FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

O&M optimization for multi-asset offshore renewable energy parks

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FINAL VERSION

Master in Electrical and Computer Engineering

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August 31st, 2022

Abstract

Large-scale offshore parks have a number of logistical and technical challenges that decisively impact their cost and implementation. All aspects of running a hybrid park, especially Operations and Maintenance, need to be properly studied to ensure a smooth transition to larger parks.

The aim of this dissertation is to model a large scale hybrid energy park, taking into consideration floating solar and bottom-fixed wind energy sources, while integrating the relevant maintenance activities and energy production models. In this context a Mixed Integer Programming (MIP) optimization model was developed to aid in finding the best Operations and Maintenance (O&M) solution, for a given scenario, while minimizing its costs. This model looks to minimize, downtime Costs, vessel decisions costs, staff costs and repairs costs. It considers weather conditions (for both energy generation, and Vessel decision), vessels characteristics (Vessel Speed, Vessel Thresholds), nodes characteristics (Mean Time to Failure, Power Output).

Acknowledgements

I want to thank a few people for the help and support they gave in this dissertation, and also to the whole six year journey that led to this.

Firstly I want to thank Luis Guimarães, my thesis supervisor.

Next, I want to thank my family, for always being there when needed. Specially my parents, my sister and João. (And Mr. Spark)

I also want to thank my other family, my dear friends: Nuno, Bia. David, Tomás, Mariana, Zé, Andreia, Rita. Tiago, Leo, João. Ana, Catarina, Filipa. Mota, and Traudi. I love you, guys!

Lastly I want to leave a special thanks to my dear friend Viana. Without you, I don't think I'd have finished this.

A sincere thank you,

Francisco

“Lost time is never found again”

Benjamin Franklin

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Abbreviations AND Symbols

CAPEX	Capital Expenditures
CBM	Condition Based Maintenance
CM	Condition Monitoring
CT	Computational Tools
DR	Discount Rate
FR	Failure Rate
IEA	International Energy Association
LCC	Lifetime Cycle Costs
LCOE	Levelized Cost of Energy
MIP	Mixed Integer Programming
MTBF	Mean Time Between Failture
MTTF	Mean Time to Fail
MTTR	Mean Time to Repair
NPV	Net Present Value
OPEX	Operational Expenditures
ORE	Offshore Renewable Energy
OWF	Offshore Wind Farm
OWT	Offshore Wind Turbine
O&M	Operations and Maintenance
PV	Photovoltaic
RKP	Repair Kit Problem
R&D	Research and Development
SC	Supply Chain
SOV	Service Operation Vessel
VL	Vessel Leasing
VS	Vessel Sharing
VHS	Vessel and Harbour Sharing
WEC	Wave Energy Converter
WT	Wind Turbine

Chapter 1

Introduction

1.1 Problem

Every large-scale offshore park project is affected by several challenges, technical and logistical. These obstacles will influence expenditure and the implementation. In a hybrid park, particularly operations and maintenance must be properly studied to ensure that scaling up the project is a smooth process. This is one of the objectives of the European project in which this dissertation is inserted - EU-SCORES (**EU**ropean - **S**calable and **C**omplementary **O**ffshore **R**enewable **E**nergy **S**ources).

1.2 Project Context

The EU-SCORES project has received approximately 45M€ of funding and is being coordinated by the Dutch Marine Energy Centre (DMEC), porject in which INESC TEC also takes part and where this work takes place (table 1.1). In Portugal, EDP and WavEC [13] are two additional participating institutions, besides INESC TEC, in which several investigation centres are involved, namely, Centro de Sistemas de Energia (CPES), Centro de Engenharia e Gestão Industrial (CEGI), Centro de Robótica e Sistemas Autónomos (CRAS) and Centro de Fotónica Aplicada (CAP).

Currently, nearly 21000 TWh are consumed worldwide every year, figure which is expected to double in the next 30 years. The EU has set ambitious goals in regards to green house gas emissions for 2050, and, in order to achieve them, the EU has also set a target of producing 300 GW via offshore wind plants [6] and 40 GW off ocean wave produced energy [14]. To accomplish these targets, a big emphasis should be put on efficient production and effective use of offshore renewable energy. Francisco Correia da Fonseca [13], a Senior Engineer at WavEC is of the opinion that that the global energetic transition will consist on the efficient and sustainable exploration of the ocean, which is possibly one of the most important resources in Portugal. He also has expressed that this project presents an excellent opportunity to showcase innovative concepts that may propel the renewable offshore energy industry in Portugal and Europe [13].

Table 1.1: List of participants in EU-SCORES Project Team

No.	Participant Name	Country
1	Dutch Marine Energy Centre	Netherlands
2	INNOSEA – LOC Group	France
3	Technische Universiteit Delft	Netherlands
4	Uppsala University	Sweden
5	Exceedence	Ireland
6	INESC TEC	Portugal
7	Oceans of Energy B.V	Netherlands
8	CorPower Ocean	Sweden
9	WavEC Offshore Renewables	Portugal
10	POM-WVL Blue Accelerator	Belgium
11	Lappeenranta-Lahti University of Technology	Finland
12	RINA offshore consultants	Italy
13	RWE Renewables	Germany
14	Energias de Portugal Labelec	Portugal
15	ENEL Green Power	Italy
16	SBM Offshore Group	Netherlands
17	Western Star Wave Limited, a Simply Blue Group company	Ireland

Portugal is a pioneer in the industry, with the first European offshore wind park having been built in Viana do Castelo, a city in the North of Portugal. EDP was largely responsible for this project. João Maciel, EDP's R&D Director, confirmed that, with this project, they intend to explore several technologies in deep sea and demonstrate how much it contributes to the production and consumption of clean energy [13].

The EU-SCORES project will have two pilots, one in Belgium, and another in Portugal. In Portugal, by the coast of Póvoa de Varzim, a wave energy park will be built, close to a wind energy park off the shore of Viana do Castelo, which will allow the project to obtain relevant data due to proximity.

1.3 Offshore Renewable Energy

According to the International Energy Agency (IEA), renewable energy accounted for 28.6% of the total global electricity generation in 2020 [15]. While this percentage is a record high value, significant efforts are needed to meet the "Net Zero Emissions by 2050" scenario [15]. The exploitation of renewable energy resources plays an important role in reducing the emission of carbon dioxide (CO2), which has had a big impact on the environment since the 18th century [16][17][18].

Currently, a wide range of onshore renewable energy resources are being exploited at a large scale, namely, bioenergy, hydropower, wind, solar, and geothermal energies [19]. However, the available onshore sites matching satisfying conditions for deployment are decreasing in quantity, making offshore renewable energy resources an attractive alternative [20]. Additionally, the development of renewable energy farms offshore is not hindered by human activities nor urban buildings, as is the case onshore. On the other hand, it has an increased cost and decreased reliability, proportional to the farms' distance from the shore [19].

Offshore renewable energy farms can produce energy using offshore wind, sunlight, waves and tides [19], with the first having been built in 1991, in Denmark [20]. Offshore wind energy is the most promising offshore renewable energy resource, having experienced a total market growth of 30% between 2010 and 2018 [21]. Furthermore, most of the renewable electricity produced offshore today comes from wind energy, with several farms installed in Europe [22].

Recently, the combination of different types of offshore renewable energies into a single hybrid system has been explored and shown to be more sustainable [23]. In the past decade, multiple hybrid systems exploiting wave and offshore wind energy have been installed across Europe as part of renewable energy projects such as H2OCEAN [24], MARINA [25], MERMAID [26] and TROPOS [27].

1.4 Offshore Operations & Maintenance

Babatunde [28] mentions that:

> "The challenges of offshore wind energy projects include, significantly high support structure cost, high Operating and Maintenance costs, high electrical infrastructure costs, high turbine costs, stricter environmental standards, and less developed construction techniques!"

The focus of the present dissertation is on the Operations and Maintenance (O&M) of a offshore hybrid park. Baagøe-Engels [11] mentions that repairs are considerably more expensive offshore than onshore. Not only the park needs expensive vessels for the maintenance, it's also weather dependant, which affects the repair times. Literature shows that the costs of O&M account for 20 to 40 percent [29].

For that reason, there's a need of development of O&M strategies, precisely in order to reduce the costs of energy. With the development of the offshore wind parks industry, O&M related business will be of great importance.

