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Cornwall FLOW Accelerator

Low Carbon Installation Logistics Report

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Contents

1 Executive Summary

The study investigated the determination of the optimal batch number and optimal batch size for the installation of a 500MW wind farm in the Celtic Sea utilizing thirty-four 15MW wind turbine generators at a location adjacent to South Wales currently commissioned for investigation under the ERDF part-supported Cornwall Floating Offshore Wind Accelerator Project. Key considerations for optimization were the minimization of carbon emissions, the minimization of installation cost, and the prioritization of timely grid connection for the field to enable field productivity and the generation of income cash-flows from the field at the earliest opportunity during the installation phase.

Key constraints considered were port proximity, port capacity, installation fleet compositions, and the associated fleet capability within the available weather windows for identified installation tasks.

In addition to exploring an installation base case based on existing port capacity, the study examined the impact on carbon emissions, mid-stream installation costs, and field productivity in the event a significant investment in port capacity was undertaken to enable a doubling of productivity from each available port.

The study assumes the most proximal port will be the installation port of choice in the first instance and port capacity will be the constraint on it fulfilling an installation task within the available weather window.

Opportunities for parallel processing of turbine installation were explored and associated penalty costs, as well as carbon impact for the additional fleet vessels to enable fast-tracking, were apportioned.

The results demonstrate, installing and commissioning in batches provides a cost-income generation benefit for the developers irrespective of the increased vessel commissioning costs of multiple batch grid connections.

The study concludes vessels with higher tolerance limits are an appropriate strategy to achieve low carbon and low-cost installation within the due date. It is recognized that the availability of a high vessel capability fleet option would be a significant operational constraint in practice. The authors acknowledge, less capable fleet options including those deployed in the study will play a role in the large-scale deployment of floating Offshore Windfarms within the Celtic Sea basin.

2 Context FLOW in the Celtic Sea

The nascent global floating offshore wind industry to date has engaged global supply chains and pan-national port infrastructure to deliver the lowest Levelized Cost of Energy (LCOE) to support the demonstrator projects currently in operation or planned.

The UK Government has committed to being at the forefront of the green industrial revolution by accelerating progress toward our legally binding 2050 net-zero emissions by creating a new target for floating offshore wind (FLOW) to deliver 1GW of energy by 2030 (Department for Business, Energy & Industrial Strategy, 2020). This is over 15 times the current volumes worldwide and is concomitant with the Crown Estate declaring its ambition to unlock up to 4GW of new clean energy capacity in England and Wales (Crown estate report, 2021) and help establish a new industrial sector for the UK within the Celtic Sea.

3 The University of Exeter Approach to Simulating FLOW

The University of Exeter has developed a tool to assess economic values and the environmental impacts of floating offshore wind farms. The assessment is based on life cycle analyses, which include five development stages: pre-development, manufacturing, assembly and installation, operations and maintenance (O&M), and decommissioning. The tool is designed to help stakeholders such as wind farm developers and policymakers to facilitate decision-making processes in FLOW development. The tool is novel in approach by concurrently computing not only the whole life cost of energy production (LCOE) but the associated whole life carbon intensity of energy production and the lifetime return of energy generated as a ratio to the whole lifetime value of energy invested.

We deployed this tool to conduct a study to determine the effect of port location on key performance metrics. Several scenarios representing varied port-function combinations were built and simulated, using the tool, to provide a comparative analysis of the impact of the choice of port location on windfarm development strategy. The tool provides the flexibility and opportunity to determine what combination of manufacturing, assembly, installation, and servicing locations yields the optimal combination of low cost, low carbon, and highest energy yield.

Initial findings indicate that a high local content in terms of port infrastructure and local supply chain performing installations & maintenance operations is competitive with globally sourced solutions in economic terms while simultaneously halving lifetime Green House Gas emissions.

4 The Literature Review

The technological innovations in floating platforms as well as the previous experiences from floating oil and gas platforms as well as fixed bottom wind turbines have led to a growing interest in the commercial development of wind farm sites located further from shore with water depths of 70m or more. With improved wind turbine technologies, installation strategies, and vessel innovations, there is the potential via rapid industrialization to observe a parallel trend to the large cost reductions experienced in the fixed wind sector substantial decline in the Levelized cost of energy (LCOE) of offshore wind projects. In spite of these technological innovations with higher technology readiness levels (Jiang, 2021), the capital cost of floating wind turbines is almost twice that for onshore or shallow water wind (Maienza,2020). Consequentially, there is a need to boost the competitiveness of offshore wind energy by assessing the major life cycle costs contributors to floating offshore wind energy.

In the current literature, key wind power economics namely, capital costs (CAPEX), Operation and maintenance costs (OPEX), and decommissioning costs (DECEX) (Ioannou et al., 2018), work on life cycle cost assessment (Judge et al., 2019; Maienza,2020), methods to enable time-efficient and cost-effective assembly and installation planning (Ursavas, 2017, Castro-santos et al.; Jiang et al.,2021), platform optimization and floating offshore wind farm cost analysis (Ghigo et al., 2021). Techno-economic analysis of floating offshore wind farms with stochastic O&M models (Rinaldi et al., 2021) and allied works are available. The focus of these recent studies has been on assessment and estimations of annual energy production, system reliability, financial analysis, related discounting factors, economical vessel combinations, and cost of capital. Most of these techno-economic analyses are based on oversimplified assumptions and representations. For e.g., operational expenditures are usually calculated as a definitive percentage of capital expenditures (Marques et al., 2019). However, the paucity of real data and experience has motivated the researchers to conduct overall cost analysis on basis of simplified assumptions with very little consideration for logistical decision-making interfaced with met-ocean conditions.

