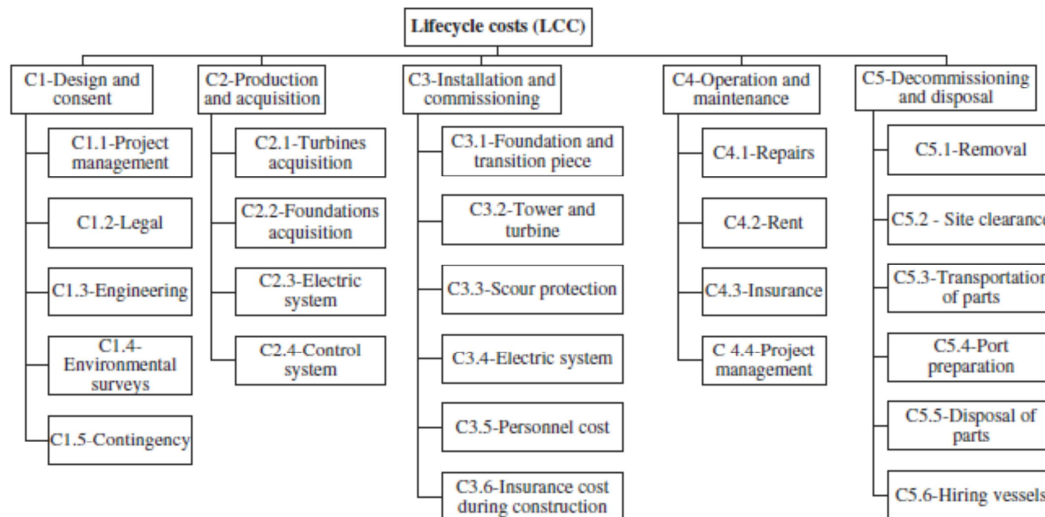


Figure 2. Break down of life cycle costs. Source: Ioannou et al. [32].

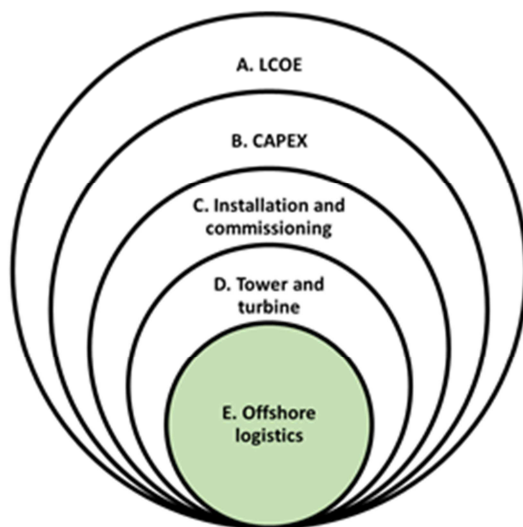


Figure 3. Offshore Logistics Cost (OLC) framework.

In their model structure, CAPEX subcategory includes all costs related to capital. As wind turbines, foundations and electrical infrastructure cover the fabrication or production costs, assembly and installation category appears to include offshore logistics costs during construction. OPEX subcategory is related to operation and maintenance, hence, offshore logistics costs related to this category are excluded. In Figure 2, Ioannou et al. [32] provide a further breakdown of the life-cycle cost of an offshore wind farm. Using their approach, category “C3 – Installation and commissioning” is recognized as the category including offshore logistics costs during construction. More specifically, “C3.2- Tower and turbine” and partly “C3.5 – Personnel cost” and “C3.6- Insurance” cost during construction are considered.

Based on the above and considering the focus on Offshore Logistics Costs (OLC) during tower and turbine construction, Figure 3 breakdown is proposed as a research framework.

Offshore logistics considered in this study is first

installation vessel used to erect the wind turbine. Often called jack-up vessel, it is a specialized vessel with retractable legs which can be lowered into the seabed to jack-up the vessel above the surface of the water and provide a stable platform which reduces the sensitivity of operations to the sea conditions [33]. To support completion works, commissioning, trial run and other activities before wind turbine hand over, different types of vessels are used and also considered as offshore logistics. Without entering into details, offshore logistics for such activities can be Crew Transfer Vessel (CTV), accommodation vessel or “hotel vessel”, with eventually special functionalities such as Dynamic Positioning (DP) associated with transfer system (i.e. Ampelmann, Safeway system), helicopters or jack up vessels with gangway.