O&M expenses are composed by all the daily associated activities related to the management of the wind farm. Labour, spares parts, transportation of people and materials, chartering of equipment for maintenance and repairs, including jack-up vessels.

Figure 1.1 shows a cost breakdown of a typical offshore wind park.

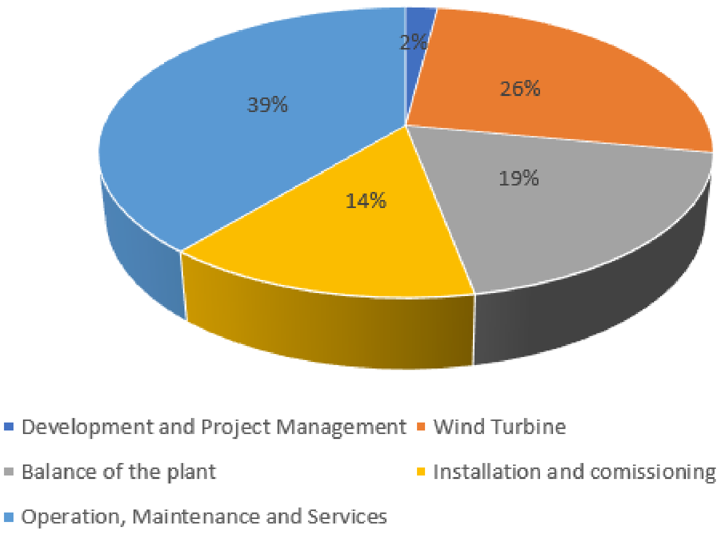


Figure 1.1: Cost Breakdown of a typical offshore wind farm

1.5 Objectives

The focus of this dissertation is to study and model the O&M, as well as its logistical and technical obstacles, in the case of an offshore hybrid park.

The model should integrate maintenance activities and energy production models, as well as take into account several inputs and problem aspects, namely:

- Environmental variables, such as wind speed, wave height, wave frequency.
- Energy output.
- Transport variables, such as availability and operability.
- Failure rates, types of failures, reliability.
- Repair efficiency.
- Crew members.

1.6 Document structure

This dissertation is divided in several chapters. The Chapter 2 presents an analysis of the state of the art. The main focus is on wind energy, as there's much more literature on this type of offshore farms than the others. The relevant literature is presented as means to find solutions on challenges that arise from trying to optimize Operations and Maintenance in offshore farms. Chapter 3 describes the problem and includes the model formulation. In the Chapter 4 data is gathered and processed, for a future simulation. Chapter 5 concludes this document, with an overview of the work that was done, as well as suggesting future research avenues.

Chapter 2

Literature Review

In this Section, a Literature review on the types of energy of the offshore farm takes place. Themes such as Operations and Maintenance, Failures, Reliability, Vessels, Weather Constraints are explored, as well as some models and tools examples.

Before following through with the analysis of the theoretical background on this subject, tt is worth noting that the idea of hybrid offshore parks is relatively new, and consequently, the literature on it is lacking. However individual offshore parks, for example wind based ones, even if the industry is recent, the literature is further developed.

Therefore, the plan for this section and next is to analyze in-depth wind offshore parks, its problems and proposed solutions.

2.1 Energy sources

In the scope of this dissertation it is important to understand the simple concepts, such as the types of energy being harnessed from the parks. This work focuses on hybrid parks, from the perspective that it combines more than one type of renewable resource: Wind energy, wave energy, and solar energy.

Wind energy, produced by wind power, is defined as the process of creating electricity through wind, or air flows that occur naturally in the earth's atmosphere. The wind turbines [WT] capture kinetic energy from the wind and generate electricity [30].

Solar energy is the transformation of sun rays into power, through photovoltaic (PV) cells [31]. The Photovoltaic cell is a solid-state mechanism like a transistor or microchip that utilizes the physical characteristics of a semiconductor to turn the sunlight into electricity. The reason why it's so appealing as a source of power, is due to its simplicity and durability [32].

Wave energy collecting can be explained as the capture and transformation of the kinetic energy of waves of the deep water or waves hitting the shores into electrical energy. This process is done through Point Absorbers.

These three types of parks are, at the moment, trending and can be seen everywhere. Precisely one of the biggest drawbacks of said parks is the noise pollution they create and their impact on the landscape. For offshore parks, these downsides no longer apply, or are less of a concern.

2.1.1 Wind Parks

In this chapter, there is a focused analysis on the wind energy parks, as is the most explored of the three, and the one that has the most literature about.

The power wind has always been used by people. It can be traced back to medieval times, it was used to pump water, and in windmills. For several centuries, fossil fuels were the main source of energy, damaging the environment [10]. This made People look for alternatives, and the wind, being a cheap, reliable, available to all, and environmentally friendly, alternative, led to now, it being adopted as a mainstream way of producing energy [10].

In the following table (2.1) are shown both main points in favor and drawbacks of wind parks in general.

Table 2.1: Advantages and Disadvantages of wind parks [9]

Advantages	Disadvantages
Cost effectiveness. Wind is one of the cheapest sources of energy accessible.	Unpredictability. The output power is dependant on direction and speed of the wind.
Clean source of energy. It does not pollute the air, like fossil fuels do.	Wind farms are expensive to construct.
Sustainable source of energy. It is not finite.	Local wildlife endangered.
Low running costs. When turbines are up and running.	Noise Pollution, and damaged landscape.

2.1.2 Offshore Wind Parks

Wind energy can be identified as either onshore or offshore. Offshore wind energy has become an increasingly attractive option.

When compared to onshore parks, offshore ones have several points going in favor and against. In the following table (2.3) is presented an overview of this.

Table 2.2: Advantages and disadvantages of Offshore wind parks [10, 11]

Advantages	Disadvantages
Offshore wind turbines are more efficient than on shore ones. Winds are stronger in the ocean, producing more output energy.	Big upfront investment needed, for construction purposes. Transportation of Human Resources and of parts and materials are expensive. O&M costs are overall higher.
Wind turbines can be bigger, permitting more energy to be harvested by the turbines. Being offshore there's less constraints space wise.	Relatively new industry. Limited access to O&M work.
Does not pose threat to (in-land) wild life.	Sea life is known to be impacted, but the effects have not been studied yet.
Noise Pollution and landscape no longer a issue.	Unpredictability from the sea and weather. Wind turbines suffer more from wind and waves.

Table 2.3: Advantages and disadvantages of Offshore wind parks [10, 11]

The offshore industry is still considered undeveloped [11].

2.1.3 Solar Parks

Similarly to wind energy, solar power is a cheap solution compared to other sources of energy, available to all. The power of the sun has been used forever, but only after the discoveries of the nineteenth century was this potential source of energy fully exploited[33]. Fueled by the space race in the 20th century, and the energy crisis of 1973, countries invested funds into alternative sources of energy, and solar power benefited from it [33] .

Currently the market is overwhelmingly led by Asian countries, namely China. In 2020, the latter accounted for 67% of the world's production, with Asia as a whole being responsible for 92% of the world's production [1]. In Figure 2.1 a graph is shown, showcasing the Asian continent's dominance in the solar energy industry.

2.1.4 Offshore Solar Parks

As is the case for wind energy, solar floating PV systems in oceans, lakes, pounds, reservoirs, have begun to be considered as a new viable solution for RE production. It is estimated that around half of the world population lives less than 100km from the coast [34], making it an attractive solution to provide electricity for big coastal cities.

The first countries to install FPVs were the United States of America and Japan, less than 20 years ago. Currently China leads the market, with Portugal being one of the notable players.

In the following table (2.4) are showcased a few characteristics of Offshore solar parks, some more favorable than others.