4.1 Logistic and supply chain current scenario in offshore wind energy

Nonetheless, the larger turbines and increasing farm sizes far from shore sites and deeper water lead to complex installation procedures with long time durations (Renewable UK, 2014). Obviously, the complexity and challenges in logistics and supply chain increase manifold as compared to onshore or shallow water wind farms. The logistical decisions are basically interfaced with transportation and installation, operations and maintenance, and decommissioning. One of the significant aspects of logistical decision-making is the type of floating platform, the vessel availability, distance from the port, and feasible weather window for transportation of the components.

Taub (2014) indicated that through innovative transport and installation processes a reduction of around 10% in the Levelized Cost of Energy is achievable. Lange, Rinne, and Haasis (2012) discussed manufacturing stages and supply network bottlenecks through a simulation tool for the installation process. Tezcaner et al., (2016) developed models to determine the installation schedules, considering weather uncertainties, that enable logistical decision-making for large-scale projects. Barlow et al., (2018) developed a simulation model for estimating the most favourable start time of the operations and scheduling the tasks considering weather disruptions. These studies aimed mainly at minimizing the installation cost and duration while determining logistical decisions such as deciding the component delivery dates, vessel hiring dates, crew allocation durations, etc. Castro- Santos et al., (2018) discussed the impact of several installation scenarios on the installation costs. These scenarios were developed considering the existence of storage space, dry transport or wet transport, number of liftings, mooring installations, and substation installations.

Operations and maintenance have received comparatively wider attention from researchers as compared to other lifecycle phases like transportation and installation, decommissioning. Several studies report the cost impact of factors such as vessel availability, major or minor repairs, weather windows, etc on operations and maintenance costs. Researchers have also illustrated the impact of O&M strategies on the overall costs of the wind farm in comparison to oversimplified approximations (Martin et al., 2016; Rinaldi et al., 2017). These studies clearly indicate the significance of logistics and asset management in realistic techno-economic analysis (Jezierski et al., 2021). The cost analysis based on the effect of failure rate, repair time, reliability and unscheduled maintenance, and availability of wind farms has been emphasized by the researchers while minimizing the O&M costs (Carroll et al.,2015; Dalgica et al., 2015; Rinaldi et al., 2018; Dao et al., 2019; Allala et al.,2021). Stålhane et al., (2019) determined the optimal vessel fleet for maintenance operations. Rinaldi et al., (2021) reviewed operations and maintenance strategies for floating offshore industries as well as those from the allied industries as well. The authors discussed the benefits and limitations of several approaches that attempt at improving the reliability of the devices and minimize the O&M costs.

4.2 Studies for de-carbonizing marine logistics

Surprisingly, the majority of focuses with respect to logistics and supply chains have been aimed at only economic benefits with negligible attention given to de-carbonizing the logistics and transportation functions. Synergies and links exist between the oil and gas industry and the floating wind energy industry. In order to analyze the significance of de-carbonizing the offshore wind industry logistics, the literature review is expanded to the oil and gas industry and fixed bottom wind farm in an attempt to draw several observations regarding carbon emissions due to logistics. As per the McKinsey report (2020), special initiatives for decarbonizing depends on geography, upstream or downstream asset management, and local policies and practices. Small procedural changes such as improved maintenance routines can lead to a reduction in carbon emissions.

The studies from the oil and gas industry indicate the significance of supplier and logistics management for achieving sustainable supply chains i.e., more environmentally and socially responsible supply chains (Ahmad et. al.,2016). Atmayudha et al., (2021) evaluated the greenhouse gas emissions for crude oil logistics activities for multiple depos and heterogeneous fleets. The carbon emissions and cost for two types of vessel fuel namely Liquified Natural Gas (LNG) and diesel versus crude oil were estimated and determined LNG to be both preferred from a cost and carbon efficacy perspective.

The ORE catapult report on decarbonizing maritime operations in the North Sea estimated that, by 2025, one-third of O&M vessels shall adopt greener technologies. The carbon emissions due to crew transfer vessels and service operations vessels, reported by Ørsted, is 42 kt CO2e for 17% share of total installed capacity in Europe.

Wang et al., (2018) compared the greenhouse emissions of onshore and offshore wind farms and indicated that the distance from the manufacturing location to the farm site has a significant influence on greenhouse gas emission intensity as compared to the emissions due to transportation at the decommissioning stage. Logistics account for a very small share (around 1% as per the ORE Catapult report) in CAPEX but contribute to a large share of carbon emission based on the distance travelled and fuel consumed by the vessels for transportation, installation, and O&M activities (Istad et al., 2020). The majority of vessels use marine gas oil and Jezierski et al., (2021) estimated the energy consumed during transportation of vessels for component replacement in order to repower the wind farm located in Treffendel (Brittany, France). They evaluated the combination of various modes of transport i.e., road, rail, and sea routes, and estimated the energy consumption in each case. Pierre et al., (2019) indicated that vessel speed and distance travelled are the main contributors to carbon emissions.

The findings of the LEANWIND (Logistic Efficiencies And Naval architecture for Wind Installations with Novel Developments) project discuss the application of lean principles to logistical processes, shore-based transport links, port and staging facilities, vessels, lifting equipment, safety, and O&M. The approach enables improvement in quality, reliability, and elimination of wasteful activities across the supply chain, throughout the life cycle of the wind farm. This enables cost reductions as well as integrates logistical activities resulting in the reduction of unnecessary travel or vessel allocation. Consequently, carbon benefits are achieved in addition to cost reductions. The benefits of lean principles for improving maintenance operations are evident in the oil and gas industry (Shou et al., 2020).