Research on offshore wind logistics during construction phase provides limited quantitative information related to costs. To cope with this aspect, this study considered mixed method concepts of qualitative literature analysis and two quantitative approaches to evaluate offshore wind turbine construction logistics LCOE share.

First quantitative approach was based on cost information found in literature. Literature review was done by selection and analysis. The selection phase was conducted by collecting a comprehensive set of articles in the focused areas, while the analysis phase was a careful and critical examination of the articles to identify patterns and recurrent themes [34]. For articles collection, main source of references used was provided by Poulsen et al. [30] analyzing OPEX logistics costs in eleven major LCOE related studies. Objective of the present study was to create a similar analysis, this time for CAPEX logistics instead of OPEX logistics: using Poulsen et al. sources was a convenient way to initiate the review, as the eleven LCOE studies are for their majority covering both CAPEX and OPEX areas. Additional relevant studies were also found using several search engines such as Google Scholar or Researchgate with key words searches such as “LCOE”, “offshore logistics” and/or “construction”. Different values found in literature were classified per categories defined in research framework

(Figure 3). Results from different identified categories were aggregated or calculated to propose an evaluation of E. offshore logistics.

Second quantitative approach was developed in two steps. A first step was a bottom up OLC calculation model. This model performs calculations, comparisons and sensitivity analysis for each scenario identified. In a second step, OLC results were used as input to two existing LCOE existing calculation models: Renewable Energy Laboratory (NREL) simplified LCOE model and Megavind Model. Variance of results were then analyzed to determine a representative range for OLC impact on LCOE.

3. Results

3.1. OLC Impact on LCOE Evaluation from Literature

Intention of this approach is to evaluate OLC impact on LCOE using existing values from literature. Only the following estimated cost ratios (categories based on Figure 3) have been found or could be deducted from relevant literature identified in Table 1:

- B. CAPEX / A. LCOE
- C. Installation and Commissioning / B. CAPEX
- D. Tower and turbine / B. CAPEX
- E. Offshore Logistics / B. CAPEX
- C. Installation and commissioning / A. LCOE
- D. Tower and turbine / A. LCOE.

No information specific to the offshore logistics costs during wind turbine construction have been found. However, offshore logistics share of LCOE could be deducted with the following formula

$$\frac{E. \text{ Offshore Logistics}}{A. \text{ LCOE}} = \text{Avg} \left(\frac{E. \text{ Offshore Logistics}}{B. \text{ CAPEX}} \right) \times \text{Avg} \left(\frac{B. \text{ CAPEX}}{A. \text{ LCOE}} \right) \quad (1)$$

Using average and ratio based on figures found in literature, results are presented in Table 2, and wind turbine construction offshore logistics have been finally evaluated to represent around 1.2% of LCOE.

Table 2. Wind turbine construction offshore logistics LCOE share evaluation.

Year	Reference	C. Installation and commissioning / B. CAPEX			D. Tower and turbine / B. CAPEX			E. Offshore logistics / B. CAPEX			C. Installation and commissioning / A. LCOE		
		min	max	central	min	max	central	min	max	central	min	max	central
2003	1			7.0%									
2005	2												30.0%
2007	3							4.0%					
2010	4			26.0%			2.3%			1.6%			
2010	5						5.7%						3.0%
2010	6	15.0%	20.0%	17.5%									
2012	7	18.0%	21.0%	19.5%	3.1%	3.6%	3.3%				11.0%	13.0%	12.0%
2012	8			20.0%									
2013	9			12.0%									
2013	10			19.0%									10.0%
2013	11			22.0%									20.0%
2013	12												
2014	13												5.5%
2014	14												
2014	15						5.0%						

Year	Reference	C. Installation and commissioning / B. CAPEX			D. Tower and turbine / B. CAPEX			E. Offshore logistics / B. CAPEX			C. Installation and commissioning / A. LCOE		
		min	max	central	min	max	central	min	max	central	min	max	central
2016	16										8.0%	9.0%	8.5%
2016	18	5.0%	30.0%	17.5%									
2016	19			19.0%									
2017	20	43.0%	85.0%	64.0%									
Averaged Value				22.1%			4.1%			1.6%			12.7%
Calculated Value (Equation 1)													

Table 2. Continued.