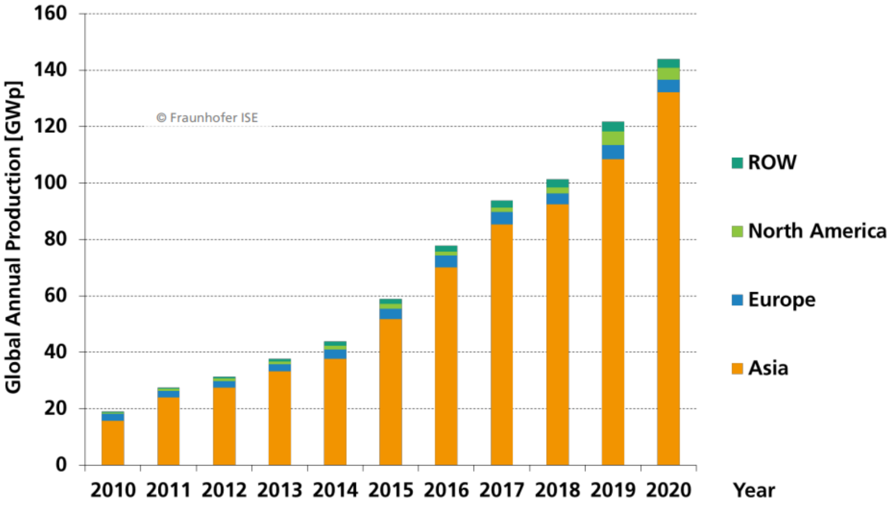


Figure 2.1: Distribution of solar energy production, on a yearly basis [1]

Table 2.4: Advantages and Disadvantages of Offshore Solar Parks

Advantages	Disadvantages
Increased solar incidence, meaning more power generation.	Exposure to marine elements like water, salinity, humidity.
Less obstacles causing shadow loss.	Exposure to algae and small marine life.
Minimizes use of land.	Faster corrosion and degradation.
Better efficiency of the FPV due to evaporative cooling.	Installation costs and challenges.
Lower quantity of dust.	Anchoring and mooring problem.
Reduces the formation of waves.	Overall Technological Challenges.
Reduces evaporation of water in lakes, ponds, reservoirs.	Operation and Maintenance Challenges.

2.1.5 Wave Parks

The power of the waves is very strong, and that motivated people to try to make use of it.

Yoshio Masuda, a japanese naval commander, is regarded as the father of modern wave energy technology, being responsible for the development of Oscillating Water Columns (OWCs), a type of wave energy converter that was commercialized by Japan in 1960's.

Wave Energy is a powerful and predictable source of energy and is arguably not utilized to its maximum potential. Nevertheless, the overall interest on the industry is increasing, with a few new commissionings. The Levelized Cost of Energy (LCOE) is reported to range between 120 to 500€/MWh [35].

Wave Energy Converters (WEC) can be divided in three categories, Attenuators, Point Absorbers and Terminators. Different types of WEC also have different modes of operating, Submerged pressure differential, oscillating water surge converter, oscillating water column and overtopping device. In the following figures, a Attenuator (2.2), a Point Absorber (2.3) and a Terminator (2.4) are presented.

Figure 2.2: Example of an Attenuator [2]

Figure 2.3: Example of a Point Absorber [3]

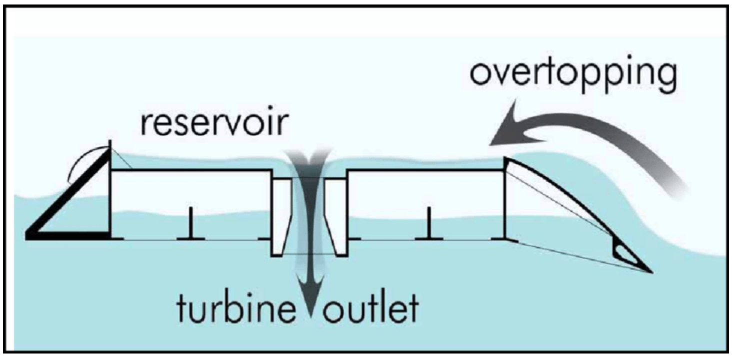


Figure 2.4: Example of a Terminator (overtopping) [4]

2.2 CAPEX OPEX LCOE

The following concepts will be referenced throughout the work. **CAPEX** (Capital Expenditure) is related to every affair before the commissioning of the offshore wind park, from design, localization, logistics, project management, etc. [36] **OPEX** (OPerating EXpenses) refers to all the costs regarding the day-to-day management of the offshore wind park [36]. **LCOE** (Levelized Cost Of Energy) is the "discounted lifetime cost of ownership and use of a generation asset, converted into an equivalent unit of cost of generation" [37].

LCC - (Lifetime Cycle Costs) are, as the name suggest, the sum off all costs, from purchase to the end of expected life

NPV - (Net Present Value) is the difference between the present value of money inflow and outflow in a period of time [38].

DR - (Discount Rate) is the interest rate used to determine future cash flows [38].

Below are shown three expressions interconnecting these concepts (2.1), (2.2) and (2.3).

$$LCOE = \frac{NPVTotalCosts}{NPVEnergyGeneration} \tag{2.1}$$

$$NPVTotalCosts = \frac{TotalCAPEXcosts + OPEXcosts}{1+DR} \tag{2.2}$$

$$NPVEnergyGeneration: = \frac{NetEnergyGeneration}{1+DR} \tag{2.3}$$

LCCs are divided in two classes of costs: CAPEX and OPEX. CAPEX involves the design of the park, its legal aspects, initial investments in its installation, comissioning and eventual decomissioning. OPEX involves the O&M costs. As it can be observed in figure 2.5.

Offshore Wind and Photovoltaics LCOE, and overall O&M costs are projected to decrease considerably in the next 30 years, as the two graphs (fig.2.6 and fig.2.7) show.

2.3 Operations and Maintenance - Costs of an Offshore Farm

O&M costs amount to a big percentage of the total costs of a project. This is heightened in a offshore projected, making up 23% of the total [39]. There are many variables that influence the costs of O&M in the case of an offshore farm. These costs can be divided in four parcels, namely, transportation, maintenance, loss of value and staff costs [40].

Transportation costs are related to distance to shore, fuel prices, the kind of vessel is used for the operation and its mobilization and docking costs, and the strategy used for the repair [40].

Maintenance can be either scheduled or provoked by a failure. Repair costs are associated to the failure of the part that needs repairs, the strategy that it is used, the cost of new parts, new parts delivery costs. Scheduled maintenance costs also depend on the strategy used [40].

Loss of value costs relate to resources available - availability- reliability, operability, environmental constraints like wind speed, wave height and visibility [40].

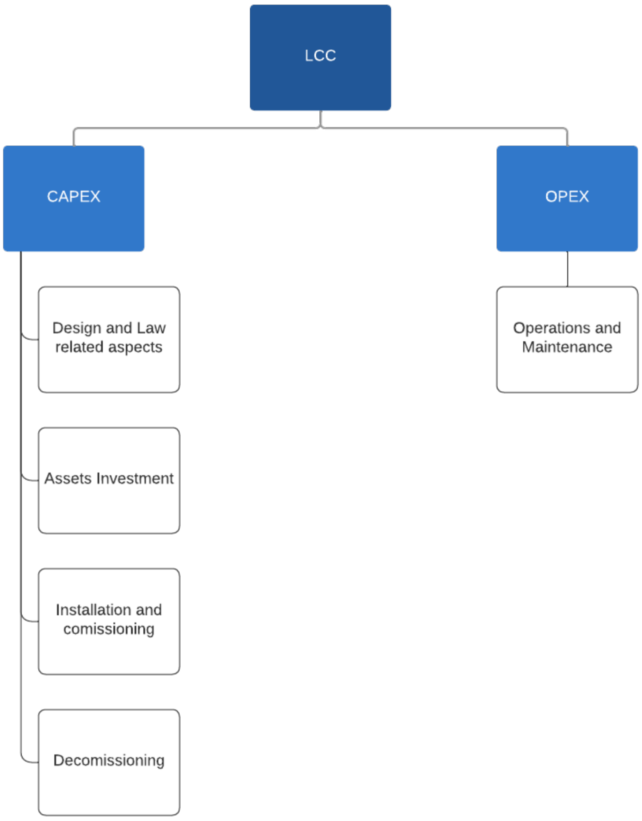


Figure 2.5: Lifetime Cycle Costs, CAPEX and OPEX

Human costs are linked to the staff needed for such operations. From the number of staff needed, to their salaries, shifts that are related to the strategy used for repairs and transportation [40].

2.4 Maintenance of an OWT - Offshore Wind Turbine

It is extremely important that operations and maintenance of a offshore wind turbine are maximized from a efficiency standpoint [12]. As the wind turbine is offshore, rapid accessibility is difficult, so urgent operations are hard to perform. And so, to prevent failures, maintenance must be performed regularly. However, its frequency must be optimum, as costs of a maintenance operation are quite high. The goal to a efficient maintenance is to maximize lifetime of the wind turbine components, while minimizing cost related operations, trips to the wind farm, staff related costs [12].