5 The Scope and Limitations of the Current Study

This study evaluates the effect of batching large farm size installation from low carbon logistics perspectives. In addition to evaluating the effect on carbon emissions, the study also considers the impact on cost and revenue generation due to commissioning in batches or phases. The logistic function for installations is largely dependent on the number of turbines to be installed within the farm site in a year. However, the maximum number of turbines that can be installed is constrained by the availability of the weather window in a year and the port capacity. In this work, a model is developed for optimizing the batch sizes for low carbon emission and low-cost objectives under these constrained conditions. The current model optimizes the low carbon logistics functions in the mid-stream installation value chain i.e., the transportation function from installation or assembly port to the farm site. The logistics from the manufacturer to the assembly site are beyond the scope of this study. The motivation for limiting the logistics consideration is that the mid-stream logistics function will largely govern the installation strategies to be derived based on vessel configuration and port capacity. As the focus of this study is limited to the installation phase, up and downstream logistics functions were excluded from the current model and the future extension of the model would be the inclusion of additional logistics activities within the value chain.

The model minimizes the total carbon emission C_e due to the mid-stream logistics of the installation value chain. The model provides the range of optimal batch sizes i.e., the number of turbines to be installed in time period $t = \{1,2,3,..T\}$, where T is the due date of the installation period or the number of years estimated for the installation of the farm. The model is given as $min \sum_{t \in T} x_i C_e$ where x_i is the integer variable that takes value 1 when a vessel configuration is assigned to a batch, otherwise 0. Figure 5.1 describes the process flow of the installation model deployed to estimate the effect of batching on the mid-stream installation cost and the carbon impact due to logistics.

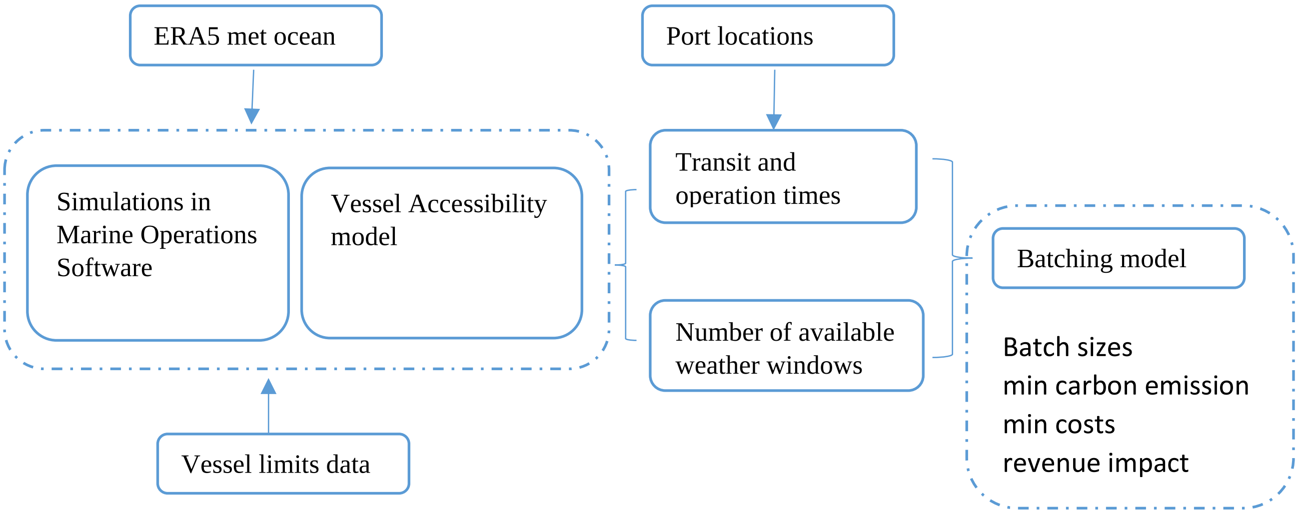

Figure 5.1: Model structure and process flow.

The carbon emissions are mainly function of the fuel consumption rate of the vessel during transit and during operation at the farm site from a port to the farm site. The transit and operation times and the available number of weather window in a year depend on the vessel limits and metocean conditions. These are estimated using marine operations software and vessel accessibility model. Additionally, the constraints on the port capacity and number of available weather windows leads to deployment of the additional vessel $v_i$where i denotes the vessel configurations. The cost function is given as the sum of fixed cost (C_{fc}), variable cost (C_{vc}) and the penalty cost (C_{pc}) and is represented as,$TC = C_{fc} + C_{vc} + C_{pc}$.

The fixed cost component depends on the farm size and is independent of the batch size. The variable cost (C_{vc}) is depends on the vessel day rate (d_r) and stand rate (s_r),the transit times (t_t) and the operation times (t_o) which are based on the metocean conditions. Thus, the vessel cost shall vary with the vessel configuration and number of turbines n_{btr} to be installed is mathematically represented as, $c_{vt} = \sum_{n_{btr} \in B_s} \left(\sum_{v_i \in V} v_i [(t_t * d_r + w_k(w * t_t * d_r) + t_o * s_r + w_k(w * t_o * s_r)\right)$. The early commissioning of the batch of turbine shall lead to revenue generation (C_{rt}) for discounting rate of r_d and annual energy production is calculated as, $e_a = p_{tr} * ca_{tr} * 8760$. For the experimentation purpose r_d is assumed to be 10% with the capacity factor of $ca_{tr} = 50\%$ for the 15 MW turbine capacity i.e., p_{tr} and 5% energy loses in the transmission. Although, a static capacity factor of 50% is used in this study, in future the E^c simulator shall integrate with energy generation module, that considers the metocean data, turbine capacity and wake effect model, for having dynamic capacity factor input to the model. The revenue generated is computed as $C_{rt} = \sum_{t\in T} r_b * n_{btr} * e_a * (\frac{1}{(1+r_d)^t})\ \forall\ t = \{1,2,\dots,T\}, r_b$ is the integer variable deciding the batch size. Parallel installations in the form of fast tracking are enabled subject to weather windows and port capacity, while searching for optimal batch sizes within the port capacity. Parallel installations indicate that the installation of more than one turbine unit at the same time. A penalty cost is introduced in the model for the fast-tracking or parallel installations of the turbine units considering the need for channelising additional vessels for the tasks.