Year	Reference	D. Tower and turbine / A. LCOE			E. Offshore logistics / A. LCOE			B. CAPEX / A. LCOE		
		min	max	central	min	max	central	min	max	central
2003	1									
2005	2									
2007	3									
2010	4									
2010	5									
2010	6									
2012	7	1.9%	2.2%	2.1%						70%
2012	8									
2013	9									75%
2013	10									
2013	11									88%
2013	12							63%	86%	74.5%
2014	13									59%
2014	14	7.0%	8.0%	7.5%						
2014	15									
2016	16									
2016	18									
2016	19									
2017	20									
Averaged Value				4.8%						73.3%
Calculated Value (Equation 1)							1.2%			

3.2. OLC Bottom Up Calculation and LCOE Models

According to Ioannou et al. [32], wind turbines installation costs are a function of the vessel day rates, the number of vessels (workboats, heavy lift vessels, Special Operations Vessels (SOVs) and jack up vessels), the duration of the installation, and the cost for the personnel required for carrying out the installation. The onshore pre-assembly method is also expected to affect the cost as well as weather conditions. Using findings from Ioannaou et al.'s work and expert knowledge, the following logistics direct and indirect costs have been considered for the wind turbine construction: installation vessel (including installation crew) (IV); accommodation vessel to support commissioning / trial runs / non-conformities rectifications / first maintenance (AV); DP

vessels to commissioning / trial runs / non-conformities rectifications / first maintenance (DP); CTVs to support commissioning / trial runs / non-conformities rectifications / first maintenance (CTV); seabed preparation (UXO campaign, boulder removals, base port jacking pads) (SB); offshore logistics management costs (OLM); and marine coordination costs (MC).

Offshore wind costs are sensitive to external factors and technical assumptions [20]. Existence of variability in costs, depending on geography, seasonality, market demand and supply, contract length, bunker costs is well recognized but have been excluded to minimize model complexity. Assumptions that have been selected, defined and used for OLC calculation are enclosed in Table 3.

Table 3. OLC calculation parameters.

Parameter	Formula name	Selected assumption	Assumption range	Unit	Source
Installation vessel (including installation crew, bunker, insurance, port fees, agency fees, communication)	IV	150,000	50,000 -250,000	€/day	[20] [21]
Accommodation vessel to support commissioning / trial runs / non-conformities rectifications / first maintenance (including crew, bunker, insurance, port fees, agency fees, communication)	AV	30,000	22,500 – 37,500	€/day	Expert knowledge ±25%
DP vessels to support commissioning / trial runs / non-	DP	40,000	30,000 – 50,000	€/day	Expert knowledge ±25%

Parameter	Formula name	Selected assumption	Assumption range	Unit	Source
conformities rectifications / first maintenance (including crew, bunker, insurance, port fees, agency fees, communication)					
CTVs to support commissioning / trial runs / non-conformities rectifications / first maintenance (including crew, bunker, insurance, port fees, agency fees, communication)	CTV	3,400	2,550 - 4250	€/day	Expert knowledge ±25%
Seabed preparation (UXO campaign, boulder removals, base port jacking pads...)	SB	30,000	22,500 – 37,500	€/turbine	Expert knowledge ±25%
Offshore logistics management	OLM	2,000	1,500-2,500	€/day	Expert knowledge ±25%
Marine coordination costs	MC	2,000	1,500-2,500	€/day	Expert knowledge ±25%
Number of turbines	NT	40; 60; 80; 100; 120; 140; 160	32 - 175	Turbine	[35]
Installation duration	ID	1; 2; 3; 4	1 - 4	Days /turbine	Expert knowledge ±25%
Commissioning/trial runs/NCRs/1 st maintenance duration / turbine	CD	5; 6; 7; 8; 9	5 - 9	Days /turbine	Expert knowledge ±25%
Accommodation vessels quantity	QAV	0; 1	0 - 1	Accommodati on vessel	Expert knowledge ±25%
DP vessels quantity	QDP	0; 1; 2	0 - 2	DP vessel	Expert knowledge ±25%
CTVs quantity	QCTV	4; 5; 6; 7	4 - 7	CTV	Expert knowledge ±25%

Offshore logistics cost (OLC) for wind turbine construction is calculated as follow

$$OLC = NT \times \left[SB + ID \times IV + CD \times \left(QAV \times AV + QDP \times DP + QCTV \times CTV + OLM + MC \right) \right] \quad (2)$$

Using all possible combinations considering selected assumptions, 1689 scenarios in total have been run. Results are presented in Table 4 and Figure 4.