There are a few different approaches in regards to maintenance. The strategies are usually divided into three categories: corrective maintenance, proactive maintenance, and opportunistic maintenance [41] [12].

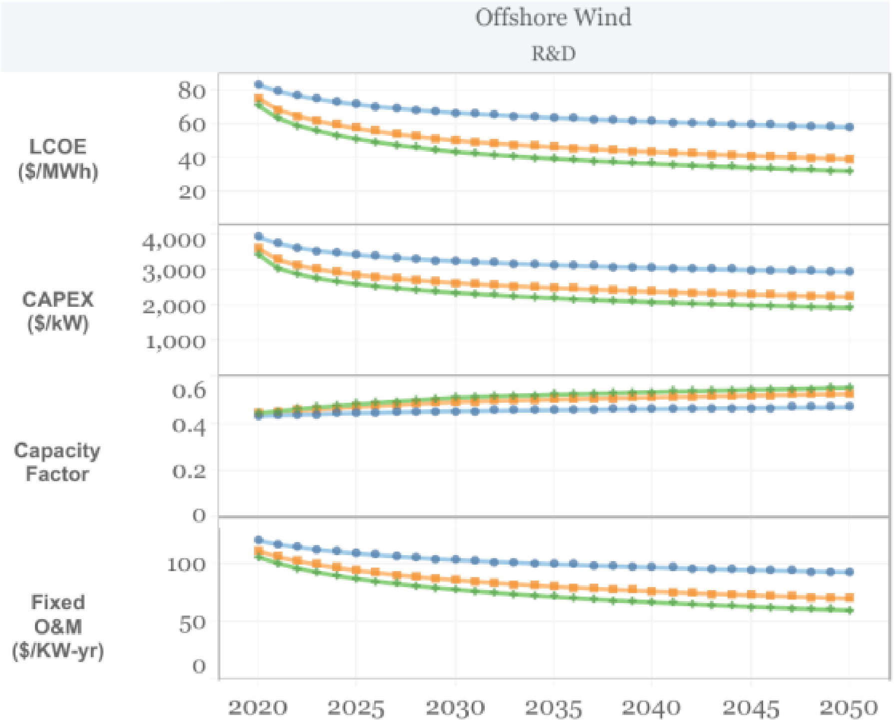


Figure 2.6: Offshore Wind projected LCOE, CAPEX and O&M Costs

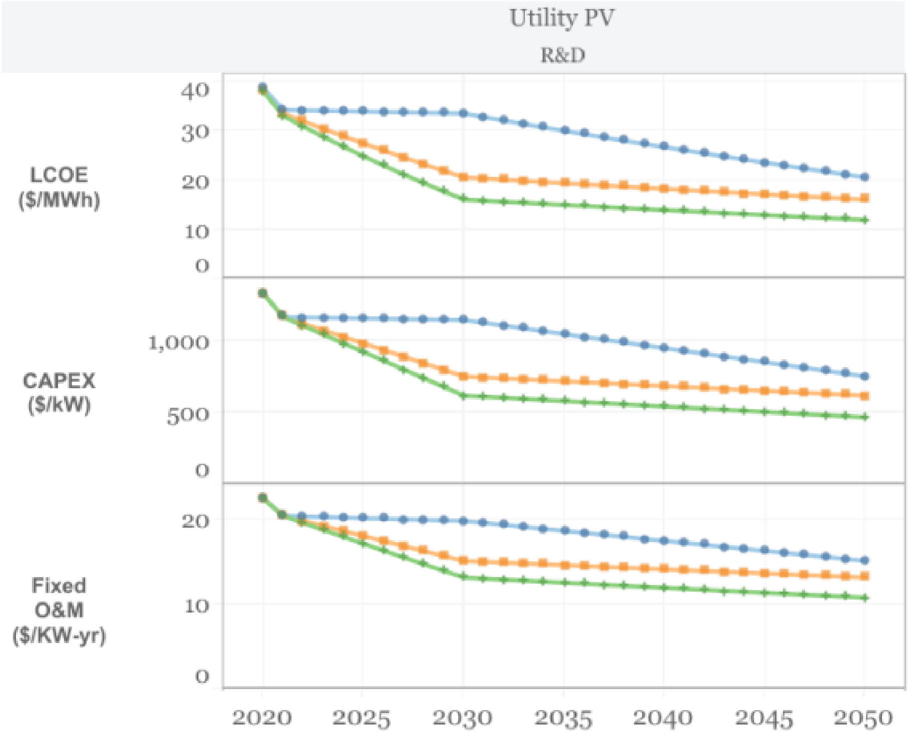


Figure 2.7: Photovoltaics projected LCOE, CAPEX and O&M Costs

Corrective Maintenance is associated with failures. Maintenance occurs when a failure occurs. This strategy is suitable to systems that have unimportant costs of downtime as it minimizes visits to the farm [12].

However, this is not the case for Offshore farms. Offshore farms usually are associated with high failure rates, and downtime costs are high [42].

Proactive Maintenance is, therefore, the way to go for offshore farms. With this strategy operations are carried out prior to major failures. It can either be Preventive, Condition Based Maintenance or Predictive [12] [43].

Preventive maintenance is a scheduled activity based on the reliability of the components [44]. Condition based maintenance CBM uses information from sensors that monitor the systems, to control the condition of the system, and that maintenance is executed before major failures. Predictive, as the name indicates, predicts when the system is going to need maintenance, avoiding major failures. It also uses information from sensors to outline a plan of maintenance [12].

2.5 Failures - WT Analysis

A wind turbine is a complex piece of engineering, mode of different components and parts. Each part susceptible to different kinds of failures.

Table (2.5) shows an overview of all the major failures associated with each part of an offshore wind turbine.

2.6 Reliability, Availability, Maintainability

For the context of this work, it is important to understand these three concepts. Reliability is defined as the probability of a operation being accomplished by a system. Reliability relates to an evaluation of the effects of failures in a system [45].

Availability is an estimate of the percentage of time that a system is operable. Availability requires an evaluation of the consequences of unsuccessful operability, and the system's needs in order to restore it to expected performance [45].

Maintainability is defined as the easiness and accuracy that takes the system to perform maintenance tasks after a failure is detected. It related to the time that a system takes to be reestablished, after it failed. Maintainability is associated with an evaluation of the accessibility and repairability of the system when a failure happens [45].

Other keywords and acronyms: FR - Failure Rate; MTTF - Mean Time to Failure; MTTR - Mean Time to Repair; MTBF - Mean Time Between Failures.

Table 2.5: Major Failures associated to components of a OWT [12]

Parts	**Major Failure**
Rotor and blade	Deterioration Corrosion Aeroelastic deflections Cracks Rotor imbalance
Shaft	Imbalance and misalignment Damage
Gearbox	Fatigue Oil leakage Elevated oil temperatures Insufficient lubrication
Generator	Overheat Vibrations Electrical phenomenons Wear High Speeds
Bearings	Overheat Wear Bearing damage
Nacelle	Fire
Tower	Fatigue Cracks Vibrations

2.7 Types of Vessels

For the sake of the O&M problem, there are a few types of vessels used for the operations and maintenance tasks [46] [47]. Helicopters (Fig. 2.8), Jack-up Vessels (Fig. 2.9), Crane Vessels (Fig. 2.10), Crew Transfer Vessels (Fig. 2.11), and other types of vehicles can be seen in the vicinity of a offshore farm, during operations and maintenance activities.

Each vessel has its advantages, disadvantages, limitations and trade-offs. Helicopters for example, are ideal for certain maintenance tasks, however they require high visibility, which may be impaired by fog. Additionally, high wind speeds and wave height may prohibit their use altogether. The same can be said for each of the remaining vessels, each having a wind speed and wave height threshold associated with them [47].

2.8 Different Strategies and Tools to Optimize O&M processes

2.8.1 Vessel Sharing

Jack-up vessels are self-elevating "ships" capable of lifting their frames from the water in order to provide a platform for large component maintenance/ repairs. These massive pieces of machinery

Figure 2.8: Helicopter Operation on a OWT [5]

Figure 2.9: Elevated Jack-up Vessel

are very much necessary in order to carry on repairs/maintenance even though leasing them brings high costs. Besides expensive, mobilization times are also high, therefore there need to be strategies trying to minimize theses costs and optimize O&M. Two solution proposed for this problem are, better chartering strategies and vessel sharing between parks [6].