The batching or phasing of installation is expected to affect the operations and maintenance strategies that shall be addressed in the integrated holistic simulator. The data populated for the experimentation purpose is collated from varied sources such as research papers, articles, and reports but largely depends on experts' perspectives and estimates. Future work would seek to analyze the results for nuanced vessel combinations based on data from industry developers.

6 Case Experiments and Results

In this study, the primary focus of the model is to determine a low carbon installation strategy. The installation strategy provides the comparative analysis of different vessel configurations for corresponding batch sizes. For the experimentation purpose, cornwall flow accelerator (CFA site 1) is the location where the installation of a farm capacity of ~500MW is considered. Milford Haven is the closest port from the CFA site 1 and ideally to accrue the cost and carbon benefits all the installations should be done from Milford Haven. But, inspite of having some infrastructural support from existing setup, Milford Haven has limited capacity and hence it would be challangeing to accomplish the installations in the desired time period. As a consideration to this constraint, Port Talbot and Falmouth are included as the installation ports alongside Milford Haven in this study. Figure 6.1 shows the location of the farm site and three installation ports in the map. Table 6.1 describes the characteristics of the case study used in this study to demonstrate the applicability of the model.

Table 6.1: Characteristics of the case study.

Site Name	CFA site 1 (longitude 51.58909, lattitude -6.19032)
Number of turbines	34
Turbine capacity	15 MW
Installation Ports	3
Port Talbot current capacity	6 turbine units
Milford Haven current capacity	4 turbine units
Falmouth current capacity	2 turbine units
Water depth	80 to 110m

Figure 6.1: Map for CFA site 1 and the three installation ports.

Figures 6.2 and 6.3 represent the significant wave height and wind speed, at CFA site 1, for a period of six months from March to August 2020. The wave height and wind speed data for CFA site 1 is populated from the ERA5 database for a period of six months where the weather conditions allow the longest duration and greater number of available weather windows for the installation tasks. However, where simulations utilize vessels with higher tolerances in harsh weather conditions it would be possible to execute installation tasks beyond the Celtic Sea spring/summer optimal conditions and will be a focus of future work.

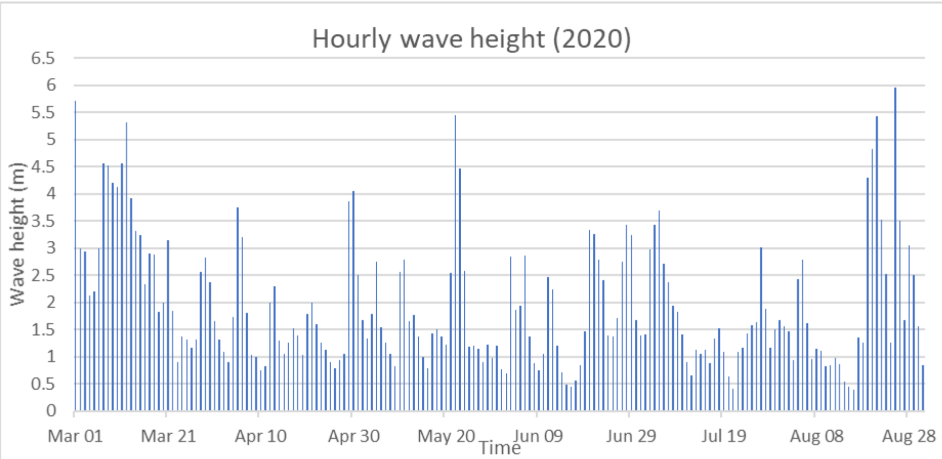

Figure 6.2 : Hourly wave height data, 2020.

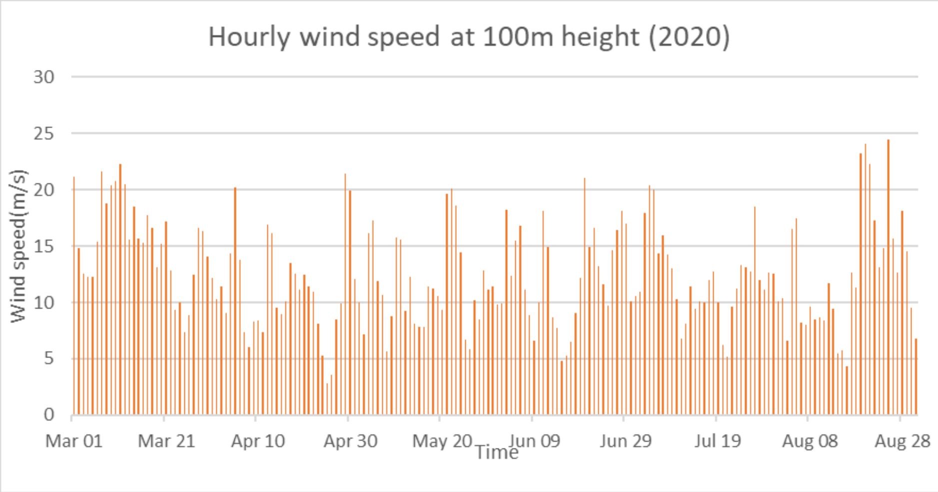

Figure 6.3: Hourly wind speed, 2020.