Table 4. OLC calculation results.

in k€	SB	IV	AV	DP	CTV	OLM	MC	OLC
Min	1,200	6,000	-	-	2,720	400	400	16,720
Max	4,800	96,000	43,200	115,200	34,272	2,880	2,880	256,032
Average	3,000	37,500	7,000	28,000	13,090	1,400	1,400	91,390

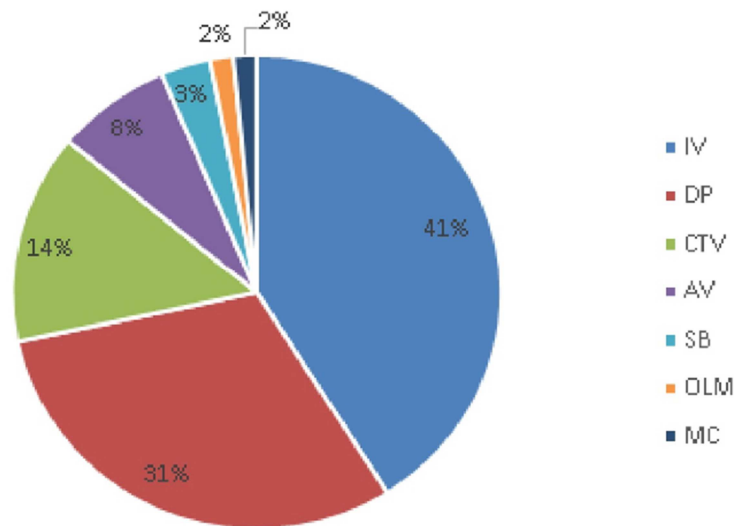


Figure 4. OLC average distribution costs.

National Renewable Energy Laboratory (NREL) [36] is proposing a simplified model to calculate LCOE. The application of LCOE is always accompanied by a great number of assumptions that can be significantly different from project to project. This is challenging and in order to cover a broad range of projects, a large number of scenarios have been run based on a selection of assumptions. Set of variables and parameters necessary to calculate the LCOE simplified expression is described in Table 5.

Table 5. LCOE calculation parameters.

Parameter	Formula name	Selected assumptions	Unit	Source
Overnight capital cost	OCC	3,500 4,000 4,500	€/kW	Adapted from: [12], [18], [20], [21], [22], [25] and [26].
Fixed operation and maintenance cost	OMC	100 150 200	€/kW-year	[12], [20], [22] and [28]
Period	n	25	years	[7]
Discount rate	i	3	%	[36]
Capacity factor	CF	45	%	[20]
Capital recovery factor	CRF	N/A	%	[36]
Turbine power rating	TPR	2; 4; 6; 8	MW	[35]

Simplified LCOE is calculated as follow

$$sLCOE = \left[\left(\frac{OCC \times CRF + OMC}{8760 \times CF} \right) \right] + (fuel\ cost \times heat\ rate) + variable\ O \ \& \ M\ cost \quad (3)$$

For this study, the following costs have not been used as this can be considered constant for the simulation, hence, no impact on sLCOE variation with