Uit het Broek [6], in their paper, explore the idea of sharing jack-up vessels. The objective with this measure is to lower O&M costs by increasing the vessel use. They also explore the idea of harbour sharing.

There are several ways in which a jack-up related activity might get delayed and so resulting in extra costs. Leasing a jack-up, mobilisation time, elevation operations, demobilisation of the jack-up. Delays in the preparation for turbine component replacement, or in the parts delivery, or crew members transfer [48].

Vessel Sharing (VS) allows different service providers to join hands and buy a jack-up vessel

Figure 2.10: Crane Vessel

Figure 2.11: First Hydrogen Crew Transfer Vessel

(instead of leasing it) and use it to carry on all replacement services for all the wind farms. The jobs are done usually FIFO (First-In-First-Out) with few exceptions. The concept of vessel + harbour sharing is close to the VS one with the difference that the demobilization process now can be made in a shared harbour (see Fig. 2.12).

Uit het Broek's[6] findings show that vessel sharing approach brings down significantly the costs, with the right amount of collaborators. It's also stated that turbine availability is up and jack-up vessels utilization is on the rise too. In the case study there were multiple parks with 50 3MW turbines each separated by 100km. For these numbers if the vessel is shared with eight or more collaborators, then it starts to have a reverse effect. In this paper still there was a finding that goes against what was believed in literature: the effects of transit time on jack-up vessels use and cost were minor. And so the Vessel + Harbour Sharing (VHS) benefits were also minor [6].

2.8.2 Optimal Stock Levels - Repair Kit Problem

In order to reduce downtime of turbines it is necessary to transport the right amount of each component to the wind park. Less is bad, may not be able to finish the job; more induces extra costs. This is known as the RKP - Repair Kit Problem. The RKP does not account as much as it

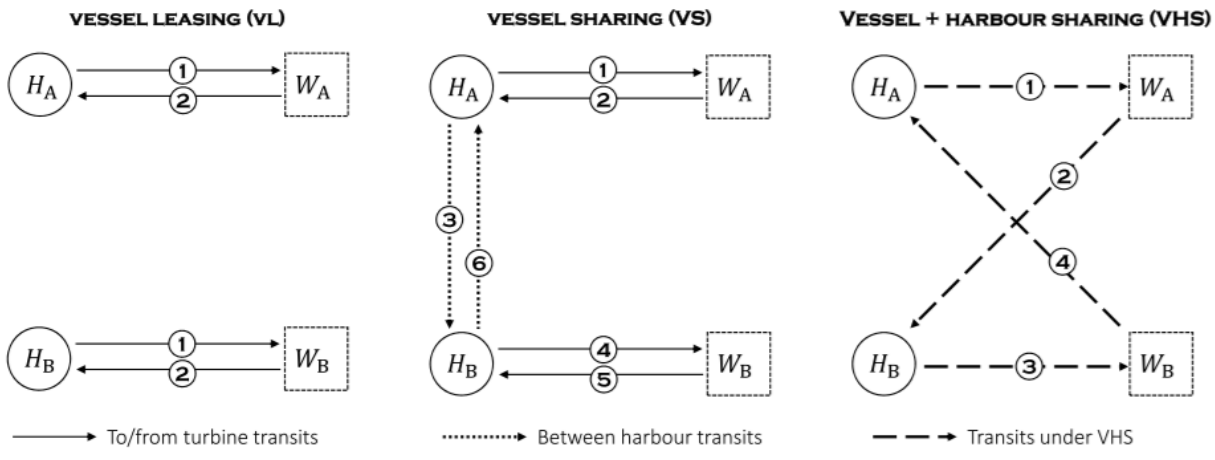


Figure 2.12: Vessel Leasing | Vessel Sharing | Vessel + Harbour Sharing [6]

should for some facets of offshore wind parks O&M, like weather deterioration. Moreira [49] in their paper, in order to tackle this problem, suggest mixed-integer programming (MIP) models to determine (tactical model) and validate (operational model) repair kits when O&M operations are executed in less than ideal environment conditions.

Their solution comprises three phases: scenario generation, tactical model, operational model. The solution scrutinizes over the impact of environmental factors, resupply, downtime cost. The findings on the paper hint that repair kits are more cost efficient the more scenarios are considered in the tactical model. This has real value for ORE - Offshore Renewable Energy - farms as it relates to Improvements on SOV - Service operation Vessel - repair kits , therefore bringing down the costs of O&M [49].

2.8.3 Wind Turbine Maintenance

Rinaldi [50], in their paper, mention briefly, in context of wind turbines, Computational Tools for O&M Planning, Condition Based Maintenance, Condition Monitoring/ Health of the machinery and SCADA Systems, Diagnosis and Prognosis, and Deterioration models.

They point towards AI related strategies as the future of O&M of wind turbines. Other industries, like automotive or aerospace, have been using CBM (Condition Based Maintenance). The same can be applied to the Offshore Renewable Energy industry [50].

2.8.4 Delphi Process

The Delphi method is "described as a set of structures for communicating to a group or as a device to gather expert opinion", says Lip-Wah Ho [51]. Plainly put, it is a process used to achieve a group decision via expert surveying. It is a multiple round, anonymous process. In each round, one agent gives the panel of experts a summary of the (anonymous) forecasts made by each of them, explaining their reasoning. The point of this is to encourage each expert to revise their previously given forecasts, taking into account the other experts' input. The objective is to converge into a more correct forecast. The process stops when a consensus is achieved.

The Delphi process was initially designed with the objective of predicting the end result of horse races. Since then it has been applied to different fields, such as supply chain management or operations management.

This method is proposed as a way to optimize O&M processes. It starts by selecting a panel of experts, followed by a brainstorm of O&M challenges. Next step is to narrow down the more important ones (by the delphi method). In the end the consensus between experts, as the more important challenges in regards to costs of O&M were the following.

- The inflexibility in planning.
- Absence of coordination of services in wind farms.
- Insufficient understanding on Operations & Maintenance management.
- Fleeting O&M contracts.

The authors denoted the lack of consensus between experts and literature, accusing how immature the industry still is, revealing gaps that should be researched [51].

2.8.5 NOWIcob

NOWIcob stands for Norwegian Offshore WInd COst and Benefit model, and it is a tool, a decision support tool that simulates O&M activities and costs. Its aim is to comprehend the sensitivity of O&M costs as it relates to variations of maintenance and logistics strategies, and therefore, help to pinpoint the best strategy for each specific wind park [52] .

2.8.6 Impact of plant upsizing

Plant upsizing has been trending positively in the offshore industry has one of the solutions to reduce LCOE. From 2010 to 2019 the average size of a wind farm grew from 190W to 400W. The relation between the Levelized Cost of Energy and the plant capacity is globally accepted in literature, and it is considered one of the driving forces on future LCOE trimmings [53].

Bigger plants bring about economies of scale, with fixed costs being dispersed over a larger number of generation nodes, namely transportation, vessel mobilization and O&M costs.

Shields [53] in their paper tries to measure the impacts of farm upscaling, and wind turbine upsizing. The authors concluded that it is financially preferable to select the bigger turbine, the larger plant capacity. An optimal farm design must take into account O&M, SC, vessels, ports, availability, staff costs, environmental constraints. If all the technological conditions are met, there are potential gains to be retained from upsizing the plants [53].

2.8.7 Scheduling and Routing Optimization on Offshore Winf Farm

Zhang [54], in their work, attempts to optmize the scheduling and Routing problem of Operations and Maintenance vessel fleet for an Offshore Wind Farm (OWF). In the article published, a mathematical model was built aiming to minimize service vessel, and production loss costs, and to give a solution to the schedule and routing of each vessel.

2.9 The Impact of the Weather conditions

Environmental constrains have a notable impact on the O&M of a Offshore Wind Park. Namely wind speed, wave height and period, or visibility.

Different Vessels have different weather thresholds, affecting their accessibility. This has consequences on the availability of the vessels, and consequently, of the turbines, in case of a failure.

The environmental conditions also have an impact on the assets performance. In the case of Wind turbine, its power curve is optimal for certain wind speeds. If the wave heights are too high, it can also impact negatively on the performance. In the case of PVs, if the weather is foggy or cloudy, power harvesting capabilities are affected.

Chapter 3

The Model

This section details how the model was developed, from its first sketch to the final product.

