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The Role of Logistics in Practical Levelized Cost of Energy Reduction Implementation and Government Sponsored Cost Reduction Studies: Day and Night in Offshore Wind Operations and Maintenance Logistics

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Abstract: This paper reveals that logistics make up at least 17% of annual operational expenditure costs for offshore wind farms. Annual operational expenditure is found to vary by a factor of 9.5, making its share of levelized cost of energy for offshore wind range from 13% to 57%. These are key findings of a 20-month research project targeting cost reduction initiatives for offshore wind systems. The findings reveal that cost-out measures are difficult to implement due to cultural differences. Implementation efforts are rendered by personnel located offshore in a harsh sea environment which is in stark contrast to the shore-based office personnel who develop studies directing cost reduction efforts. This paper details the company motivation to join industry-wide cost reduction initiatives. A business case for offshore wind operations and maintenance logistics yielding 1% savings in levelized cost of energy is included on how to expand working hours from daytime to also work at night.

Keywords: operational expenditure (OpEx); operations and maintenance (O&M); levelized cost of energy (LCoE); offshore wind; cost reductions; logistics; shipping; supply chain management (SCM)

1. Introduction

In this paper, new research is presented which indicates that the often government sponsored levelized cost of energy (LCoE) policy studies for offshore wind cost reductions [1–3] are hard for industry practitioners to understand, let alone implement. The research indicates that operational expenditure (OpEx) is the cost component within wind farm LCoE calculations that represents the single most significant variance in different studies and reports. This OpEx variance has a big impact on the overall project LCoE as OpEx is a recurring cost item during the 20–25 year operational phase of an offshore wind farm (OWF). Operations and maintenance (O&M) costs make up approx. 50% of offshore wind OpEx and the research findings presented in this paper show that logistics makes up at least 34% of O&M costs and consequently at least 17% of OpEx costs. Logistics is therefore a key cost factor which deserves more focus at a policy level, in academia, and from practitioners.

The research findings include an analysis of eleven LCoE cost-related studies and reports which are made, often at the request of, and with funding from, governments, in order to help the subsidized offshore wind energy industry focus on reducing costs to make wind competitive compared to other energy forms [4–6]. Although extensive experience has been amassed since the first wind turbines were erected offshore in the early 1990s in Europe, installing and operating wind power plants in the ocean is no easy task and the pivotal role of shipping and logistics is exacerbated offshore compared to similar operations when performed on land [6]. The analysis of the eleven LCoE cost-related studies and reports examined in combination with the actual learnings from the parallel case study efforts make this research unique and novel. This research provides the most in-depth analysis of LCoE cost-related studies and reports hitherto, the research couples the analysis of the LCoE related studies and reports with a practical cost-out case study angle for the first time, and through a detailed logistics analysis the research presented in this paper illuminates some of the challenges which make offshore wind cost calculations very difficult to compare as well as contrast.

The research design is based on the findings from active participation in a 20-month industry practitioner focused offshore wind LCoE cost reduction initiative in Denmark [7] which serves as the practitioner case study part of this research. The offshore wind industry LCoE cost reduction initiative case study is being facilitated by a Danish not-for-profit and non-government offshore industry member association, Offshoreenergy.dk (OE). OE is a national cluster organization and innovation network for the offshore industry in Denmark [8]. As part of the research project, and the case study developed within the actual cost reduction initiative, a group of offshore wind energy related companies voluntarily got together during 2014–2017 via OE. The companies met from August 2014 to jointly work on implementable cost-out initiatives for the offshore wind industry and it was felt that it was justified to join the initiative as the learning institution representative. By December of 2014, a total of five work streams for potential cost reductions had been selected by the industry practitioners, using the Danish 400 mega-Watt (MW) Anholt OWF as a baseline case [9]. Logistics emerged as a significant theme from practitioners to wish to focus on and as such, 3 of the five work streams had to do with logistics.

In the following, one of the business cases actually developed from the practitioner case study will be presented in detail in order to demonstrate a tangible roadmap from desktop and shore-based government sponsored LCoE studies to practical offshore implementation at a company level. As part of the analysis of the business case, the case study research findings are presented in terms of the reasoning and motivation on the part of the companies for joining this cross-industry initiative. Inherently built-in cultural difficulties will be presented because the research unveiled that such differences exist between shore-based offshore wind personnel and personnel operating offshore or at operational sites in ports to actually execute and implement the cost savings. Findings from the case study will be presented regarding benefits and disadvantages caused by assets and skilled personnel moving from the offshore oil and gas (O&G) industry, often referred to as the petroleum industry in academic contexts, see e.g., [10], to the offshore wind logistics industry.

Throughout the case study efforts, LCoE savings were encountered for offshore wind expressed as a percentage by different company representatives. As company representatives were questioned in more detail and the topic researched further from a perspective of what the cost savings share was indeed measured as a percentage of, significant ambiguity was found in the unit of analysis applied by practitioners, consultancies, government studies, and organizations alike. Challenges existed with the assumptions, calculation process, and methodology behind the different studies and reports providing the basis for the calculations. Consensus did not exist on how to calculate savings due to many different methodologies being used which individually seemed to make sense but do not leave room for comparison. Findings are therefore presented on what causes the annual OpEx component of LCoE cost calculations for offshore wind to vary by up to a factor 9.5 in government funded LCoE studies. Being only one of four cost components in the LCoE calculation [11], the research indicates that the relative OpEx share of total LCoE may vary from 13% to 57% over the life-cycle of an OWF project as a result of the variance within OpEx itself. Finally, research findings are presented which indicate that logistics makes up at least 17% of OpEx costs but could make up as much as 32% depending on how individual cost items are measured and described.

The geopolitical case study context is that of the oil price dropping to a level of United States Dollars (USD) 22.48 per barrel in January 2016 compared to its June 2014 high of USD 110.48 [12].

This has caused distortion in the O&G industry [13]. Because of the fuel component of LCoE calculations [14], oil-generated energy has therefore become relatively cheaper making the journey for offshore wind to reach parity with fossil fuels even steeper [5]. Significant job creation is expected within the offshore wind industry over the coming years [15] and some of the world's largest fossil fuel companies are now seen to be implementing strategies to actively "diversify into low-carbon energy" [16–18] with wind as a strong contender based on e.g., resource efficiency [19]. Idle O&G assets and personnel are seeking deployment in the offshore wind logistics arena which may lead to lower costs and increased industry maturity within wind O&M logistics [20]. Irrespective of the possible contribution from the O&G context (e.g., learnings from O&G in the Gulf of Mexico described by Kaiser and Snyder [21] which could be applied to offshore wind in the North Sea), it is critical for further diffusion of offshore wind as an important renewable energy technology that it becomes cost competitive with other energy forms in terms of comparable LCoE [22]. This ought primarily to be done through cost reductions made by the offshore wind industry itself and with logistics accounting for at least 18% of LCoE within offshore wind [22] according to the definition of offshore wind logistics [22], the area of logistics as researched for the offshore wind O&M life-cycle phase in this paper represents a major cost reduction opportunity. The real-life industry-wide OE project in Denmark is an interesting academic research project and several key reasons served as the motivation to get involved:

- Going it, it was estimated that this particular industry practitioner initiative had a good chance to succeed in producing tangible cost-out initiatives due to the relatively narrow scope of O&M logistics.
- It was important to craft a research design which could actively contribute to the steering of the government sponsored and policy level cost-out studies/reports towards a practical trajectory which may actually be implemented by companies in real life, onshore as well as offshore.
- A strong desire existed academically to obtain information about O&M logistics from the participating companies and in return contribute with a scholarly perspective to the industry practitioner dialogue and process.

Geopolitically, the journey towards a wind energy electricity source being competitive in its' own right, compared to other energy sources [5], has been made more challenging as a result of the drop in the oil prices. At the time when the practitioner case study opportunity emerged, the need for cost reductions within offshore wind had therefore become even more pronounced which was the final academic justification to get actively involved.

In the next section, the research questions, the key academic terms, and an introduction to the case study will be presented. In Section 3, the results of the case study will be presented followed by Section 4 with the discussion. To conclude, Section 5 sums up the findings and provides input for further research within the area of O&M logistics and LCoE reductions for offshore wind.

2. Research Objectives, Academic Definitions, and Case Study Introduction

Measured in comparable LCoE, offshore wind is not competitive with other energy sources [5], with other renewable energy forms [23], nor can offshore wind projects survive without government subsidies [5–7,24]. Proponents of offshore wind argue that other factors should be considered when evaluating whether to continue offshore wind diffusion. Such factors include job creation [15], CO_2 emission cost avoidance [25], low offshore wind subsidy levels compared to subsidies for dark energy technologies such as coal [5], [26] (p. 7), and the issue of avoiding to take up scarce land areas onshore [27]. Conversely, opponents of offshore wind diffusion argue that animal life is disturbed, that near-shore offshore wind turbines distort the view of humans, that wind power production cannot be stored, that the grid cannot handle an energy form which is intermittently on/off, and that the subsidy levels are too costly for tax payers.

When comparing LCoE across different energy sources [5], renewable energy forms do not depend on a particular type of fuel to generate electricity and heat [28]. Traditional fossil fuel based energy sources such as coal, oil, and gas do depend on fuel. For fossil fuels, the fuel itself therefore makes up a large portion of the LCoE life-time calculation for these energy forms. Within the European Union (EU), most energy research and development funding is by far directed into nuclear fission while offshore wind receives the least attention and funding [5]. Within the EU, fossil fuels such as coal enjoy far more government subsidies than renewables such as offshore wind [5]. Globally, fossil fuel subsidy levels stood at USD 490 billion against renewables of USD 135 billion in 2014 [26] (p. 7), [29]. Wind power was furthermore found to be the only power source not presenting a security risk to the EU [30] which is important from a geopolitical perspective.

Government studies of LCoE for offshore wind in Denmark [31], the United Kingdom [1], Germany [2], and across industry coupled with academia [3] provide definitions of LCoE for offshore wind and create break-downs of the end-to-end life-cycle cost composition of an OWF [22]. Consultancies [16,32–34] and different wind energy associations [15,35–37] provide historical data on actual offshore wind diffusion along with scenarios for deployment and costs going forward as forecasts until 2020, 2025, 2030, and 2050. Especially the government LCoE studies for offshore wind also point to possible areas of potential cost reduction opportunities. The government LCoE studies are often made with extensive input from industry practitioner representatives [1,2].