6.1 Vessel Configuration assumptions

The metocean data along with the vessel limits is processed to estimate the number of available weather windows for a vessel configuration. Table 6.2 describes the vessel limits for different vessel types (Stumpf and Hu, 2018; Hu, B. and Yung, 2020).

Table 6.2: Vessel limits used in this study.

Vessel Type	Max. significant wave height (m)	Max. wind speed (m/s)
Anchor handling tug supply vessel (AHTS)	2.5	20
Tug boat	1.65	14
Cable laying	3.5	15
Jack-up barge	1.65	16
Crew transfer vessel (CTV)	1.7	15
Service operation vessel (SOV)	3.5	8

Different vessels have different weather limits and tolerance to operate in harsh weather conditions and varying fuel consumption rates. Intuitively, the vessel types affect the installation schedules, costs, and carbon emissions. This study investigates the impact of different vessel combinations or fleet configurations on the installation cost and associated carbon emissions. In the current time frame, there is a limited experience with the installation vessel configurations. The experiments are conducted for the four-vessel configurations derived on the basis of expert opinions and the 4Coffshore and DNV articles. For the first vessel configuration, three AHTS were deployed with two cable-laying vessels. Depending on the vessel limits of this fleet configuration and the associated metocean state, fifteen to twenty weather windows of seven days were available for installation. For the second vessel configuration, three tugboats for the transfer of the wind turbine unit (WTG) to the farm site from the installation port with one AHTS for mooring system installation and one crew transfer vessel, and two cable-laying vessels were used. Depending on the vessel limits of the identified fleet combinations and metocean conditions, eight to twelve weather windows of seven days would be available for installation. For the third configuration, two Jackup vessels with one AHTS, one crew transfer vessel, and two cable-laying vessels were used. In this instance, for this fleet configuration, eight to twelve weather windows of seven days would also be available for installation. For the fourth vessel configuration, three SOV with one AHTS and two cable-laying vessels were used.

In this final instance, eight to fifteen weather windows of seven days would be available for installation. Table 6.3 summarizes the different vessel configurations used in this study.

Table 6.3: Vessel configurations for the study.

Notation	Vessel Configurations	Description
Vessel Config-1	3:AHTS,1: Cable laying,1:DP2 cable laying	AHTS: for installation and connection of mooring system, towing turbine unit. Cable laying:inter-array cable laying and connection. DP2 cable laying: export cable laying
Vessel Config-2	2: Tugboats(main), 1:Tugboat(assisting), 1:AHTS, 1:CTV, 1: Cable laying,1:DP2 cable laying	Tugboats: towing turbine unit from port to farm site, AHTS: for installation and connection of mooring system. Cable laying:inter-array cable laying and connection. DP2 cable laying: export cable laying.CTV:for tranfer of crew members.
Vessel Config-3	2: Jackup, 1:AHTS, 1:CTV, 1: Cable laying,1:DP2 cable laying	Jackup: towing turbine unit from port to farm site, AHTS: for installation and connection of mooring system. Cable laying:inter-array cable laying and connection. DP2 cable laying: export cable laying. CTV:for tranfer of crew members.
Vessel Config-4	3:SOV,1: AHTS, 1: Cable laying,1:DP2 cable laying	CSOV: towing turbine unit from port to farm site, AHTS: for installation and connection of mooring system. Cable laying:inter-array cable laying and connection. DP2 cable laying: export cable laying

6.2 Batch Number

Simulations were conducted for varying batch numbers and the corresponding batch size for around 150 scenarios. The batch number indicates the number of phases in which the units are installed and commissioned. The batch size indicates the number of turbine units installed on the offshore farm site. The simulations are conducted to analyze the impact of batching phases and batch sizing on the installation cost. The results indicate the opportunity to generate revenue when installation and commissioning are done in phases. For the batch number of more than one the revenue generated surpasses the cost of midstream installation when installed and commissioned. Ideally, it would be preferred to install and commission all the turbine units in one year. But the capacity constraints and the resource constraints as well as metocean conditions cause a hindrance. The results demonstrate, installing and commissioning in batches provides a cost-income generation benefit for the developers irrespective of the increased vessel commissioning costs of multiple batch grid connections.

6.3 Batch Size

The impact of the variations in three factors namely, different vessel types, availability of the weather windows, and port capacity, on the carbon emission during the installation phase is also analyzed for computing the optimal batch size of the wind turbine units to be installed and commissioned in phases. The estimation of the batch sizes to be phased annually is calculated for the primary objective of low carbon emissions and low-cost impact and the earliest available deployed energy generation to provide the earliest income stream from the partially deployed field. Alongside the optimal batch sizes for the low carbon emission objective, the optimization tool also provides an opportunity to know the different possible options while considering the tradeoff between the carbon emissions, cost of installation, and the estimated revenue generation.

6.4 Impact of Port capacity, vessel configuration, and weather windows

Intuitively, the availability of a larger weather window provides buffers to the capacity of the port. The results also demonstrate that vessel configurations with a larger number of operational weather windows i.e. vessel configurations 1 and 4 in this study, generate the greatest number of batching options for the installation of 34 wind turbines (15 MW per turbine, populated in ~500 MW farm capacity). The simulations demonstrate that as the availability weather window decreases the possible choices of the batching diminishes. Given the current infrastructural availability and capacity of the port, there would be constraints on the port's holding capacity. So, on the basis of the current capacities of the ports, it is assumed that the maximum holding capacity for Port Talbot, Milford Haven, and Falmouth is 6,4 and 2 turbine units respectively based on independently sought expert opinion. The results demonstrate that for vessel configurations 2 and 3, with the available number of weather windows (8 and 10, respectively) the installation batching i.e. (year 1, year 2, year 3) could be done in three possible options, either (12, 10, 12), (12,12,10) or (10, 12, 12). The carbon emission and the cost for all three of these options for vessel configurations are equivalent. However, the possibility of early revenue generation indicates option (12, 12, 10) as a preferred choice for a developer seeking the earliest revenue stream to enhance the liquidity of early-year project cash-flows. In instances where the available weather window increases beyond 12 then the possible options increases from 3 batching options to 21 batching options. Conversely, vessel configurations 1 and 4, where the available number of weather windows is significantly greater ranging between 15 to 20, generate the largest number of batching options. Figure 6.4 presents the carbon emissions generated for the four-vessel configurations with different batching options. Vessel configuration 4 is observed to have the lowest carbon emissions under the baseline port constraint. Vessel configuration 1 generates the highest operational income-cost metric under the baseline port capacity constraint but at a significant emissions penalty relative to all other fleet configurations.