To model such a complex problem, firstly, all possible aspects that could be modeled were researched. Afterwards, all the possible inputs were written down and represented in the map shown in Fig. 3.1. Finally, the model could then be built.

3.1 Problem statement

A given offshore park is attempting to optimize its operations and maintenance activities. In this offshore park there are several nodes (Wind Turbines or PVs or WECs) $(i \in N)$ that need to be operated on and maintained. These nodes are divided in clusters $(c \in C)$ to which a vessel $(v \in V)$ is sent to perform a maintenance task $(m \in M)$. Each maintenance task requires a set time for it to be executed. There are two type of tasks, maintenance ones, and corrective ones, for when a failure happens.

There are different kinds of vessels, each with a different average travel speed . Each kind of vessel also possesses different weather thresholds, meaning, different limits to certain environmental variables, like Wind Speed, Wave Height and Visibility.

Each task for it to be executed, requires a minimum number of crew members and the parts needed for the job. However vessels do not have unlimited space, consequently, there's a max capacity for both personnel and load weight of parts. Crew members possess a time limit offshore based on the decided shift length. It could be 12hour, 24hour shifts.

Each node has a projected Power Output based on the weather conditions.

There are a few different classes of costs in this problem: Transportation costs and Downtime costs, Staff Costs and Repairs Costs. The transportation costs can be divided in two sections: Fixed costs and Variable costs. The first one is related to the vessel chartering and it's measured in its cost per day. The second one is related to the moving costs. It accounts for the fuel cost and distance travelled . In order to minimize costs, only one vessel is allowed per cluster. Downtime Costs relate to the time that a node is down, either failed or being maintained, the power output

Figure 3.1: A map of possible inputs to consider in the O&M model

wasted and the cost of energy. Staff Costs consist of the expenses caused by the wages of the personnel. Spare Parts Costs are the fees paid for the new parts used for maintenance tasks.

The objective is to optimize Operations and Maintenance, by minimizing its costs.

3.2 Model formulation

Indexes and Sets

i: node

v: vessel

m: maintenance activity

c: cluster

t: minute

d: day
N: Set of nodes
C: Set of clusters
V: Set of vessels
T: Set of minutes
D: Set of days

Parameters

$Dist_{i,j}$: Distance between node i and node j (in Km)
$CFixd_v$: Fixed cost for chartering or purchasing vessel v for use per hour
$FuelCons_v$: Fuel cost for vessel v (€/Km)
VS_v: Average travel speed for vessel v (Km/h)
H_m: Hours required to execute maintenance task m
$PowO_{t,i}$: Average power output in kWh of node i, on minute t,
$CEner$: Cost of Energy
$MTTF$: Median time to fail
$WindS_t$: Wind Speed at minute t
$WaveH_t$: Wave height at minute t
Vis_t: (in)Visibility at minute t
$TWindS$: Threshold of WindSpeed for a vessel to leave port
$TWaveH$: Threshold of Wave Height for a vessel to leave port
$TVis$: Threshold of Visibility for a vessel to leave port
$MinP_m$: Minimum personnel required for task m
$CPer_d$: Cost per person, per day
$CapPer_v$: Vessel personnel capacity cap for Vessel v
$PartsNeed_m$: Parts required for task m
$PartsCost_d$: (Average) Parts Cost, per day
$CapPar_v$: Parts capacity cap for Vessel v

Decision Variables

$VLeftN_{v,i,t}$: binary variable. 1 if Vessel v left Node i, at minute t, 0 otherwise.

Auxiliary Variables

$VLeftPort_{v,t}$: binary variable. 1 if Vessel v left port, at minute t, 0 otherwise.
$F_{i,t}$: Node i fails at minute t
M: integer variable, also known as Big M, a sufficiently big number
$VAvai_v$: binary variable, indicates if Vessel v was selected for use in the solution
$NDown_{i,t}$: binary variable, indicates if Node i is down at minute t

$VIsv,i,h$: binary variable. 1 if Vessel V is in node i, at minute t, 0 otherwise.

$VWas_{v,i,h}$: binary variable. 1 if Vessel V has been to node i, at minute t, 0 otherwise.

$NStartFix_{i,t}$: binary variable. 1 if Node i started being fixed, at minute t, 0 otherwise.

$NCurrF_{i,t}$: binary variable. 1 if Node i is currently fixed, at minute t, 0 otherwise.

$NEndFix_{i,t}$: binary variable. 1 if Node i finished being fixed, at minute t, 0 otherwise.

$VClus_{v,c,d}$: binary variable. 1 if Vessel v was in Cluster c in day d, 0 otherwise.

$VBackPort_{v,t}$: binary variable. 1 if Vessel v is going back to port, at minute t, 0 otherwise.

$VEng_{v,t}$: binary variable. 1 if vessel is engaged at time t, 0 otherwise.

$MSche_{i,t}$: binary variable. 1 if maintenance scheduled on node i, at minute t, 0 otherwise.

$PoBoard_{v,d}$: integer variable. Number of people on board of a vessel v, at day d.

$PaBoard_{v,d}$: integer variable. Number of parts on board of a vessel v, at day d.

$BELONGStoDAY_{d,t}$: integer variable. Moment of time t belongs to day d.

Objective function

The objective function of this mathematical formulation is to minimize the sum of all costs related to Operations and Maintenance of a hybrid Offshore parks.

In order to proceed to operate or maintain any wind turbine or PV, as it's an offshore farm, there are costs that arrive from the vehicle used to perform such activities. This vehicles, or vessels, are expensive to purchase, so a more conservative approach is used - chartering. And for each type of vessel, there is a different cost associated with it. It's given by 3.1.

$$VesselCharteringCost = \sum_{v\in V} CFixd_v \cdot VAvail_v \tag{3.1}$$

These costs are fixed, and are given per day. But they don't consider fuel consumption of the vessel. Depending on the consumption of the vehicle, and the distance to node, some extra (variable) costs are added. As it can be seen in 3.2.

$$VesselTransitCost = \sum_{v\in V}\sum_{t\in T}\sum_{i\in N} VLeftN_{v,i,t} \cdot 2 \cdot\ Dist_i \cdot\ FuelCons_v \tag{3.2}$$

It is also necessary to quantify the downtime cost. Every time a node stops producing, due to malfunction, or a scheduled maintenance task, it equals to loss of production that can be translated to a added cost. It can be given by 3.3.

$$DowntimeCost = \sum_{i\in N}\sum_{t\in T} CEner \cdot PowO_{i,t} \cdot (NDown_{i,t}) \tag{3.3}$$

Staff costs must also be taken into account. Maintenance tasks require a certain manpower. Each person needed for the job requires a salary. And so, Staff Costs are given by 3.4.

$$StaffCost = \sum_{v\in V}\sum_{d\in D} PoBoard_{v,d} \cdot CPer_d \tag{3.4}$$

Lastly, Spare parts used for maintenance also contribute for the total costs. For each day's work there is a value to the cost of new parts acquired to proceed to execute said tasks. As it can be seen in 3.5.

$$SparePartsCost = \sum_{v \in V} \sum_{d \in D} PaBoard_{v,d} \cdot PartsCost_d \tag{3.5}$$

Considering all the terms above we have 3.6.

$$\min(VesselCharteringCost + VesselTransitCost + DowntimeCost + StaffCost + SparePartsCost) \tag{3.6}$$

Which translates to 3.7.

$$\begin{aligned} \min \sum_{i \in N} \sum_{t \in T} CEner \cdot PowO_{i,t} \cdot NDown_{i,t} + \sum_{v \in V} CFixd_v \cdot VAvail_v \\ + \sum_{v \in V} VLeftPort_{v,t} \cdot 2 \cdot \; Dist_i \cdot \; FuelCons_v + \sum_{v \in V} \sum_{d \in D} PoBoard_{v,d} \cdot CPer_d \\ + \sum_{v \in V} \sum_{d \in D} PaBoard_{v,d} \cdot PartsCost_d \end{aligned} \tag{3.7}$$

3.2.1 Model constraints

In this subsection are presented basic constraints that help formulate the proposed model. To start it is necessary to enforce the relation between the variables $VLeftN_{v,i,t}$ and $VLeftPort_{v,t}$. This is given by 3.8.

$$\sum_{i \in N} VLeftN_{v,i,t} \leq VLeftPort_{v,t} \qquad \forall v \in V, t \in T \tag{3.8}$$