2.1. Research Objectives

From a supply chain perspective, an OWF can be divided into four distinctively different life-cycle phases, i.e., Development & Consent, Installation & Commissioning, Operations & Maintenance, and Decommissioning [7,38]. Logistics makes up a significant portion of the cost of each of these four life-cycle phases and is often embedded or hidden in other cost items not captured by current LCoE models [22], let alone the O&M life-cycle phase with downstream implications (e.g., to failure mode and effects analysis [39]). This paper presents an in-depth review of logistics aspects of the O&M life-cycle phase. The O&M phase starts [40] (p. 4) when the construction of the OWF has been completed including full commissioning of the different wind turbines and offshore sub-station as well as grid connection [7,38]. Typically, the OWF can operate for 20–25 years before it needs to be decommissioned including site abandonment/restoration [1,2,41]. The annual OpEx costs to manage, administer, insure, operate, inspect, maintain, repair, and make replacements within the OWF are included in the LCoE calculations. Within the OpEx calculations, the logistics cost component had qualitatively been estimated at 26% by the world's leading OWF operator [22]. From this point of departure, this research project was conducted with the following upfront propositions and motivations:

(a) Major LCoE models and cost reduction initiatives for offshore wind [31] (pp. 1–3) are crafted by a certain type of people, organizations, and companies. These more conceptual studies have a certain audience and are generally characterized by a high degree of complexity, rigor, and financial backing. Is it indeed feasible for the industry practitioners to implement the identified LCoE savings opportunities from these government LCoE studies?

(b) The harsh sea environment within offshore wind is not native for offshore wind inasmuch as wind turbines were first put up on land and subsequently moved into the sea. Do cultural differences exist between shore-based personnel creating the government LCoE studies and the offshore personnel of the industry practitioners required to implement many of the actual cost-out savings needed for LCoE to factually decrease?

(c) The major government sponsored LCoE and cost reduction studies are very broad and cover the entire life-cycle of an OWF. These LCoE studies often involve a vast range of consultancies as well as management level industry practitioners and maintain a somewhat high-level perspective [31] (pp. 1–3). Could a specific life-cycle phase, such as O&M, be examined in detail and generate practically implementable cost-out opportunities that can realistically be implemented by industry practitioners to reduce the cost of offshore wind?

2.2. Offshore Wind Operational Expenditure

A good definition of OpEx within offshore wind has been provided in a study for the UK Renewables Advisory Board [40] (p. 4): OpEx "... includes all expenditure occurring from immediately after point of takeover, whether one-time or recurring, related to the wind farm, measured on an annual basis. Excluded are expenses inherent to the operation of the operators business but not directly related to the operation and management of the wind farm". OpEx is sometimes referred to as variable costs [35] (p. 45), [42], operating & maintenance costs [43], operating costs [1], operations cost [2], or operation, maintenance, and service costs [44]. OpEx may be broken further down to separate costs between "physical maintenance" and "non-physical services such as insurance" [14]. Some studies include added dimensions such as grid transmission charges and seabed rent [1] whereas others point out that present calculation regimes do not include key parameters such as lost revenues due to downtime caused by ineffective operations [45] (p. 365) or logistical factors such as weather windows and vessel availability [46] (p. 5).

From an accounting point of view, the recurring operating costs (OpEx) of a project are deducted from the income in the profit/loss statement of the project on an annual basis. Conversely, the initial capital costs (CapEx) of a project are put on the balance sheet of the project when incurred and subsequently depreciated. Cash flows and profitability are therefore treated very differently accounting wise [47] (p. 119). To be able to understand the value of any project at the time of making the investment decision, the corporate finance perspective prescribes that net of the future revenues less the future costs is discounted back to the time of making the investment decision using a discount factor often referred to as the weighted average cost of capital (WACC). CapEx and OpEx are therefore important terms to fully understand when making investment decisions [47] (p. 121).

As a phenomenon, LCoE focuses on the cost aspect of some of these same accounting and corporate finance terms [1] (p. vii) and as also described by Poulsen and Hasager [22]. The goal of the LCoE measure is to be able to compare the lifetime costs by electricity output unit of different energy producing plant types (for a good example of how to compare costs, see for example Namovicz [48]). According to the Megavind [3] LCoE calculator, development expenditure (DevEx), CapEx, OpEx, and site abandonment expenditure (AbEx)/decommissioning costs make up the cost factors used in LCoE calculations for offshore wind. From the research presented in this paper, OpEx is the LCoE cost component with the single most variance between different studies, reports, and calculations. This variance has a big impact on the overall project LCoE as OpEx will incur during each year of operations over the entire O&M life-cycle phase of the project which is usually 20–25 years for offshore wind.

2.3. Offshore Wind Operations and Maintenance

Originally, maintenance as a concept can be traced back to work performed by craftsmen before the Industrial Revolution. Later in history, Admiral Nelson's flagship, HMS Victory, was carefully maintained to an extent where almost all of her parts were replaced more than one time. The HMS Victory used timber corresponding to some 40 hectares of wood meaning that the effort to fell this wood, ready the timber, and ultimately replace it made the vessel a very valuable asset worthy of the expansive maintenance [49]. A review of maintenance history and maintenance management literature based on a number of books published and extensive consulting efforts on the topic was presented in London and cited by many [50]. Another study concluded that the concept of maintenance has evolved through four phases from being "a necessary evil", to internal company focused "technical specialization", through to being a "profit contributor", to finally becoming partnership driven with "positive cooperation" [51].

An early O&M example from the military context was the need for having US airplanes operational at all times for air combat during World War II which required intensive maintenance and repair (M&R) after completed missions in order to get the planes airborne again as soon as possible. The detailed need for such M&R efforts had to be balanced by researchers considering that the war time life-cycle of the airplanes was short and that "major parts" would therefore not need maintenance [52].

M&R understood as "maintenance & repair" is often used as a separate academic theory stream in different fields such as construction [53] and the electric industry [54]. Competing theory streams use the same abbreviation of "M&R" differently, e.g., maintenance & renewal [55], maintenance & replacement, maintenance & rehabilitation [56].

Within the O&G industry, O&M is often referred to as inspection, maintenance, and repairs (IMR) thus including the inspection function as a means to diagnose the problem at hand [34]. Another commonly used abbreviation [10,57,58] within sub-sea O&G is inspection, repair, and maintenance (IRM). Different theory streams include a wider array of functions such as inspection, repair, maintenance, and replacement (IRMR) in their definition [59]. The different groupings of several lines of thought into different theory streams make literature searches and comparisons of academic literature difficult across industries and one recent literature review found a total of 10 different maintenance management techniques within the many groupings of tasks [60]. Each maintenance management technique is either quantitative or qualitative in nature and each technique such as Total Productive Maintenance (TPM) is described extensively in literature and across different industries (for TPM as an example, please refer to e.g., Nakajima [61] and McKone, Schroeder, and Cua [62]).

O&M for OWFs can be split into four distinctively different generations of evolution according to Petersen [63]: "Run to failure", "systematic maintenance", "condition based", and "failure elimination". An offshore wind O&M taxonomy built on several sources has been crafted by May [46].

2.4. The Logistics Share of Offshore Wind Operations and Maintenance Costs

The logistics share of OpEx or O&M costs in offshore wind is not clearly defined in literature, nor in various cost reduction/LCoE studies Whereas the offshore wind industry is a young and somewhat immature industry [22,45,64], the topic of logistics within offshore wind O&M academic literature has been covered at operational, tactical, and strategic levels as summarized by Shafiee [65] and operations reviewed from a perspective of the wind turbine generator (WTG) and impact on the grid [66,67]. As determined in a separate study [22], logistics itself was previously not defined for offshore wind nor had a share of LCoE been attributed to logistics. The offshore wind logistics definition of that study [22] (p. 13) encompasses the O&M logistics chain and when prior academic work on OpEx cost shares of LCoE is reviewed as a starting point, it was concluded that several recent and very extensive studies [46] (p. 5), [63] (p. 3) were based on relatively few and quite similar sources. Upon reviewing these sources, it was found that one source [42] based its estimate that OpEx equals 30% of LCoE on a single study on offshore wind from 2007 but was very rich on onshore examples. Another source [68] was rather specific on OpEx cost items but contained a variance between the referenced minimum and maximum monetary values equal to a factor 2.3. Therefore, it was found to be necessary to scope and define what O&M logistics is for OWFs and perform a more detailed study of this phenomenon. This tallied with a prior recommendation for researchers to perform further research in the form of specific quantitative studies of the logistics costs for OWFs [22] (p. 20). In performing such a quantitative study as part of this research, with focus on logistics for the O&M life-cycle phase in particular, a total of eleven studies were analyzed in detail. These particular studies were selected because they had previously been included in related work scopes [1,2], [31] (pp. 1–2), [34] (p. 3), [44], because they were cited by major recent academically related O&M research efforts (such as May [46], Petersen [63], and Brink, Madsen, and Lutz [69]), or because they have been broadly recognized by academicians and/or practitioners to be of major relevance to the offshore wind industry [35,40,68,70,71]. These eleven different studies were performed by and on behalf of different—often government—constituencies from 2007 through 2015 (see Table 1 below for a high-level presentation of the eleven studies). Similar to earlier conclusions by e.g., Blanco [42] (p. 1374) and Dinwoodie et al. [72] (p. 8), it was determined as part of this research that the studies are very different in their fundamental assumptions and methodology including key parameters such as OWF capacity in MW and WTGrating. It was also concluded that none of the studies have a clear logistics definition nor does any single study break down logistics as a separate OpEx/O&M cost item.

Table 1. Analysis of inclusion of O&M logistics in eleven major LCoE related studies.