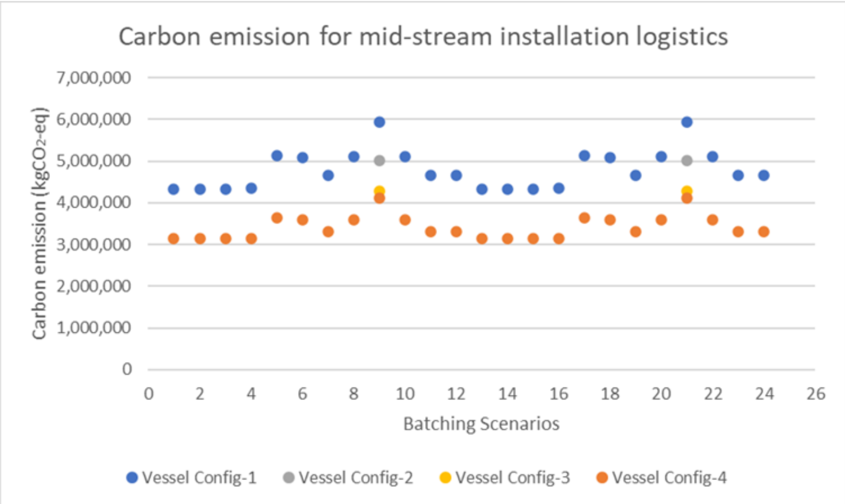

Figure 6.4: Carbon emissions for different vessel combinations, baseline port capacity.

For the purposes of investigating the investment case for local regional port infrastructure, development batching scenarios (as shown in appendices I and II) have been calculated for the four identified fleet combinations but with an assumed doubling of existing capacity at each regional port considered in the analysis. Figure 6.5 illustrates that the enhanced infrastructure and associated ports capacity generate a larger number of batching options across the range of fleet configurations considered. In this instance vessel configuration 2 is observed to have the lowest carbon emission and highest operational income-cost metric under the enhanced port capacity constraint. The enhanced port capacity allows accelerated parallel installation of wind turbine units and effective fast-tracking of the installation task.

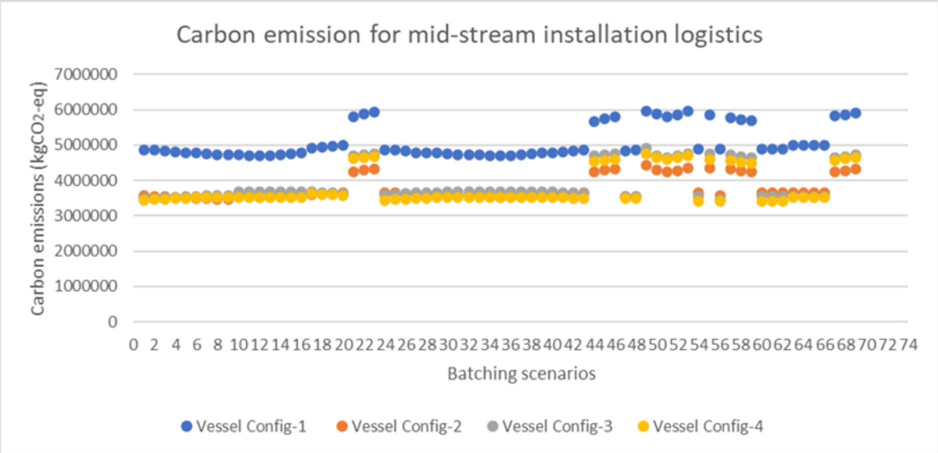

Figure 6.5: Carbon emissions for different vessel combinations, enhanced port capacity.

Table 6.4 and 6.5 describes the optimal batch size for each vessel configuration such that the carbon emission is minimized.The mid-stream installation costs and the revenue generated during installation stage is also included in the tables. The two tables represent the results considering baseline port capacity and future enhancement to twice the current capacity. The available weather windows are shown alongside the vessel configuration number.

Table 6.4: Batch size for each vessel configuration with lowest carbon emission for baseline port capacity.

Scenarios batch size (batch1, batch2, batch3)	Vessel configuration; number of available weather window in a year	Baseline port capacity		
		Carbon emission ($kgCO_2$-eq)	Mid-stream installation cost (£)	Revenue during installation stage (£)
15, 15, 4	1; 15	5,430,427	82,469,030	232,137,326
12, 12, 10	2; 15	4,431,358	98,174,833	231,165,524
12, 12, 10	3; 8	4,286,937	165,831,187	231,165,524
15, 15, 4	4; 8	3,154,161	166,466,919	232,137,326

For the baseline port capacity as well as enhanced port capacity, vessel configuration 4 represents the results with minimum carbon emission having the batch size as 15 for year 1, 15 for year 2, and 4 for year 3 for the baseline and 19,15,0 respectively in the enhanced scenario. However, the highest annual income – overall cost is achieved when you also consider the constraint of the lowest increase in aggregate carbon emissions from vessel configuration 2 albeit at the expense of nearly 1,000 tonnes of increased emissions with a 12,12,10 batch size configuration.