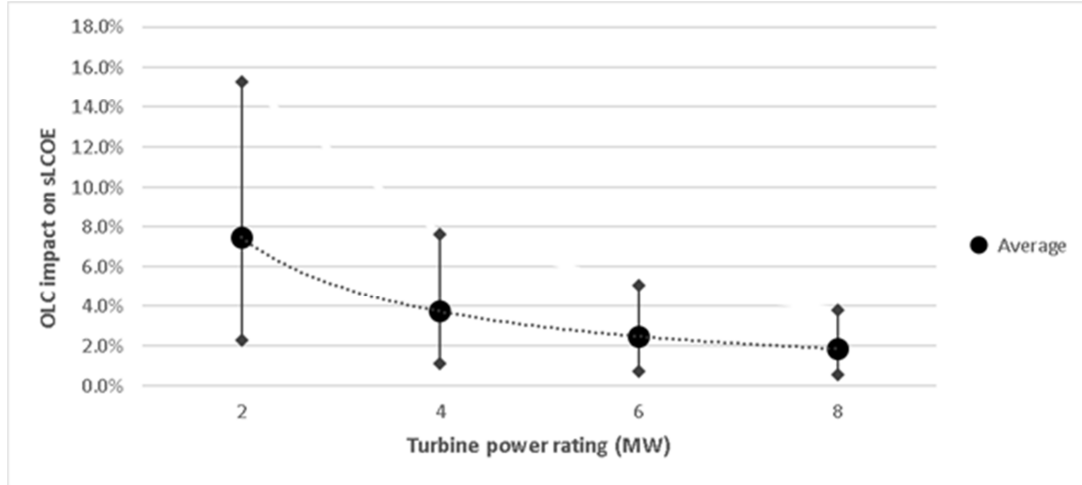
$$(fuel\ cost \times heat\ rate) + variable\ O \ \& \ M\ cost \quad (4)$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (6)$$

The following formula has been finally implemented:

$$sLCOE = \left[\left(\frac{OCC \times CRF + OMC}{8760 \times CF} \right) \right] \quad (5)$$

Using all possible combinations, 756 scenarios in total have been run. For each scenario, corresponding OLC result previously found was subtracted to capital cost to calculate the impact on sLCOE. Results are presented in Figure 5.

**Figure 5.** OLC impact on sLCOE function of turbine power rating.

In order to compare results obtained with NREL model, another simulation was conducted with Megavind Model [37]. LCOE model available from Megavind populated with fictive data was used and developer post-tax formula was considered. In this example, a 4MW turbine is considered and CAPEX cost values were adjusted with corresponding OLC results previously found. OLC impact on Megavind LCOE is found to be between 1.8% and 6.8%, with 4.2% in average.

Considering Figure 5, it can be concluded that OLC may represent from 0.6 to 15.3% of LCOE. Megavind Model

results indicate approximately similar impact compared to NREL model for a 4 MW turbine (4.2% average with Megavind model compared to 3.7% average with NREL model). This provides comfort in results found.

4. Discussion

OLC calculation gives an indication on the main costs related to offshore logistics during construction and can help to prioritize improvements efforts. Figure 4 shows that installation vessel cost is the most important in average

(41%), followed by DP vessel (31%) and CTV costs (14%). In order to explore research question [Q2], the present chapter discusses LCOE cost reduction opportunities concerning offshore logistics during wind turbine construction phase. Four categories from existing literature are evaluated and classified. These categories are in particular applicable to improve IV, DP and CTV costs, identified as the main cost drivers for offshore logistics during construction:

Improving weather limits to reduce waiting on weather costs: Increasing offshore operations weather limits is a topic considered to reduce waiting on weather time and in consequence offshore logistics costs. For example, Irena [12] recommends increasing maximum wind speed at which installations may be completed. Such improvement could be achieved by better technical lifting and improved vessel capabilities [38.] Concerning lifting, one of the more restrictive operations during construction is lifting the turbine blades, which are sensitive to wind. Improvements have been made already to increase weather conditions range in which blades can be lifted by installation vessel [9]. In 2015, High Wind NV introduced a boom lock system, which can be fitted to cranes to provide stability for lifting operation in winds averaging 15 meters per second (m/s). Siemens (2014) also developed a new lifting frame for its blades that allow for operation in average wind speeds of up to 14 m/s and can automatically connect and disconnect from the blade, removing the need for manual intervention. By increasing operability from the estimated 8 m/s to 12 m/s limit in 2012, these innovations are reducing downtime related to weather for an installation vessel and in consequence reducing project schedule and cost as well as construction risk. Research and further improvements on this topic are therefore of high interest for the industry. Concerning vessel capabilities, Berger [39] expects further innovation and specialization of vessels for offshore wind industry. While skills and equipment from the offshore oil and gas industry can be used in offshore wind, there are important differences and dedicated vessels are preferred. New crew transfer vessels dedicated to offshore wind industry are gradually being introduced, such as surface effect ships, as example, Wavecraft vessels, which increases vessel speed from 20 to 35 knots and increases the limit on technician transfers from 1.5 m significant wave height (Hs) to 2.5 m Hs. For projects that are at greater distance from port, service operations vessels are considered such as Esvagt and Ulstein Verft [9]. These vessels are designed to be able to transfer personnel to wind turbines via smaller crew transfer vessels but most importantly via motion-compensated gangways. Weather-related downtime is estimated to be reduced from 40- 45% with regular crew transfer vessels to 10-15% with such support operation vessels [40]. Concerning installation vessels, trend is to use larger and more powerful ships in order to utilize the economies of scales of larger turbines [22] and allowing more turbines to be transported and installed in one trip [17].