Year	Study	Cost Itemization
2015	Megavind 2015 LCoE calculator [3]	Built-in template data based on 400 MW OWF modeled after Danish Anholt OWF. Contains up to 15 OpEx/O&M cost line items with 7 pre-suggested types of which none can be attributed to logistics
2015	Douglas-Westwood offshore wind global forecast 2025 [34]	Forecast up to 2025 of global OWFs. Defines OpEx as a percentage range of CapEx costs. Breaks OpEx down into 6 cost items of which 3 can be directly attributed to logistics
2014	BVG Associates UK Supply Chain Assessment [44]	500 MW OWF using 6 MW WTGs. Operation, maintenance, and service costs defined as 39% of lifetime costs. Operation, maintenance, and service costs split between minor service and major service with cost items defined but not further broken down
2013	Prognos and Fichtner Group Germany cost reduction [2]	Extensive study with 3 different sites ranging from 320 to 450 MW OWFs modeled with 4, 6, and 8 MW WTGs based on distance to shore and water depth. O&M costs modeled for different scenarios and costs provided per MW per year. Insurance costs are separated
2013	GL Garrad Hassan offshore wind O&M spend guide for Scottish Enterprise and The Crown Estate [68]	500 MW OWF using 6 MW WTGs. OpEx cost items broken down into 18 line items of which 5 can be fully attributed to logistics. OpEx provided per line item
2012	The Crown Estate UK cost reduction pathways study including sub-studies in work streams [1,73]	Extensive study with 4 different 500 MW sites modeled based on distance to shore, water depth, and wind speeds. Operating costs estimated at 33% of total LCoE [1] (p. 15)
2011	Deloitte study on offshore wind competitiveness for Denmark [31]	Study considers O&M to be out of scope [31] (p. 4)
2010	BVG Associates for UK Renewables Advisory Board offshore wind sector value break-down report [40]	500 MW OWF using 5 MW WTGs. 5 O&M cost items discussed including operation, maintenance, and license fees. One cost item is port activities. Costs also segmented into labor, materials, and other where "other" includes vessels and cranes.
2009	European Wind Energy Association report on the economics of wind energy [35]	The report is largely built based on onshore wind technology and findings except one section on offshore wind based on 2 MW WTGs and a park capacity of 160–200 MW. The onshore wind O&M break-down has 5 line items of which none can be attributed to logistics. Offshore wind O&M defined as a cost per MW hour (MWh).
2009	Vattenfall VindKraft third annual technical report for Kentish Flats OWF [71]	30 WTG OWF with 3 MW capacities. 6 OpEx cost items including administration, insurance, lease & rent. O&M under warranty from OEM. Estimated OpEx costs broken down per line item.
2007	Offshore Design Engineering OW cost study for UK Department of Trade and Investment [70]	Early study based on 30 WTGs each with 3.6 MW capacities, near shore. 5 OpEx cost items of which 4 were WTG related and 1 related to vessels. OpEx costs set as a percentage of CapEx.

The most detailed OpEx cost itemization was found in the study made for Scottish Enterprise and The Crown Estate [68]. In this particular study, OpEx costs have been broken down into 18 different cost items which have been separately described in the study (see Table 5). Following overall logic of other studies for The Crown Estate at that time [1,44,73], costs for a 500 MW OWF with a WTG rating of 6 MW has been modeled by GL Garrad Hassan [68]. Of the 18 cost items, it was possible to attribute five fully to O&M logistics.

2.5. Case study Introduction

Leading OWF developer and operator DONG Energy Wind Power set out to reduce LCoE for offshore wind by 40% in 2020 compared to 2012 costs [22]. This was supported by a number of EU governments [1,2] as well as the EU Commission. In addition, many different initiatives were started by academia [64], practitioners (for example the Cost Reduction Forum of OE which is the practitioner related topic of this paper), and academia in collaboration with practitioners [69] in order to support this goal to reduce cost. DONG Energy Wind Power has committed to delivering the cost reduction targets for two Dutch OWF projects with a rated capacity of 700 MW [74] as construction of these OWFs will be completed by early July 2020 with an option to extend the completion up to no later than

July 2021 [75]. Similarly, Swedish utility Vattenfall has committed to delivering the Danish Vesterhav Syd, Vesterhav Nord, and Kriegers Flak OWFs by winning even lower auction bids in Denmark [76].

As an organization, OE is a non-profit cluster organization with members primarily from the small- to medium sized enterprise (SME) segment. OE focuses on offshore and separates between O&G and renewables. Offshore wind is the main activity within renewables for OE. OE is based in Esbjerg, Denmark which is the major European hub port for wind energy. Some of the key goals of OE are to facilitate strategic collaboration to create innovative solutions to promote the Danish offshore industry, to foster internationalization, and to act as an enabler when it comes to funding applications for industry, government, and/learning institution collaboration. To support the offshore wind industry's attempt to cut costs by 40% in 2020, OE launched the Cost Reduction Forum (CRF) in August, 2014. This was done after extensive consultation with the offshore wind industry based in Denmark and internationally. Whereas each organization consulted felt that they were doing what they could in their own right regarding cost reductions for offshore wind, especially the SME members of OE felt that a lot more tangible results could be achieved if an industry-wide effort spanning all parts of the offshore wind market could be put together. OE set out to do so and in designing the set-up with the companies, it was important for the CRF initiative to have a learning institution representative actively join up and participate in the work process. This was done in the form of a case study [77] with the detailed methodology applied being a combination of student learning project supervision, participant observation, interviews, focus groups, and action research [78–80].

From January, 2015 the academic involvement was increased along with the active participation in the leadership of one of the five specific work stream working groups tasked to review potential cost reductions within the area of O&M logistics. Following two series of intensive meetings in the practitioner working group, five specific O&M logistics cost-out initiatives were in different stages of completion by the time academic case study participation was terminated in April 2016 (see Table 2 for an overview of the five cost-out initiatives).

In total, 30 organizations comprised the main CRF member organizations (see Table 3).

Table 2. The five cost-out initiatives for O&M logistics.

Initiative Name	Cost-Out Initiative Description	Idea Agreed
Lean in O&M logistics	Eliminate waste from quay side up to in within the offshore wind farm site	First series of meetings
Working 24/7	Adding a night shift to present daytime operations (12/7) during maintenance campaigns	First series of meetings (and the focus of this research)
Asset sharing	The sharing of vessels and helicopters between different offshore wind projects	Second series of meetings
Parts, tools, and consumables pre-planning	Optimization of advance packing of parts and tools including location of tools	Second series of meetings
O&M logistics vision 2025	Vision for the future of O&M logistics in both near shore and far shore context	Second series of meetings

Table 3. Main Cost Reduction Forum member organizations.

Utilities	OEMs	EPCi	Engineering and Design	Shipping and Trucking	Logistics and Forwarding	Ports	Suppliers of Manpower	Learning Institutions
DONG Energy	MHI Vestas	MT Højgaard	Rambøll Offshore Wind	A2sea	Blue Water Shipping	Port of Esbjerg	Apro Wind	Aalborg University
Vattenfall	Siemens Wind Power	Per Aarsleff	Blaaholm	Torben Rafn	Deugro	Port of Grenaa	Alpha Offshore	
E.On	Envision		Granly Engineering		Nils Winther		Total Wind	
	Bladt Industries		Thomas as				Global Wind Service	
	Semco Maritime		AH Industries Solutions				VB Enterprise	
			R&D					

From the time the case study coverage was initiated in August 2014 until coverage was terminated in April 2016, a total of 3 CRF meetings had been conducted as follows:

- 25 August 2014: Inaugural meeting and kick-off. Through a focus group set-up, rules of engagement established and the Anholt OWF chosen as a "base case" scenario to work from and ensure focus on tangible results [9].
- 2 December 2014: Brainstorm meeting. The 30 participating organizations could attend an OE facilitated focus group session. The focus group session led to the establishment of five different working groups, each dealing with a single focus area on behalf of the CRF (see Figure 1).
- 8 October 2015: Progress review meeting. Progress from the working groups engaged with the five different focus areas was reported back to the CRF forum. Only working group 4 on O&M logistics (the group included in this paper) had made real progress. Other work groups were kicked off including Group 3 which had obtained separate public funding to progress in a more comprehensive manner to review installation and commissioning (I&C) logistics. Figure 1 below outlines the structure of the Cost Reduction Forum compared to the work groups working on the individual areas of possible cost reduction.

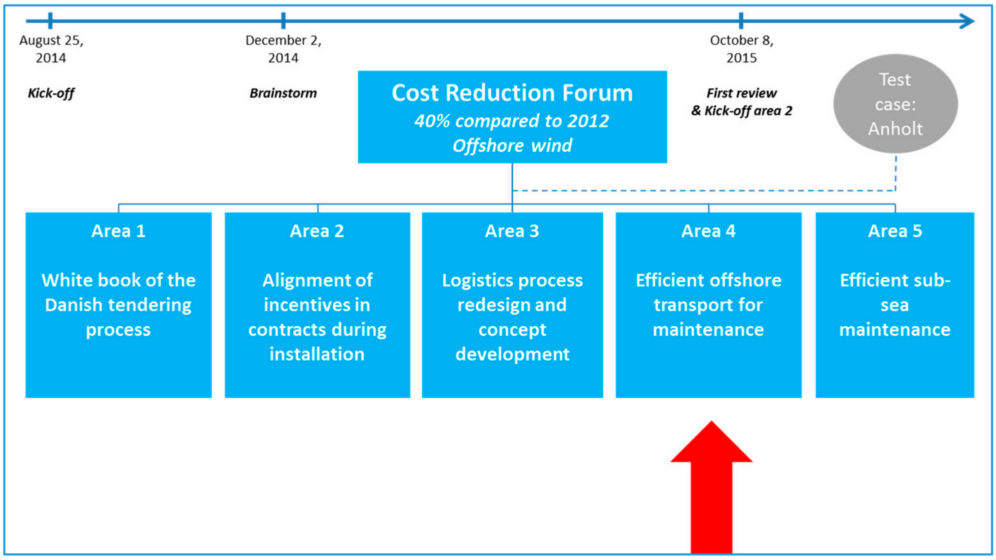


Figure 1. Offshoreenergy.dk Cost Reduction Forum structure including work groups.

The detailed research on potential cost reductions for offshore wind O&M logistics as reported in this paper is a direct result of the decision to actively join the work of CRF Group 4. The research team consisted of two researchers, both members of the CRF group 4 O&M logistics initiative. The Group 4 research design for the first series of meetings to generate cost reduction ideas and business cases was carried out in January and February of 2015 where an initial interview protocol was designed for open-ended semi-structured interviews [79]. During March 2015, coinciding with the European Wind Energy Association (now WindEurope) Offshore Wind 2015 conference in Copenhagen, a total of 18 interviews were carried out. The interview guide was specific in terms of focus on the logistics processes involved in the O&M phase of the OWF life-cycle and ideas for cost reductions. Fourteen of the interviews were carried out face-to-face and four additional interviews carried out by phone. The interviews were summarized in writing with a focus on cost reduction ideas which were highlighted. The initial interview summary interview process yielded a total of 36 cost reduction ideas within the area of O&M logistics which were reviewed by the researchers and further grouped during a workshop focus group.