Only vessels selected by the model for use can be leveraged in the solution. This is shown in 3.9.

$$\sum_{t \in T} VLeftPort_{v,t} \leq M \cdot VAvai_v \qquad \forall v \in V \tag{3.9}$$

To ensure the flow conservation of the model some constrains need to be accounted for. At any given time, a node is down if it has failed, and it still did not finish getting fixed, as it is shown in 3.10.

$$\sum_{t'=0}^{t} F_{i,t'} - NEndFix_{i,t'} \leq M \cdot NDown_{i,t} \qquad i \in N, t \in T \tag{3.10}$$

For a node to start being fixed, a vessel must leave port and travel to the node, taking into account transit time. This is given by 3.11.

$$\sum_{v \in V} VLeftN_{v,i,t-\lceil 60 \cdot Dist_i / VS_v \rceil} \leq M \cdot NStartFix_{i,t} \qquad t \in T, i \in N \tag{3.11}$$

For a node to be currently getting fixed, it needs to have started getting fixed, but not yet finished being fixed. This is presented in 3.12.

$$\sum_{t'=0}^{t} NStartFix_{i,t'} - NEndFix_{i,t'} \leq M \cdot NCurrF_{i,t} \qquad i \in N, t \in T \tag{3.12}$$

For a node to finish being fixed it must start being fixed, and operated upon for H_m. As it is shown in 3.13.

$$NStartFix_{i,t-\lceil H_m \rceil} \leq M \cdot NEndFix_{i,t} \qquad t \in T, i \in N \tag{3.13}$$

Only when a node is fixed, the vessel can advance for the next node, as it is stated below in 3.14.

$$NEndFix_{i,t} - 1 \leq M \cdot (1 - VLeftN_{v,i,t}) \qquad \forall t \in T, v \in V \tag{3.14}$$

The vessels only leave shore if the conditions are met. Firstly, the vehicles cannot leave if there's no maintenance scheduled or a failure has occurred. On the following inequality, if neither of the binary variables on the left side of the inequation have value 1, forces the variable $VLeftPort_{v,t}$ to be 0. Meaning that if there's either a malfunction or a scheduled maintenance, the vessel must not leave port. This is expressed in 3.15.

$$F_{i,t} + MSche_{i,t} \leq M \cdot (1 - VLeftPort_{v,t}) \qquad \forall t \in T, v \in V \tag{3.15}$$

Secondly, the vessels are also barred from leaving the port if the weather does not allow it. The thought process behind this constraint is the following: if the Wind Speed is higher than its threshold, the left side of the inequation gives a value between 0 and 1. This forces the right side to be positive, and consequently, the variable $VLeftPort_{v,t}$ to be zero. Meaning that the vessel cannot leave at that time as is reflected in 3.16.

$$\frac{WindS_t}{TWindS} - 1 \leq M \cdot (1 - VLeftPort_{v,t}) \qquad \forall t \in T, v \in V \tag{3.16}$$

Similar thought process is used for this constraint. If the Wave Height is higher than its threshold, the left side of the inequation gives a number between greater than 0. This forces the right side to be positive, and consequently, the variable $VLeftPort_{v,t}$ to be zero. Meaning that the vessel cannot leave at that time. This is given by 3.17.

$$\frac{WaveH_t}{TWaveH} - 1 \leq M \cdot (1 - VLeftPort_{v,t}) \qquad \forall t \in T, v \in V \tag{3.17}$$

Once again, the same thought process is applied for this constraint. If the Visibility is higher than its threshold, the left side of the inequation gives a number between 0 and 1. This forces the right side to be positive, and consequently, the variable $VLeftPort_{v,t}$ to be zero. Meaning that the vessel cannot leave at that time as it is showcased in 3.18.

$$\frac{Vis_t}{TVis} - 1 \leq M \cdot (1 - VLeftPort_{v,t}) \qquad \forall t \in T, v \in V \tag{3.18}$$

Each vessel leaves and returns to harbor only once a day. The sum of all the times a vessel leaves port in a day cannot exceed one. This is shown in 3.19.

$$\sum_{t \in T} \sum_{v \in V} VLeftPort_{v,t} \cdot BELONGStoDAY_{d,t} \leq 1 \qquad \forall d \in D \tag{3.19}$$

Similarly the sum of all the times a vessel arrives to port in a day cannot exceed one. It is given by 3.20.

$$\sum_{t \in T} \sum_{v \in V} VBackPort_{v,t} \cdot BELONGStoDAY_{d,t} \leq 1 \qquad \forall d \in D \tag{3.20}$$

Vessel availability is also important for this problem. We need to make sure the vessel is always available for the solution. This is expressed below 3.21, 3.22, 3.23, 3.24, 3.25.

$$\sum_{v \in V} VLeftPort_{v,t} \leq VAvai_v \qquad \forall t \in T \tag{3.21}$$

$$\sum_{v \in V} VBackPort_{v,t} \leq VAvai_v \qquad \forall t \in T \tag{3.22}$$

$$\sum_{v \in V} VIs_{v,i,t} \leq VAvai_v \qquad \forall i \in N, t \in T \tag{3.23}$$

$$\sum_{v \in V} VWas_{v,i,t} \leq VAvai_v \qquad \forall i \in N, t \in T \tag{3.24}$$

$$\sum_{v \in V} VClus_{v,i,t} \leq VAvai_v \qquad \forall i \in N, t \in T \tag{3.25}$$

To avoid any unnecessary costs, and overall confusion of the problem, each cluster is associated with one and only one vessel at a given time. Meaning that only one vessel is deployed to a certain cluster at a time. This is shown in 3.26

$$\sum_{v \in V} V_{v,c,t} = 1 \qquad \forall c \in C, t \in T \tag{3.26}$$

Bad weather conditions can occur out of nowhere, consequently, a vessel can be in transit and a storm appear out of nowhere rendering the maintenance activity impossible. This calls for a constraint to the model, forcing the maintenance vessel back to port if the weather to it obliges. The thought process behind this constraint is the following: if the Wind Speed is higher than its threshold, the left side of the inequation gives a number between 0 and 1. This forces the right side to be 0 (or negative, but for this case that's redundant), and consequently, the variable $VBackPort_{v,t}$ to be one. Meaning that the vessel must return to port as it is stated in 3.27.

$$(\frac{WindS_t}{TWindS} - 1) \cdot VEng_{v,t} \geq M \cdot (VBackPort_{v,t} - 1) \qquad \forall t \in T, v \in V \tag{3.27}$$

Similar thought process is behind this next constraint: if the Wave Height is higher than its threshold, the left side of the inequation gives a number between 0 and 1. This forces the right side to be 0 (or negative, but for this case that's redundant), and consequently, the variable $VBackPort_{v,t}$ to be one. Meaning that the vessel must return to port. This is suggested in 3.28.

$$\left(\frac{WaveH_t}{TWaveH} - 1\right) \cdot VEng_{v,t} \geq M \cdot (VBackPort_{v,t} - 1) \qquad \forall t \in T, v \in V \tag{3.28}$$

Once again, same thought process, if the visibility parameter is higher than its threshold, the left side of the inequation gives a number between 0 and 1. This forces the right side to be 0 (or negative, but for this case that's redundant), and consequently, the variable $VBackPort_{v,t}$ to be one. Meaning that the vessel must return to port as it is given by 3.29

$$\left(\frac{Vis_t}{TVis} - 1\right) \cdot VEng_{v,t} \geq M \cdot (VBackPort_{v,t} - 1) \qquad \forall t \in T, v \in V \tag{3.29}$$

Onto to the staff related constraints. Different tasks require different number of crew members for its execution. There is a minimum number of personnel necessary for each task. The constraint given by Eq. 3.30 forces the variable $NStartFix_{i,t}$ to be zero if the Number of minimum personnel on board for a required task is less than the the number of personnel on board of the vessel.

$$\frac{MinP_m}{PeBoard_{v,d}} - 1 \leq M \cdot (1 - NStartFix_{i,t}) \qquad \forall i \in N, t \in T, m \in M, v \in V, d \in D \tag{3.30}$$

There is a limit to the amount of people in board of the vessel. The amount of personnel on board of the vessel must not be higher than its capacity is shown in 3.31.

$$PeBoard_{v,d} \leq CapPer_v \qquad \forall v \in V, d \in D \tag{3.31}$$

Maintenance tasks require new parts for the operations. Different tasks demand different new parts. This following constraint makes sure that the vessel possesses the required material to perform the maintenance activity. If not the variable $NStartFix_{i,t}$ takes value zero, meaning the maintenance tasks is not started. 3.32 shows this.

$$\frac{PartsNeed_m}{PaBoard_{v,d}} - 1 \leq M \cdot (1 - NStartFix_{i,t}) \qquad \forall i \in N, t \in T, m \in M, v \in V, d \in D \tag{3.32}$$

There is a limit for the maximum load of new parts a vessel can take. To make sure it does not get exceeded the following constraint 3.33 is used :

$$PaBoard_{v,d} \leq CapPar_v \qquad \forall v \in V, d \in D \tag{3.33}$$

Chapter 4

Simulation - Data Collection

In the previous chapter it was provided insight on the o&M model of an Offshore Farm. This chapter focuses on gathering data for the model. Raw data was collected from multiple sources(4.1, 4.2), and in some cases that data had to be treated (4.3, 4.5). In other cases, data was computed (4.4), and other are simply suggestion of inputs (4.6).