Table 6.5: Batch size for each vessel configuration with lowthe est carbon emission for enhanced port capacity.

Scenarios batch size (batch1, batch2, batch3)	Vessel Configuration, number of available weather window	Enhanced port capacity		
		Carbon emission ($kgCO_2$-eq)	Mid-stream installation cost (£)	Revenue during installation stage (£)
19, 15, 0	1;15	4,876,206	72,777,546	243,151,084
19, 15, 0	2;15	3,660,784	93,379,901	243,151,084

19, 15, 0	3;8	3,559,357	154,692,109	243,151,084
19, 15, 0	4;8	3,408,949	128,402,933	243,151,084

For cost minimization as the primary objective, fleet configuration 1 is the least cost option but with the highest carbon emissions.The fleet configurations 2 and 3, display that the carbon emissions and the cost decreases when the current capacity of the port is extended. This indicates that the extension in the port capacity would be utilized to reduce the challenges due to a limited number of available weather windows. The increase in the port capacity allows the parallel installation of the turbine units enabling a greater number of installations to be achieved within the limited availability of the weather window. Parallel installations require a greater number of vessels to be deployed and resulting in total costs being only marginally lower than achieved under the baseline port capacity constraint.

6.5 Carbon Intensity of Installation Strategy

Infrastructural development to enhance the port capacity and the exploitation of vessels with higher vessel operational limits (fleet combinations 1 and 4) enables the performance of installation tasks in harsher weather conditions generating significant costs benefits but at the expense of significant increases in the carbon intensity of installation tasks in the case of fleet configuration 1. A lowest emissions strategy would refute the case for port investment in purely carbon terms with the high vessel limit capability fleet operating from the port most adjacent to the farm being fully utilized before deferring to more remote ports is the carbon output of choice.

7 Interpretation

Weather windows restrict the pace of installation for vessels with lower vessel limits. However, with innovation in vessels design, it would be soon possible to have larger vessels with higher tolerance to the metocean conditions. It is clear from the results that, the vessels with higher tolerance limits fleet configuration 4 yields the largest number of available weather windows and generates aggregately lower carbon emissions irrespective of infrastructure investment. Deploying vessels with higher tolerance limits is an appropriate strategy to achieve low carbon and low-cost installation within the due date. It is recognized that the availability of a high vessel capability fleet option would be a significant operational constraint in practice. In practice, less capable fleet options including those deployed in the study will play a role in practice. In such cases, the cost and the carbon emissions are expected to be higher, as shown by the results, due to the need for deploying a greater number of vessels for parallel installations. The baseline port capacity poses a challenge to the feasible parallel installations. This constrained scenario indicates that there are chances for schedule slippage and installation would be delayed leading to major cost implications. One of the opportunities to tackle this challenge is through expansion in the port infrastructure to enable them to deploy a greater number of preassembled wind turbine units. The current study would indicate there is an opportunity to invest in a more capable vessel fleet against a backdrop of enhanced port capacity while achieving a significant reduction in operational cost for the farm site considered (CFA Site 1) but with only a marginal increase in aggregate emissions (8%). In the instances where only a less, capable fleet is available significant port infrastructure is necessitous to significantly reduce aggregate carbon emissions (In excess of a 20% reduction in aggregate carbon emissions for vessel fleet combination 2).

8 Further Work

One of the obvious extensions of the model is to estimate the end-to-end logistics functions and their corresponding carbon emission, cost, and revenue generation. The current model optimizes the batch sizes of the turbine units to be installed annually, which is an input to the upstream manufacturing, production planning and hence, scheduling the logistics functions linking mid-stream and upstream activities will provide an opportunity of integrated supply chain and thus, affect the cost and the carbon implications of the installation. Further, the current model assumes the availability of the vessels to be flexible. However, the availability of the vessels is in practice limited and the model will need to extend to consider resource constrained logistics scheduling and batching for minimizing the installation costs and carbon emissions. Batching or phasing of installation means early energy production and will affect the operations and maintenance of the turbines with the earlier operation of part of the field necessitating earlier planned maintenance and unscheduled maintenance tasks. In the future, the effect of installation strategies for logistics efficiency on O&M strategies will need to be inter-linked.

The assessment of energy production in this study has been simplified by using a static capacity factor, without considering the realistic wind resources pertaining to the chosen farm site and the wake effects associated with the positioning of wind turbines. For future studies, the wake effects in a specified farm design will be evaluated using analytical wake calculation models, e.g., Jensen's model. The partial overshadowing as a result of relative distances among wind turbines in a wake field will also be accounted to enable realistic simulation of energy production and its impact on installation and O&M strategies for the development of floating offshore wind farms. In fact, a wake calculation has been incorporated in the E^c simulator to enable farm layout optimization. Finally, the key performance indicators in the lifecycle assessment, e.g., LCOE, Carbon Intensity, and Energy Return on Energy Invested (ERoEI), will be calculated for the identified optimal low carbon installation solutions using E^c simulator, to further verify their effectiveness and provide insights for the installation of floating offshore wind farms in real life.