Effectively, Group 4 had a very narrow O&M logistics focus and as such, it made sense that some of the main CRF member forum organizations took part in the Group 4 work and that particularly knowledgeable subject matter experts were invited to join as well (see Table 4). At the inaugural Group 4 O&M logistics meeting on 13 April 2015, a focus group setting was facilitated by OE to jointly review and qualify the 36 cost reduction ideas and the total number of ideas was increased to 44. The ideas were grouped into five categories and a delimitation session performed where only cost savings ideas from quay side up to and within the OWF site were deemed to be included for the group going forward. The findings from the focus group session were summarized in writing and shared with all participants for comments and edits.

Table 4. Specialized CRF Group 4 O&M logistics member composition.

Main CRF Forum Members Also Participating in Group 4	Specialist Firms in Group 4 (Rounds 1 and 2)
DONG Energy	Hvide Sande Skibs og Både Byggeri
Vattenfall	Dansk Offshore Transport
E.On	Valling Ship Management
Siemens Wind Power	Esvagt
A2Sea	Danish Yacht
DBB Jackup/Ziton	World Marine Offshore
Thomas as	Uni-Fly
Niels Winther Shipping	K2 Management
Port of Esbjerg	Maersk Broker
Aalborg University	Waypoint North/SeaState Aviation
	Siemens Service
	Oddfjell Windservice AS
	FairWind

Shortly after the Group 4 kick-off meeting, a follow-up meeting was conducted on 4 May 2015. At this meeting, two more ideas were generated and all ideas prioritized using a funnel technique with several criteria: Impact on LCoE, investment required, time need to implement the idea, alignment with the participating companies' own strategies, and probability of successful implementation. Three projects were chosen at the meeting for sub-work groups to focus on in detail: How to make the O&M logistics process more lean (the lean sub-group), how to work daytime and at night for preventive maintenance and repair campaigns (the 24/7 sub-group), and how to more objectively evaluate safety. The work performed was again summarized in writing and shared with all focus group participants. The lean and 24/7 sub-groups subsequently gained the most traction and were chosen as the projects to move forward with.

During August 2015, the lean and 24/7 sub-groups each met twice to perform more detailed work on how to practically realize the selected projects, selection of elements to be focused on in a business case, and detailed discussions about business case calculations. These meetings were smaller sub-working group meetings facilitated by OE and were more hands-on and practical in nature. Each meeting was summarized in writing and the results were shared with the participants for comments/edits. The business case documents were also included as they started to take shape from the discussions (mainly Microsoft Excel spreadsheet models). A subsequent online focus group meeting was facilitated by OE and supported by emails in order to jointly review and actively evaluate the results of the work crafted by the two sub-work groups working separately on the lean and 24/7 business cases. Additional focus was put on implementation planning, risk analysis, and an evaluation of the likeliness of the success of each of the projects. The business case documents were updated further and the overall discussions summarized and shared along with the business case documents to all participants.

Three extensive face-to-face business case review meetings were conducted as semi-structured open-ended interviews with selected key players in terms of actual operational knowledge. The three interview participants were carefully hand-picked from the team members of working group 4 based on their perceived ability to evaluate the process of generating the business cases, answer questions to fill in the last remaining assumptions for calculations, and also review the business case calculations themselves. A single interview protocol had been developed for this purpose of final validation and the questions were split between the interviewees.

The final versions of the business cases for lean and 24/7 were presented at the 8 October 2015 CRF meeting where the key CRF member organizations were represented. The progress of Group 4 including the lean and 24/7 business cases caused the main CRF member organizations to express satisfaction with the work efforts rendered thus far. An extended focus group session itself, the CRF forum entered into a review of the work results generated by Group 4 including detailed feed-back and comments to the working group members. A further brainstorming focus session about subsequent and "second series" of group 4 O&M logistics cost reduction ideas took place as part of the 8 October 2015 CRF meeting itself. Already on 26 November 2015, the second series of cost reduction business case working group meetings was kicked off with a focus group meeting to prioritize this new set of O&M logistics cost reduction ideas. More participating organizations had now joined and the meeting was facilitated by OE by splitting the meeting participants in 3 groups working on different methods to prioritize the cost reduction ideas. At this session, three ideas were selected for further focus thus taking the total number of business cases being worked on by Group 4 to a total of five (see Table 2).

Three of the organizations participating in the work efforts of Group 4 never really became actively involved in the detailed work efforts associated with building the business cases. Of the remaining 22 organizations, a total of 26 people were actively engaged and the organizational split was 38% top management, 38% middle management, 19% execution layer, and 4% site layer. In this paper, the 24/7 business case of extending working hours from day to night will be used as the representative example of the work efforts rendered within this practitioner case study.

3. Results

The results from this research are divided into two parts. One part is the empirical findings from the practitioner case study and the other part is the quantitative analysis of eleven LCoE related cost studies. To present ***the case study findings***, a detailed review of one out of a total five business cases has been included in this paper. This approach has been developed with an aim towards exemplifying work done in order to create practically implementable business cases useful for taking costs out of the logistics chain. The selected business case is that of working daytime and at night 24/7 instead of only during daytime. In the work to quantify the savings generated from the different business cases, ***eleven different LCoE related cost studies*** for offshore wind were analyzed with the goal to be able to quantify the savings as a percentage of either O&M costs, OpEx, or LCoE in an accurate manner. In doing this quantitative work, the first realization was that the unit of analysis utilized in the various studies differed greatly, e.g., OpEx measured as a percentage of CapEx [34,65], OpEx as a percentage of LCoE measured as a sum of the discounted lifetime electricity output (in MWh) [1], annual OpEx per kWh [35], total OpEx costs as a percentage of total lifetime costs [44], OpEx per MW per year [2], total OpEx costs per year for the OWF [3], or outright costs per OpEx line item [68,71]. One study on behalf of Scottish Enterprise and The Crown Estate concludes in terms of unit of analysis that O&M " . . . is best considered on a per turbine basis as costs tend to scale most strongly with turbine numbers, rather than per MW of installed capacity" [66]. However, other and more elaborate cross-industry studies on potential cost reductions in the UK [1] and Germany [2] used very complex scenario modeling with different WTG ratings, foundations, distances to shore, water depths, and wind speeds. Both of these studies [1,2] make use of OpEx costs measured by MW per year and on the basis of the complex scenario models providing a more representative view of the reality within offshore wind, it was decided to also utilize the OpEx/MW/year unit of analysis in the following.

3.1. Differences in the Dimensions Used for Calculations

Besides the differences noted in terms of the unit of analysis, it would seem that the different studies have evolved dramatically over time. This learning curve built into the study logic applied can be demonstrated by the different dimensions that have gone into the calculation of LCoE in the different studies. Apart from the macro level country LCoE differences such as whether the offshore sub-station is part of the national country level scope or that of the developer, as reviewed in earlier work [22] (pp. 4–6), a number of other differences in terms of dimensions applied for OpEx became clear from the detailed analysis performed of the eleven studies. Examples of differences in dimensions include:

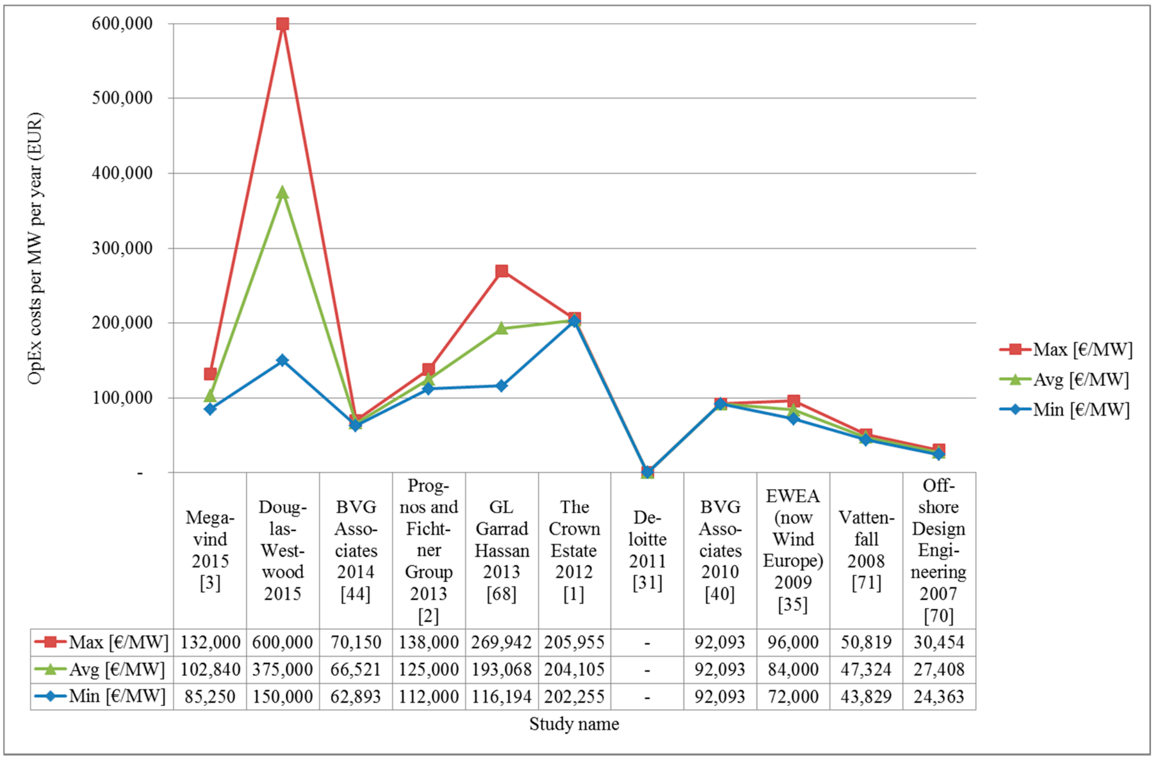
- WTG rating determines the number of WTG positions to be operated and maintained. The bigger MW rating of each WTG, the fewer positions to maintain in some scenarios where the OWF concession is based on over OWF MW rating [1]. In other scenarios, the OWF concession is based on an award of a certain number of WTG positions [2] which means that the annual energy production will be higher if the WTG rating is increased. A higher WTG rating means lower LCoE in both studies, however, as new technology is introduced, insurance premiums and the cost of capital (WACC) will increase due to increased project risks.
- Higher project risks will increase WACC and 1% increase in WACC equals a 6% increase in overall LCoE costs for an OWF [1] (p. ix). The same study cites logistics topics " . . . installation costs and timings, turbine availability and operating and maintenance costs . . . " to be the key project risks and WACC influencers.
- Distance from the OWF to shore significantly affects the overall O&M logistics strategy for the individual OWF. Only later studies [1,2] with different site scenarios are able to distinguish whether the O&M strategy should be land-based (using crew transfer vessels (CTVs) operating daily from a shore base) or sea-based (with fixed platform/floating hotel vessel [floatel]/service operation vessel (SOV) enabling personnel to stay offshore for longer periods of time). The sea-based scenarios are more expensive in both studies.
- Water depth determines the kind of foundation type to be used [44] and this again determines O&M efforts needed subsea. OWFs further from shore in deeper waters use more expensive foundations [1] that are less proven in terms of technology and therefore more expensive to insure due to increased technological risk which again negatively impacts WACC [2].
- The initial O&M warranty period for WTGs is contractually paid for as part of the CapEx costs as the WTGs are sold including warranty [40] (p. 5). This creates " . . . invisible costs covered in the supply chain during warranty periods" [40] (p. 17) which effectively means that OpEx costs are frequently artificially deflated.
- OpEx costs are not constant over the life-cycle of the OWF. One study for the UK Department of Trade and Investment highlights that " . . . final costs being higher as the farm comes to its life end and maintainability and reliability issues increase" [70]. Other studies consider that early OWFs need to have their operating life extended as they were designed for a 20-year operational life only. Costs for "repowering" or "end of service life extension" for WTGs [34] or prolonging operating life of WTGs [2] are considerable and have undergone some study also by academia [81]. Some operators consider costs for repowering or prolonging operating life to be outside of the normal realm of O&M costs and one operator treats these types of actions to be refurbishments which are accounted for financially as maintenance projects or maintenance investments [63] (p. 27).
- One of the studies quantifies that a learning curve will produce cost savings for an operator of an OWF over time [70].
- LCoE definitions are specific about OpEx and AbEx costs being used in a discounted manner in order to be able to compute the comparable numbers [1–3]. Some studies do, however, make use of undiscounted OpEx numbers [44] (p. 11).