Minimizing work offshore and improving processes: Adaptation of installation processes and optimized installation methods are expected to reduce offshore wind LCOE [20, 22].

Vis et al. [41] recommend a pre-assembly strategy that presents the optimum choice between the lowest number of lifts possible and the maximum number of turbines that can fit on a vessel. Assembly strategy has an impact on the installation vessel costs. The more preassembled components, the less lifts necessary offshore, the shorter it will take to install the turbine and the less work to do offshore. The same work to be done is relatively cheaper onshore compared to offshore [24]. Shifting several offshore construction operations onshore or to port is also underlined by IRENA [12]. Another beneficial method is the offshore transfer of hardware from feeder vessels to jack-up installation vessels, avoiding the need for these high-cost vessels to return to port to collect another batch of turbines [13].

Implementing an economy of scale: Berger [39] indicates that larger wind farms enable cost reductions from scale economies and the mobilization and demobilization of expensive offshore transport and installation equipment. According to the Crown Estate [20], even with no further innovation, the shift from 4 MW to 6 MW turbines will reduce installation CAPEX per MW by up to 30% (up to 45% if moving from 4 MW to 8 MW turbines). This is in line with results from Chapter 3: Figure 5 indicates that wind turbine power rating has an influence on OLC impact on LCOE. The higher the turbine power rating, the lower the OLC impact. This is confirmed by the current trend to install larger wind turbines [9]. Offshore wind turbines size currently installed is 4 MW and most recently installed wind turbines in 2018 were over 5 MW [35]. Model results could be explained by the fact that no additional operational time was considered with increasing offshore wind turbine power rating. In other words, offshore logistics costs sensitivity to wind turbine power rating is low with this model. However, it could be interesting to evaluate such influence of power rating, especially installation vessel capability may reach some limitations (deck size, crane load capacity, nominal load capacity).

Optimizing vessel use: Scholz-Reiter [42] identified installation vessels as the bottleneck in wind farm installation processes. Their utilization should be as high as possible and they should be used in the most efficient way. Lange et al. [43] proposed for example decision support simulation tool for logistics strategies during the offshore wind farm construction phase. These simulations can help to use the available weather windows at sea optimally and deploy the expensive installation units efficiently. This optimization vessel use research topic is further developed by Chartron et al. [44, 45].

5. Conclusions

Offshore wind industry is challenged to improve its LCOE and logistics appears to be a key element in cost reduction potentials. Despite the limitations that have been highlighted, this paper has evaluated specifically what could be the share of offshore logistics in particular during wind turbine construction. From literature, it appears to represent around 1.2% of LCOE. With a bottom up

approach, it could be evaluated with broader range between 0.6 and 15.3%, depending on the wind turbine power rating. However, if we disregard the 2MW wind turbine, which is not anymore the type of turbine being installed, offshore logistics share could be currently evaluated with a range between 0.6 and 7.6% of LCOE. It has also been demonstrated that the higher the wind turbine power rating, the lower the offshore logistics impact on LCOE (as example, from 0.6 to 3.8% only for 8 MW). Such results answering to research question [Q1] also offer guidance for researchers and practitioners dealing with the subject, giving a better understanding of the real impact of logistics during offshore wind turbine construction.

In terms of implication, this paper reveals some priorities and provides some indication on how to reduce offshore logistics costs. Increasing weather limits to reduce waiting on weather costs, minimizing work offshore, improving processes, using economy of scale and optimizing vessel use are areas identified to reduce this LCOE share and pave the way to answer research question [Q2].

In order to straighten results found, a continued research agenda should consider the following topics: gather offshore logistics costs during wind turbine construction phase on actual projects to confirm conclusion, follow cost trends of actual logistics costs and focus on areas of improvements identified to reduce costs.

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