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Appendix:

Appendix I: The feasible batching scenarios for baseline port capacity

Installation				Baseline Port capacity			
				Weather window = 15		Weather window = 8	
Batching Scenarios	Installation Batch 1	Installation Batch 2	Installation Batch 3	Vessel Configuration 1	Vessel Configuration 4	Vessel Configuration 2	Vessel Configuration 3
1	4	15	15	✓	✓	-	-
2	5	15	14	✓	✓	-	-
3	6	14	14	✓	✓	-	-
4	7	13	14	✓	✓	-	-
5	8	12	14	✓	✓	-	-
6	9	11	14	✓	✓	-	-
7	10	10	14	✓	✓	-	-
8	11	10	13	✓	✓	-	-
9	12	10	12	✓	✓	✓	✓
10	13	10	11	✓	✓	-	-
11	14	10	10	✓	✓	-	-
12	15	10	9	✓	✓	-	-
13	15	4	15	✓	✓	-	-
14	15	5	14	✓	✓	-	-
15	14	6	14	✓	✓	-	-
16	13	7	14	✓	✓	-	-
17	12	8	14	✓	✓	-	-
18	11	9	14	✓	✓	-	-
19	10	10	14	✓	✓	-	-
20	10	11	13	✓	✓	-	-
21	10	12	12	✓	✓	✓	✓
22	10	13	11	✓	✓	-	-
23	10	14	10	✓	✓	-	-
24	10	15	9	✓	✓	-	-

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Appendix II: The feasible batching scenarios for enhanced port capacity

Installation				Enhanced Port capacity			
				Weather window = 15		Weather window = 8	
Batching Scenarios	Installation Batch 1	Installation Batch 2	Installation Batch 3	Vessel Configuration 1	Vessel Configuration 4	Vessel Configuration 2	Vessel Configuration 3
1	1	15	18	✓	✓	✓	✓
2	2	15	17	✓	✓	✓	✓
3	3	15	16	✓	✓	✓	✓
4	4	15	15	✓	✓	✓	✓
5	5	15	14	✓	✓	✓	✓
6	6	14	14	✓	✓	✓	✓
7	7	13	14	✓	✓	✓	✓
8	8	12	14	✓	✓	✓	✓
9	9	11	14	✓	✓	✓	✓
10	10	10	14	✓	✓	✓	✓
11	11	10	13	✓	✓	✓	✓
12	12	10	12	✓	✓	✓	✓
13	13	10	11	✓	✓	✓	✓
14	14	10	10	✓	✓	✓	✓
15	15	10	9	✓	✓	✓	✓
16	16	10	8	✓	✓	✓	✓
17	17	10	7	✓	✓	✓	✓
18	18	10	6	✓	✓	✓	✓
19	19	10	5	✓	✓	✓	✓
20	20	10	4	✓	✓	✓	✓
21	21	10	3	✓	✓	✓	✓
22	22	10	2	✓	✓	✓	✓
23	23	10	1	✓	✓	✓	✓
24	15	1	18	✓	✓	✓	✓
25	15	2	17	✓	✓	✓	✓
26	15	3	16	✓	✓	✓	✓
27	15	4	15	✓	✓	✓	✓
28	15	5	14	✓	✓	✓	✓
29	14	6	14	✓	✓	✓	✓
30	13	7	14	✓	✓	✓	✓
31	12	8	14	✓	✓	✓	✓
32	11	9	14	✓	✓	✓	✓
33	10	10	14	✓	✓	✓	✓
34	10	11	13	✓	✓	✓	✓
35	10	12	12	✓	✓	✓	✓
36	10	13	11	✓	✓	✓	✓
37	10	14	10	✓	✓	✓	✓
38	10	15	9	✓	✓	✓	✓
39	10	16	8	✓	✓	✓	✓
40	10	17	7	✓	✓	✓	✓
41	10	18	6	✓	✓	✓	✓
42	10	19	5	✓	✓	✓	✓
43	10	20	4	✓	✓	✓	✓
44	10	21	3	✓	✓	✓	✓
45	10	22	2	✓	✓	✓	✓
46	10	23	1	✓	✓	✓	✓
47	5	10	19	✓	✓	✓	✓
48	5	9	20	✓	✓	✓	✓
49	10	5	21	✓	✓	✓	✓
50	1	12	22	✓	✓	✓	✓
51	1	10	23	✓	✓	✓	✓
52	5	5	24	✓	✓	✓	✓
53	5	4	25	-	-	-	-
54	1	7	26	-	-	-	-
55	1	6	27	-	-	-	-
56	1	5	28	-	-	-	-
57	24	10	0	✓	✓	✓	✓
58	25	9	0	-	-	-	-
59	26	8	0	-	-	-	-
60	27	7	0	-	-	-	-
61	28	6	0	-	-	-	-
62	29	5	0	-	-	-	-
63	30	4	0	-	-	-	-
64	31	3	0	-	-	-	-
65	32	2	0	-	-	-	-
66	33	1	0	-	-	-	-
67	15	0	19	✓	✓	✓	✓
68	10	24	0	✓	✓	✓	✓
69	9	25	0	-	-	-	-
70	8	26	0	-	-	-	-
71	7	27	0	-	-	-	-
72	6	28	0	-	-	-	-
73	5	29	0	-	-	-	-
74	4	30	0	-	-	-	-
75	3	31	0	-	-	-	-
76	2	32	0	-	-	-	-
77	1	33	0	-	-	-	-
78	0	15	19	✓	✓	✓	✓
79	11	23	0	✓	✓	✓	✓
80	12	22	0	✓	✓	✓	✓
81	13	21	0	✓	✓	✓	✓
82	14	20	0	✓	✓	✓	✓
83	15	19	0	✓	✓	✓	✓
84	16	18	0	✓	✓	✓	✓
85	17	17	0	✓	✓	✓	✓
86	18	16	0	✓	✓	✓	✓
87	19	15	0	✓	✓	✓	✓
88	20	14	0	✓	✓	✓	✓
89	21	13	0	✓	✓	✓	✓
90	22	12	0	✓	✓	✓	✓
91	23	11	0	✓	✓	✓	✓
92	34	0	0	-	-	-	-
93	0	0	34	-	-	-	-
94	0	34	0	-	-	-	-