Last but not least, the studies use the terminologies O&M and OpEx intermittently and interchangeably. Early academic work on LCoE concluded that their definition of O&M could explain

50% of OpEx, mainly for onshore wind [42] (p. 1377). Early practitioner work for the UK government stipulates O&M as a share of OpEx for offshore wind to be between 60% and 75% [70]. A paper recommending strategies to be applied for O&M in the UK offshore wind sector in 2015 and 2016 points to their definition of O&M making up some 52%–54% of OpEx [82] (p. 3) with costs for lease, transmission, and insurance considered to be excluded. This latter paper [82] bases its calculations on interpretations of the UK cost reduction study [1] including comparisons with key conclusions from one of the sub-work streams [73] of this extensive UK cost reduction study.

3.2. Comparison of Operations and Maintenance Calculations

Having selected a unit of analysis and with due attention paid to the different dimensions applied in the eleven studies subjected to the analysis, any studies with O&M numbers were first converted to OpEx numbers to ensure that an adequate comparison could be made of the annual OpEx figures per MW. Figure 2 shows the annual minimum (min), average (avg), and maximum (max) OpEx costs per MW per year converted to Euro (EUR). Due to the learning curve observed within the LCoE related studies pertaining to the calculation of OpEx costs and the different OpEx dimensions described earlier, the minimum and maximum ranges for OpEx costs in absolute terms per MW per year vary from EUR 24,363.- to EUR 600,000.-.



	Megavind 2015 [3]	Douglas-Westwood 2015	BVG Associates 2014 [44]	Prognos and Fichtner Group 2013 [2]	GL Garrad Hassan 2013 [68]	The Crown Estate 2012 [1]	Deloitte 2011 [31]	BVG Associates 2010 [40]	EWEA (now Wind Europe) 2009 [35]	Vattenfall 2008 [71]	Offshore Design Engineering 2007 [70]
Max [€/MW]	132,000	600,000	70,150	138,000	269,942	205,955	-	92,093	96,000	50,819	30,454
Avg [€/MW]	102,840	375,000	66,521	125,000	193,068	204,105	-	92,093	84,000	47,324	27,408
Min [€/MW]	85,250	150,000	62,893	112,000	116,194	202,255	-	92,093	72,000	43,829	24,363

Figure 2. Calculated annual OpEx cost ranges per mega-Watt for the eleven studies.

If the very early studies from before 2010 are excluded, where WTG rating and the total OWF capacity were smaller and mainly based on exclusively near shore locations which make these studies hard to compare to later studies, a minimum/average/maximum OpEx cost of EUR 62,893.-/166,895.-/600,000.- may be obtained respectively (a variance factor of 9.54 between minimum and maximum values). If these minimum and maximum OpEx cost numbers per MW per year are applied to a simplified LCoE calculation following the principles of Megavind [3] where it is possible to simultaneously apply the corresponding minimum and maximum ranges for CapEx in the respective study scenarios, the relative proportion of the discounted total life-cycle OpEx costs as a percentage of LCoE fluctuates from 13.1% to 56.5% as illustrated in Figure 3.

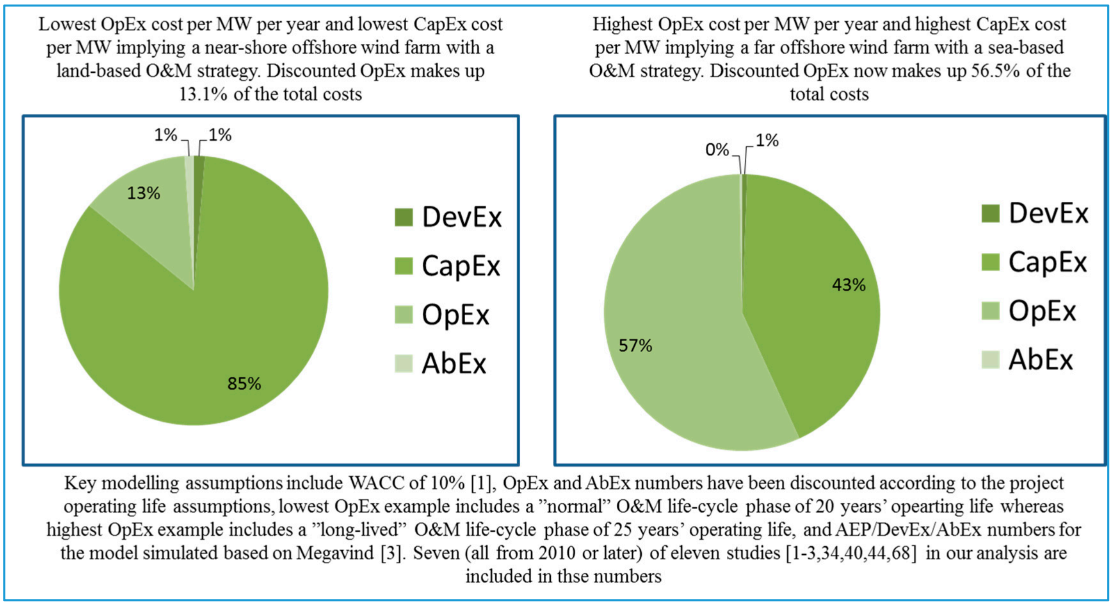


Figure 3. Scenarios displaying fluctuations in Operating Expenditure share of total costs.

These findings highlight the importance that applying the right O&M strategy whilst carefully monitoring OpEx costs can have a very significant impact on whether to enter into an OWF project at all from a financial perspective. The right O&M strategy with OpEx cost balancing greatly impacts the overall profitability of the OWF project over its life-time. The different dimensions used and settings for OpEx cost models seem to be somewhat subjective and the actual application for each OWF project therefore becomes critical.

3.3. Ascertaining the Logistics Share of Operational Expenditure for Offshore Wind

One of the eleven studies analyzed included a very detailed cost itemization of OpEx costs [68] and this was selected as the "logistics base case" for determining the logistics share of OpEx. When the 18 cost items (outlined in Table 5) are compared to the definitions of OpEx in the other studies analyzed and academic literature, it was found that although itemized in the greatest level of detail, several line items were still missing (see Table 6). Each line item contained in the base case cost model (Table 5) contained both a minimum and maximum amount provided by the source.

Individual OpEx line items that are similar in their descriptions across different studies analyzed were found to vary in size and this is also the case for logistics. Using "Port Operations" as an example, this line item ranges from approx. 1.2% of O&M [68] to 5% of OpEx [34] to 31% of OpEx [40]. Another example is the "Vessel costs" line item (including helicopters) which ranges from 9% of OpEx [34] to 30% of O&M [68] to 38% of O&M [70]. It was possible to ascertain that the different results vary based on the data itself (actual costs vs. simulations), the data collection method (quantitative modeling vs. qualitative interviews), and the actual OWF projects modeled (the LCoE dimensions applied). The research efforts indicate that the individual OpEx cost line items were furthermore aggregated and described at a somewhat high level due to the immaturity of the O&M part of the offshore wind industry [40,42,70]. This should be contrasted and compared to other industries where more detailed and advanced phenomena can be analyzed [83,84].

Table 5. Cost line items in the logistics base case study (table developed based on [68]).

Contract Package	Additional Explanation	Minimum (GBP)	Maximum (GBP)	Logistics Factor
Onshore logistics	Shore base	400,000	700,000	100%
Workboats	Crew transfer vessels (CTVs)	2,000,000	3,000,000	100%
Aviation	Helicopters	1,500,000	3,000,000	100%
Crane barge services	Wind turbine installation vessels (WTIVs)	4,000,000	12,000,000	100%
Senior authorized person and marine co-ordination	On-site senior authorized person, monitoring of vessels/personnel 24/7	400,000	800,000	100%
Export cable surveys and repairs	Surveys, repairs, remotely operated vehicle (ROV), cable laying vessels (CLVs)	50,000	200,000	80%
Array cable surveys and repairs	Surveys, repairs, ROV, CLVs	200,000	500,000	80%
Scour and structural surveys	Divers, ROVs, surveys, inspections, repairs, survey vessels	200,000	600,000	80%
Foundation repairs	Paint, cleaning, grout, scour, repairs, lighting, vessels	100,000	600,000	80%
Offshore accommodation/base	Fixed platform or floating (floatel, service operation vessel [SOV])	10,000,000	20,000,000	70%
Lifting, climbing & safety equipment inspections	Inspections, drills, certified personnel, vessels	100,000	200,000	60%
Offshore substation maintenance	Inspections, services, repairs, paint, WTIVs, CTVs	50,000	200,000	40%
Administration	Financial reporting, public relations, procurement, inventory/HSSEQ/permits management, administration	200,000	500,000	20%
Onshore electrical	Skilled personnel, some logistics	20,000	100,000	10%
Turbine maintenance	Skilled personnel	2,000,000	8,000,000	0%
Turbine spare parts, components, consumables	Excl. storage and sourcing	3,000,000	6,000,000	0%
SCADA and condition monitoring	Data monitoring, analysis	400,000	800,000	0%
Daily weather forecasting	Wind, wave, atm pressure, precipitation, temperature, visibility	40,000	90,000	0%
		24,660,000.-	**57,290,000.-**	

Table 6. Missing line items in most detailed levelized cost of energy related cost study.

Line Item	Source	Included in This Study
Seabed rental	The Crown Estate 2012 [1]	No
Insurance	Prognos and Fichtner Group 2013 [2]	No, found to be able to explain about 25% of the delta from O&M to OpEx
Transmission charges	The Crown Estate 2012 [1]	No
Weather windows	May 2016 [46]	No
Lost revenue	Dinwoodie and McMillan 2013 [45]	No
Vessel availability	May 2016 [46]	No

In the eleven studies, each line item had been applied with a more or less thorough description within its source. From this description, a calculated proportion of the line item contents ("the logistics factor") was applied in a manner within which it was possible to attribute to the definition of offshore wind logistics [22]. For several line items of the base case (Table 5), the logistics factor is 100% as the descriptions of the line items can be fully correlated with logistics beyond any reasonable doubt. An example could be the line item "Senior authorized person and marine coordination". In other cases, the logistics factor attributed had to be less than 100% if the description of the line item was ambiguous or only partly inclusive of logistics tasks. "Administration" was one example of a somewhat ambiguous line item which—in most descriptions reviewed—contained logistics related costs such as "Inventory management for parts and consumables" as well as "Procurement activities". In the analysis using the logistics base case [68], a logistics factor of 20% has—as an example—been attributed to "Administration" and the logistics base case has both a minimum and a maximum cost range. Table 7 shows that if logistics is conservatively attributed only to those line items that can be classified with 100% accuracy as being logistics costs, logistics makes up a minimum of 17% of offshore wind OpEx costs if the lower cost ranges are applied. Conversely, if the logistics factor is applied to all line items at the higher cost ranges, logistics could make up as much as 31% of OpEx. These numbers happen to tally with previous qualitative research findings of Poulsen and Hasager [22] (p. 15) on this topic in the world's leading offshore wind operator.

Table 7. The logistics costs share range of operational expenditure.

Logistics Costs	Minimum Cost Levels	Maximum Cost Levels
Cost line items with a logistics factor of 100%	17%	17%
All cost line items with logistics factor applied	32%	31%

Even at the lowest share of close to 17% of OpEx costs excluding many cost line items (detailed in Table 6), logistics ought to be a focus area for any operator of OWFs. This should be the case when evaluating the overall project viability before the investment decision as well as later on when the OWF becomes operational and the warranty period ends.

3.4. Calculated Savings from the Business Case on Working 24/7

Only one of the eleven studies related to LCoE mentioned working 24/7 as an area where costs may potentially be reduced [1] (p. 62). The results from producing the 24/7 business case indicate that by extending working hours to also include night time operations, a savings of approx. EUR 1.8 million per year can be realized. For a 400 MW near shore OWF with a land-based O&M set-up as modeled in the business case, this equals a reduction of just above 1% of LCoE.

The practitioner business case is based on a number of assumptions and the savings generated are based on using CTVs in a land-based or sea-based far offshore O&M set-up. The business case logic applied follows other studies that also utilize several sites with multiple dimensions applied [1,2]. No significant savings were found working 24/7 in the scenario modeled for a sea-based O&M set-up operating exclusively using SOVs. Therefore, the sea-based scenario was based on either a fixed accommodation platform set-up and/or stationary floatel set-up. Several assumptions were considered and subsequently ruled out in the business case as these criteria were deemed to be similar whether working daytime only or daytime and at night. These excluded criteria with a zero-sum impact on the business case comprised the overall OWF output yield measured in MW rating, the individual WTG yield rating in MW, number of WTG positions within the OWF, number of trips to WTGs during the summer season, and fuel consumption. Other assumptions have been entered as criteria in the 24/7 business case which effectively act as "levers" which—if altered—may impact the overall results of the business case:

- Number of vessels needed if working daytime (12/7) vs. also at night (24/7)
- Night-shift add-on salary payment for technicians
- Night shift add-on to cover on-shore support for monitoring purposes
- Months per year working 24/7
- OWF capacity factor
- Time for production stop per WTG as a result of faults/repair time
- Number of errors/faults/stoppages per wind turbine per month
- Price of electricity during and after subsidy period

A good example of a lever in the business case model is the OpEx costs per MW/year. The business case is built based on the Danish Anholt OWF and to some extent also the Danish Horns Reef I OWF. This has resulted in a near shore OWF modeling assumption with a land-based O&M strategy estimated at EUR 104,250.-/MW/year based on the focus group practitioner interviews and a linear view on OpEx costs included in the Megavind [3] 400 MW Anholt reference case. In the case study work forming part of this research, this number had been applied throughout the life-cycle of the OWF (the OWF life-cycle has in this case been set to be 25 years). However, following the analysis of the eleven government sponsored LCoE cost-related studies, a more realistic number for OpEx seems to be EUR 170,000.-/MW/year. In the land-based 24/7 CTV scenario, applying this higher and more realistic annual OpEx cost level affects the overall LCoE savings from 0.75% impact to 0.73% (see Figure 4). This can be explained as follows: When the annual OpEx lever is increased, the overall share of OpEx as a part of LCoE increases. Kept at a constant level in terms of savings impact in actual monetary values, the relative savings impact as a percentage of LCoE decreases. The business case model utilizes the Megavind [3] LCoE calculator tool methodology to compute the savings impact on LCoE. The Megavind [3] (p. 7) calculator tool offers four different LCoE calculation perspectives (developer costs pre-tax and post-tax, society costs pre-tax and post-tax) and a choice was made to work with the developer costs including tax, i.e., the Megavind "developer post-tax" scenario [3]. This scenario most accurately reflects the true project LCoE to be compared across OWF projects in different countries.

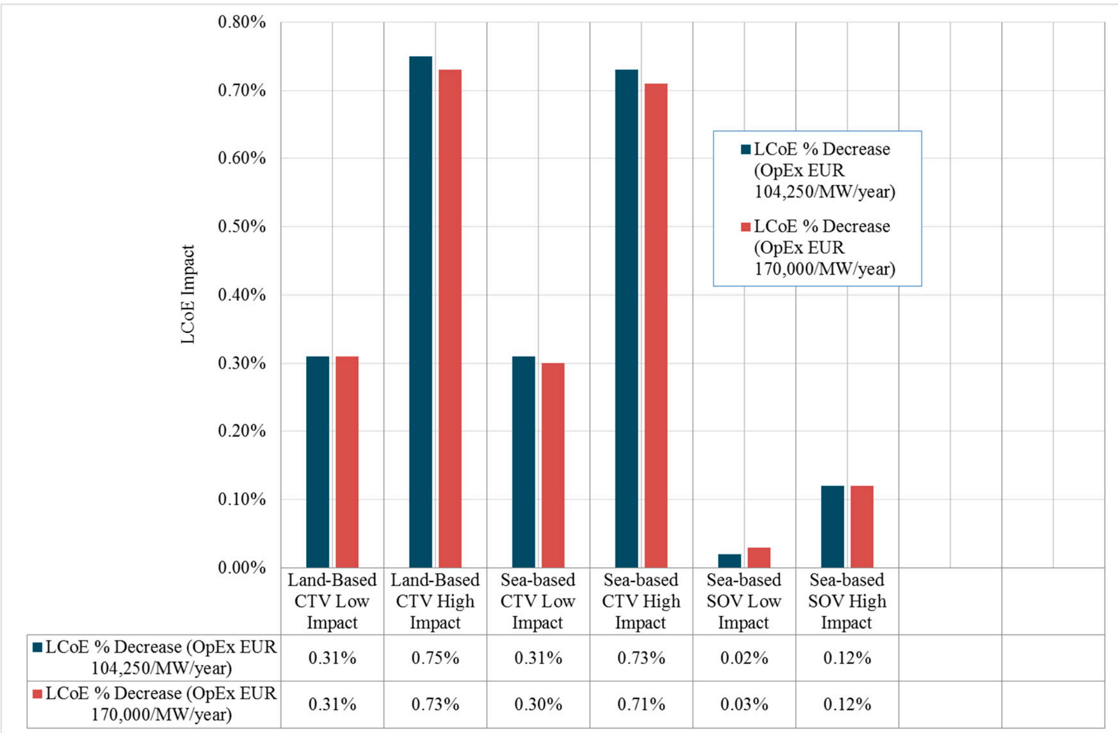
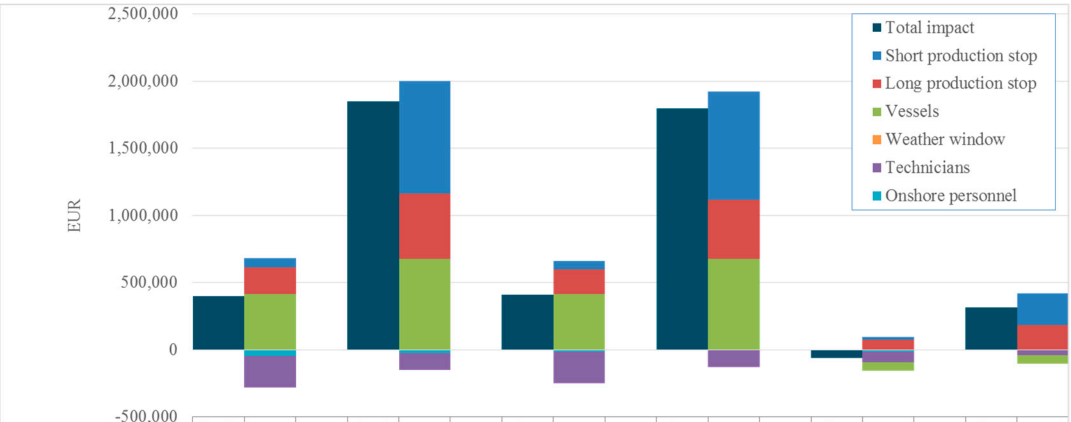


Figure 4. Selected business case impact on offshore wind farm levelized cost of energy.

Another example of a lever is the weather window which determines offshore WTG accessibility. The focus group work yielded a result of 15 days per month with no OWF accessibility for a land-based set-up using CTVs. The focus group work furthermore yielded a perception among the subject matter experts that the weather is less adverse during night time. This hypothesis was tested based on wave data from Fino-1 and Sylt, courtesy BSH and the MARNET network, respectively. The significant wave height data was subjected to a statistical test (*t*-test) and it was concluded that there is no significant difference between daytime and night wave heights. As this is very OWF site specific, the business case was left with this lever open to adjustment based on a site-specific analysis of weather data observations. In this respect, it is worth noting that it is possible to better exploit WTG accessibility weather windows if the work continues 24/7.

The business case model for 24/7 operates with three scenarios that each have a low and high impact sensitivity analysis which provide output ranges per scenario respectively. Figure 5 outlines the key outcomes of the business case cost savings components where the high impact ranges are primarily a result of lower costs for technicians and higher subsidy prices per MWh used for early OWFs (in this case Burbo Bank Extension based on www.4coffshore.com [85] contrasted against recent DONG Energy Wind Power [75] Dutch award subsidy price including a higher number of errors per WTG per month and long production stops).



	Land-Based CTV Low Impact		Land-Based CTV High Impact		Sea-Based CTV Low Impact		Sea-Based CTV High Impact		Sea-Based SOV Low Impact		Sea-Based SOV High Impact	
Total impact	399431		1850510		409631		1794961		-61571		315873	
Short production stop		68917		838948		66626		811056		19376		235865
Long production stop		200104		487186		180538		439550		75253		183215
Vessels		415188		674520		415188		674520		-61160		-61160
Weather window		0		0		0		0		0		0
Technicians		-236520		-126144		-236520		-126144		-78840		-42048
Onshore personnel		-48257		-24000		-16200		-4020		-16200		0

Figure 5. Business case outcome for working 12/7 (left columns, daytime only) and 24/7 (right columns, daytime and at night) for three cases (land-based CTV, sea-based CTV and sea-based SOV) for low and high impact estimates.

The scenarios and low/high impact sensitivities do not change in terms of absolute cost savings values as the lever with annual OpEx/MW cost is altered as the analysis is moved from near shore to far offshore. However, OpEx as such becomes higher within the Megavind [3] calculator tool as DevEx, CapEx, and AbEx are kept constant. With a higher annual OpEx for the far offshore output, this results in OpEx growing as a share of LCoE compared to the land-based O&M example for near shore Danish OWFs like Anholt and Horns Reef III. Conversely, the production as well as number of errors per WTG per month are parameters which could be expected to be higher for a far offshore OWF because of higher wind speeds and the cost savings impact of working 24/7 would therefore be further amplified.

3.5. Why Companies Chose to Join the Industry-Wide Cost Reduction Initiative

A particular area of interest for this research design was to determine why companies are interested in joining these industry wide cost reduction initiatives. The empirical evidence collected centered around 3 major areas:

- The larger companies attended with senior managers from staff functions working exclusively to reduce LCoE. These larger companies were interested in working with other large companies to steer cost saving initiatives. Simultaneously, the larger companies wished to work with SMEs to benefit from a more agile, lean, and innovative approach to the market. The larger companies felt that the combination of other large companies with SMEs generated a mix of companies useful for the quest towards lowering the costs for offshore wind.

- The SMEs attended with top managers who at times brought practitioners with hands-on experience to the focus group meetings and subject matter expert interviews. In addition, the SME top managers often had hands-on subject matter expert experience themselves. The SMEs used the cost reduction initiative to try to impact the industry overall because the offshore wind industry is very immature and therefore driven by different operators on a project-by-project basis. The SMEs were individually not significant enough to impact a large group of operators and hoped to be able to get close to decision makers from larger companies in a more informal setting.
- Common to large companies and SMEs was the wish to be able to work together as a larger group across the offshore wind industry to create truly useful cost-out opportunities which no individual company would have otherwise been able to develop or implement on their own. A sense of unity and urgency existed in the different working group meetings which resulted in passionate discussions and innovative dialogue. No single company had this much O&M logistics experience amongst their ranks of employees and the diversity in the working group composition yielded a very unique foundation to create useful business cases to be applied by all in an open access manner.

The sheer opportunity to meet new customers and suppliers respectively was a clear undeclared driver for some participants. As work progressed and the OE CRF became more widely known, more participants voiced interest in becoming part of the work which provided for better opportunities academically to triangulate data points used in the business cases and thereby strengthen the validity of the results presented.

4. Discussion

The key finding of the part of the research efforts focused on the eleven LCoE cost-related studies is that what constitutes the OpEx part of LCoE is not very clearly defined or agreed. Because of the inconsistencies in both unit of analysis and key assumptions making up the different LCoE calculation methods, the variance of the OpEx share of LCoE is significant. When the O&M portion of OpEx was subsequently analyzed, it was again found that definitions and assumptions varied extensively in terms of how each of the eleven cost studies was put together. As the area of logistics as a cost element within the annual O&M expenditure was further understood, a significant variance was again encountered in terms of the individual line items that make up the total logistics costs as part of O&M. For the logistics portion, supposedly easy-to-compare areas like costs of vessels, helicopters, and ports displayed great variance within the eleven reports reviewed.

These findings correspond to the separate case study performed within the organization of the world's largest offshore wind operator [22] and that research study indicates the root cause being that logistics is an area which is not yet subjected to proper organizational focus within offshore wind. The detailed line-item cost breakdowns of the government sponsored LCoE cost-related studies are immaturely applied and uncoordinated across different studies which ultimately make the studies impossible to compare.

4.1. Government Sponsored Studies—Not Useful for Practitioner Implementation

The first research question set out to understand whether practitioners can understand and implement the government sponsored LCoE cost-related studies. When the case study findings are combined with the analysis of the eleven LCoE cost-related studies and reports, the emerging pattern is that the government sponsored LCoE studies are used at policy level to drive strategic thinking and work with industry to lower the future costs for offshore wind energy. This work is contrasted within the case study part of this research where industry practitioners working ashore devised specific LCoE cost-out measures for their site colleagues working offshore to realize and implement immediately.

From the analysis, the largely government sponsored LCoE cost-related studies and reports are primarily driven by a strong desire at policy level to avoid subsidies for wind energy and to ensure that offshore wind is competitive with other energy forms. In the case study, the large OWF operators ultimately in control of the offshore wind projects took part as well as the SMEs serving the individual OWF projects and it was observed how their respective involvement and motivations varied considerably. At the policy level, the ability to utilize the government sponsored LCoE cost-related studies to generate ideas for cost savings opportunities supported by the proper research and analysis are the key success factors utilized to determine forward trajectories of offshore wind diffusion. At the execution level, the OWF operators attended the practitioner case study to ensure that they could benefit from any possible cost savings ideas generated whereas the SMEs attended mainly to be able to speak to the operators in a more united manner, with a stronger voice.

It was not easy to produce a clear path from the largely government sponsored LCoE cost-related studies and reports at policy level to the case study work with industry practitioners to create practical cost-out initiatives. This was mainly because the industry practitioners ultimately focused on the cost models of the operators involved in the case study, not government policy/industry strategy matters, as being the driving force behind the need for LCoE reductions. As such, the largely government sponsored LCoE cost-related studies were not directly tied to the work performed by practitioners in the cost reduction case study.

As a final caveat, it is worth mentioning that if applying the most extreme OpEx estimate of EUR 600,000.- year in the higher range applied of the study [34], it would, according to the calculations forming part of this research, not be possible for the OWF to be profitable even under the highest subsidy schemes seen hitherto.

4.2. Cultural Barriers between Cost-Out Initiative Planning and Implementation

The second research question pertained to the interest in understanding whether cultural differences exist between the players involved in devising the paths for cost reduction and those responsible for the actual cost-out implementation. Here, the first major finding had to do with the different types of stake-holders. A pattern of several distinctively different levels of cost reduction efforts therefore emerged from the research in terms of stake-holders and objectives:

- Government (policy/industry strategy level);
- Operator (OWF portfolio and operator specific cost model/experience);
- Shore based execution personnel (defining the cost reduction initiatives);
- Site personnel located either in offices ashore or offshore in the harsh marine environment and whether their background, as well as experience, were onshore or offshore based (responsible to implement and execute the cost-out initiatives such as working at night).

In the largely government sponsored LCoE cost-related studies forming part of the research, the involvement of major consulting firms to lead the analysis portion, perform the research, and engage with the industry practitioners was integral to the contents produced. In the case study, 77% of the participants were from the top management and middle management layers of the companies whereas only 23% were from the office execution/offshore site layers tasked to actually implement the cost-out business cases. In the government sponsored LCoE cost-related studies, the consultancies with government backing gained access to a broad base of industry stake-holders representing the entire offshore wind market in a very adequate, balanced, and justifiable manner. Conversely, the case study participant roster contained four participants from three operator organizations and three participants from a major OEM meaning that 74% of the case study participants were from SME organizations. Within the operators and OEM segment, the case study participants were comprised exclusively of shore based personnel with an onshore background. Within the SME participant segment, 80% of the case study participants had an offshore background.

In the government sponsored LCoE cost-related studies, it was determined that most of the directly involved participants appear to be office based and this was similar in the practitioner case study forming part of this research. The execution layer of the organizations as well as the responsible parties at e.g., port sites and offshore maritime operations are not well represented in the analytical phase of planning the cost-out measures to be implemented.

In the case study, a significant cultural barrier was experienced as the difference between being shore based working from a secure desk location in an office with theoretical concepts and ideas is very different from being deployed into an offshore site. When working offshore with harsh weather conditions and health/safety considerations to be taken into account as part of the daily operations, the background as well as experience from having worked offshore in the past was very important and could be directly contrasted to that of onshore personnel such as technicians working offshore.

4.3. Offshore Wind Logistics Operations and Maintenance Savings Are Achievable

The third and last research question pertained to whether it would be possible to create practically implementable cost-out initiatives by analyzing a particular life-cycle phase in much more detail and by joining a practitioner work effort as a case study. This research substantiates that cost reductions in the offshore wind O&M life-cycle phase are indeed possible through cost-out initiatives. This is evidenced by the work with business cases in the case study described in detail in this paper. The lean initiative, the asset sharing business case, the pre-planning of parts/tools/consumables, as well as the 24/7 business case presented in more depth are all examples of practical and short-term cost-out initiatives that can be applied by the operators and/or OEMs together with the SME suppliers serving them.

Separately, cost reductions may also be achieved through innovation as evidenced by the separate case study about offshore wind logistics innovation with DONG Energy Wind Power [22]. It is, however, critical that the organization driving the innovation has a certain size and mass to be able to accommodate and also test the innovation cases being worked with. And here, the offshore wind innovation conundrum exists in terms of wanting innovation on the one hand versus wishing to reduce risk by only using fully tested and proven concepts on the other hand [22]. Significant differences exist in terms of supply chain composition, readiness, and set-up between Europe and Asia [86].

To get offshore wind to be competitive with other energy forms, the paths of practically implementable cost-out initiatives and innovation need to be combined and logistics would be an ideal demonstration ground.

4.4. Application of the Studies Was Possible for Several of the Business Cases

Individually, each LCoE cost-related study can be very useful. In the practitioner case study, the selected business case pertaining to extending the operational working hours offshore at sea to 24/7, the Megavind [3] LCoE calculator tool was successfully applied and it was found to be appropriate.

However, for one of the more conceptual business cases forming part of the case study such as creating a vision for the future of O&M logistics in 2025, the Megavind LCoE calculator tool [3] would not be similarly appropriate.

Most of the case study business cases were fairly sophisticated in nature and based on a learning curve in Europe of offshore wind dating back to 1991. Many of the findings should also be applicable in Asia where especially the fastest growing market of China has cited O&M and logistics as significant gaps that need to be filled [86]. However, O&M logistics for floating wind turbines have not been considered within the case study performed [87].

4.5. Case Study Findings about Operations and Maintenance Logistics Strategies

One of the three goals identified as a justification for joining the practitioner cost reduction case study was to learn about offshore wind O&M logistics. Several dimensions emerged from the analysis of the eleven studies and the case study efforts as ***structural considerations*** for O&M logistics strategy going forward.

The ***distance from shore*** to the OWF would determine if a shore-based or sea-based O&M set-up would be required. These decisions would again have significant implications on the shipping and logistics strategy and thereby the costs involved.

The degree to which OWF operators are able to ***obtain data*** from the OWF in general and each WTG position in particular to use for preventive maintenance efforts would also have an impact on the shipping and logistics strategy. Advanced utilization of condition monitoring and structural health monitoring software and kits [46] would create an environment of more precisely pre-planned O&M activities. If done correctly, preventive maintenance of main components such as the generator or gearbox could avoid significant costs for jack-up vessels with cranes to have to be deployed on short notice for major repairs. The operators, who were part of the practitioner case study, expressed that whereas they were generally aware of the existence of these softwares and kits, their access was via the WTG OEMs which means that in practice, several different systems and kits operate in parallel because operators generally utilize WTGs from more OEMs. Each OEM would continuously upgrade their solutions with a strong focus on protecting intellectual property rights and the operators would constantly try to gain full access to already purchased software, especially towards the end of the warranty period. Reviews of new technology and kits were cited as constantly being performed by the operators and for existing and future OWFs, a clear business case proof had to exist in order to justify investments on the part of the operators. For such business case proofs, logistics was cited to play a key role for work performed subsea, below water, as well as topside, above the waterline, due to the high overall cost share attributed to offshore wind logistics.

Different supply chains exist for O&M activities which can be planned long in advance compared to scenarios where an offshore asset ceases to operate and needs to be diagnozed and subsequently repaired in an ad-hoc and unplanned manner. In the pre-planned scenario, efficiencies can be built in through efforts such as lean. When an asset breaks down and diagnostics as well as subsequent repairs need to happen quickly, the supply chain is mobilized swiftly and in an ad-hoc manner. This causes the supply chain to be more expensive to deploy as the deployment is often bespoke and without economies of scale.

Whether the preventive maintenance or the needed repairs take place ***topside or subsea*** also greatly affect the shipping and logistics strategy. Implications, in terms of deployment of vessels carrying divers and remotely operated submarines with cameras and repair capabilities, need to be considered for subsea operations on foundations and cables. This is contrasted to bringing technicians, parts, tools, and consumables to wind turbines and/or offshore sub-stations for preventive maintenance and/or repair work above water where the technicians and equipment are transferred from vessels to the OWF asset.

Finally, the implications of a break-down or damages incurred to an export cable and/or a sub-station were in the research efforts found to be comparatively more severe and thus warrant a different shipping/logistics response. In such break-down cases, damages could cause an ***entire OWF asset to be unavailable*** which could often be very costly for the operator if the downtime is over an extensive period of time due to e.g., a cable damage which needs to be located. Situations where the entire OWF asset is down may be contrasted and compared to a break-down of an individual WTG unit within an OWF which is also critical but with very different cost implications for the operator.

5. Conclusions

This research has provided new knowledge about the learning curve involved in order to produce the largely government sponsored LCoE cost-related studies within the offshore wind industry. It was found that this learning curve has been steep over the last ten years as evidenced by the analysis of eleven extensive studies. As part of the research presented in this paper, OpEx as a single component of the LCoE calculation was found to be able to vary by a factor of 9.5×. When applied to a commonly accepted LCoE calculator tool for offshore wind [3], this high variance resulted in creating a range of 13%–57% for the OpEx portion of LCoE in the low/high scenarios presented in this paper. It would therefore seem prudent for a standardized methodology for cost modeling to now be implemented, for example in line with the work done by Strategic Energy Technologies Information System [88]. Alternatively, the use of LCoE as a way to evaluate progress of offshore wind compared to other industries would seem to be futile.

As a phenomenon, LCoE is already being subjected to harsh criticism for not being an accurate measure to compare energy forms. For wind, this is argued to be of particular relevance as wind is intermittent in nature and therefore non-dispatchable from a grid perspective [89]. Dispatchable energy forms are more valuable to the overall grid balancing and this is argued to be a critical flaw of the LCoE measure itself. Other ways to compare energy forms have been proposed e.g., by Evans et al. [27], Ueckerdt et al. [28] and Dale [90]. LCoE in combination with Levelized Avoided Cost of Energy is being proposed by the United States (US) Energy Information Agency [91] as a new methodology to make evaluations more holistically for an area, region, or country [92].

For now, the analysis of OpEx and O&M costs within offshore wind presented in this paper reveals that different assumptions have been applied to the different LCoE studies by different countries and that these assumptions have changed as the wind energy technology has evolved over time. If the main objective at policy level of producing LCoE cost-related studies is to create an opportunity to benchmark costs at a certain point in time compared to the future, as well as, compare the costs of offshore wind to other energy forms, the findings presented in this paper call for further research efforts which are critically needed in order to devise solutions on how to apply the assumptions of the cost studies down to a line-item cost level. This was evidenced by the work efforts rendered as part of this research to exemplify our findings within the specific areas of shipping, logistics, and port line item costs as analyzed in this research.

The work presented in this paper from the case study with industry practitioners on practically feasibly and immediately implementable cost-out initiatives in the form of business cases has been very useful in terms of actively being part of the process of understanding how to contrast the often very policy level macro studies of LCoE cost-related issues sponsored by governments to real-life practitioner cost reduction pressures. Working intensively at the practitioner level with action research, it became apparent that further research should be undertaken to further study the impact of the key structural dimensions identified in this paper (Section 4.5) to have a major influence on O&M logistics strategy going forward.

It became evident from this research that the cultural gap between shore-based personnel and the maritime personnel, often working offshore at sea and being ultimately responsible for the majority of the actual, practical cost-out implementation work, is a critical area in need of further research (Section 4.2). This cultural gap could in fact be an important barrier to the actual realization of cost savings as opposed to desktop efforts to identify, simulate, and track more theoretical initiatives organized without a true ability on the part of the operators and supporting companies to determine the true bookkeeping impact.

Finally, the work with the very specific 24/7 cost-out business case example yielded an opportunity to compare this not only to the LCoE cost studies and reports but also to the separate, prior case study on offshore wind logistics and logistics innovation [22]. Whereas the goals and objectives of logistics cost-out (the topic of this paper) and logistics innovation (the topic of the former paper [22]) are somewhat similar in terms of the wish to bring forward tangible cost reductions, the methodology and processes would need further research as well. The two paths to cost reductions for offshore wind are metaphorically as different as night and day. And working both night and day is exactly what is required from the offshore personnel having to work 24/7 should the key business case of this paper be implemented by OWF operators going forward.

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Abbreviations

The following abbreviations are used in this manuscript:

AbEx	Abandonment expenditure, decommissioning cost
AEP	Annual energy production
Avg	Average
CapEx	Capital expenditure
CRF	Cost reduction forum
CLV	Cable laying vessel
CTV	Crew transfer vessel
DevEx	Development Expenditure
EU	European Union
EUR	Euro
EPCi	Engineering, procurement, construction, and installation companies
Floatel	Floating hotel vessel
GW	Giga-Watt
HSSEQ	Health, safety, security, environmental, and quality
I&C	The installation and commissioning life-cycle phase of an offshore wind farm
IEA	International Energy Agency
IMR	Inspection, maintenance, and repairs
IRM	Inspection, repair, and maintenance
IRMR	Inspection, repair, maintenance, and replacement
LCoE	Levelized cost of energy
M&R	Maintenance and repair, maintenance and renewal, maintenance and replacement, maintenance and rehabilitation
Max	Maximum
Min	Minimum
MW	mega-Watt
MWh	Mega-Watt hours
O&G	Oil and gas
O&M	Operations and maintenance
OE	Offshoreenergy.dk
OEM	Original equipment manufacturer
OpEx	Operational expenditure
OWF	Offshore wind farm
ROV	Remotely operated vehicle
SME	Small to medium sized enterprise
SOV	Service operations vessel
TPM	Total productive maintenance

UK	United Kingdom
US	United States of America
USD	United States Dollars
WACC	Weighted average cost of capital
WTIV	Wind turbine installation vessel
WTG	Wind turbine generator

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