4.1 Wind Data

For the simulation, wind data from Aguçadoura, Portugal was picked, since it is a relevant place for the offshore industry in the country, and for this project. Historical wind and wave data from said location was retrieved, as shown in Fig. 4.1.

For reference, 1 knot equals to approximately 0.514m/s

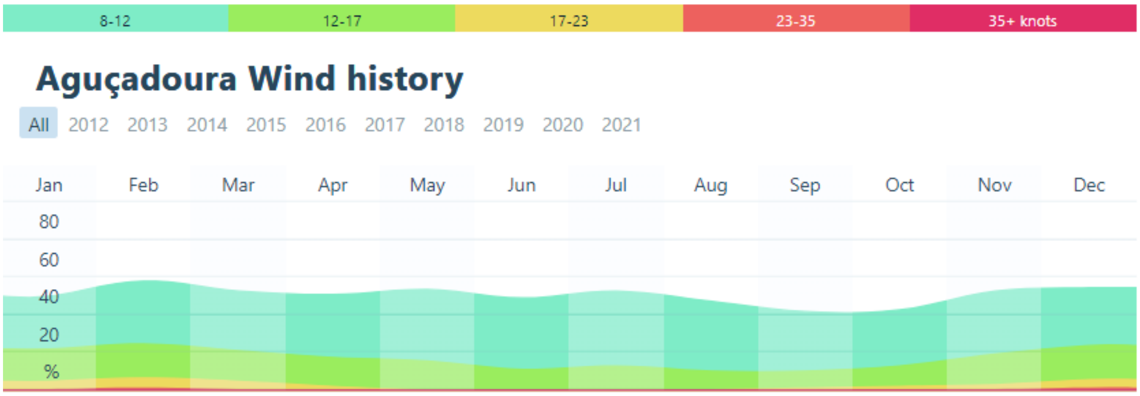


Figure 4.1: Wind data for Aguçadoura, Portugal [7]

4.2 Datasheets of proposed WT and PV

In order to compute the total output power, information on the power to wind speed ratio, and power to solar irradiation were needed. Consequently, a Wind turbine [8] and solar PV[55] were selected for the purpose. Fig. 4.2, contains data referring to the power curve of the chosen wind turbine model.

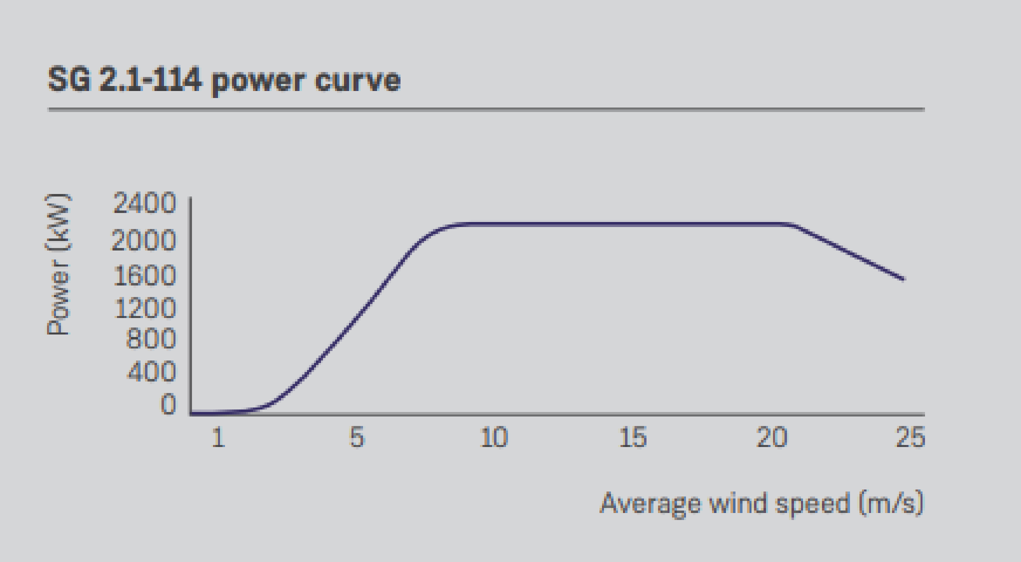


Figure 4.2: Power Curve of the chosen WT [8]

From this data, and the previous data from wind, it is possible to roughly predict the power output. A value of capacity factor of 0.4 was considered for the purpose.

4.3 Vessels and Weather Thresholds

Data regarding four different vessels and respective wind speed and wave height thresholds[47] are tabulated in table [47] 4.1.

Table 4.1: Vessels and its weather thresholds

Vessel	Wind Speed Threshold	Wave Height Threshold
Work Boat	12m/s	1.5m
Jack-up Vessel	10m/s (working) 15m/s (travelling)	2m
Crane Vessel	10m/s (working) 15m/s (travelling)	2m
Mother Vessel	15m/s	4m

4.4 Mean Time to Failure

The MTTF of a OWT used for this problem is 1103h [56]. With this value taken into account a simulation was run for a node (turbine), considering a normal distribution. This simulation was run for a year, and the results are tabulated on the Table 4.2. The turbine had 14 failures in the span of that year, first of which happened at minute 11847 (roughly 8.23 days). The first failure on this turbine occurred at the ninth day after the beginning of the simulation (Appendix A).

Table 4.2: Failures on a Wind Turbine in a span of a year

11847	68274	74277	126603
162725	214953	270742	234248
385258	401988	404115	459279
521116	565229		

4.5 Economic Considerations

A survey was done revolving around costs (fixed and variable) of different vessels, staff costs, energy costs, [47] with its results shown in Table 4.3.

Table 4.3: Economic Considerations

Item	**Cost**
Work Boat	2.000€ per day
Crane Vessel	90.000€ Mobilization and Demobilization +20.000€ per day
Jack up Vessel	100.000€ Mobilization and Demobilization +15.000€ per day
Personnel Wages	50€/hour
Energy Tariff	0.12€/kWh

4.6 Task Characteristics and Requirements

Table 4.4 shows two examples of tasks characteristics and requirements, tasks which possess the right structure necessary for use in the model.

Table 4.4: Possible Tasks

	Task 1	**Task 2**
Task Description	WT or Gearbox Malfunction	Solar PV, Scheduled Cleaning
Task Category	Category 2	Category 1
Vessel required	Jack-up Vessel	Work Boat + Mother Vessel
Personnel required	5 crew member job	4 crew member job
Time required	6h	4h

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The work carried out in this dissertation aimed to improve Operations and Maintenance and Energy Production models of a large scale hybrid energy park, considering floating solar and bottom-fixed wind energy sources. The proposed methodology uses a optimization model to investigate the optimal solutions for this problem.

This methodology consists of minimizing the costs of all the factors that impact Operations and Maintenance, and Energy Production of a hybrid farm. The developed MIP (mixed integer programming) optimization model attempts to bring together several ideas from different models found in literature. This model gathered tips from Scheduling and Routing models, Vessel Fleet strategy models, Staff impact models and attempts to combine them into a new one, specially tailored for the problem in hand.

The initial plan for this work, was to firstly, elaborate a theoretical background check on the problem, then proceed to build a optimization model, gather data to simulate the model, and run simulations with that data and comparing results. However, the plan was ambitious, and so, it was decided that the implementation of the model was to be done later.

5.2 Future Work

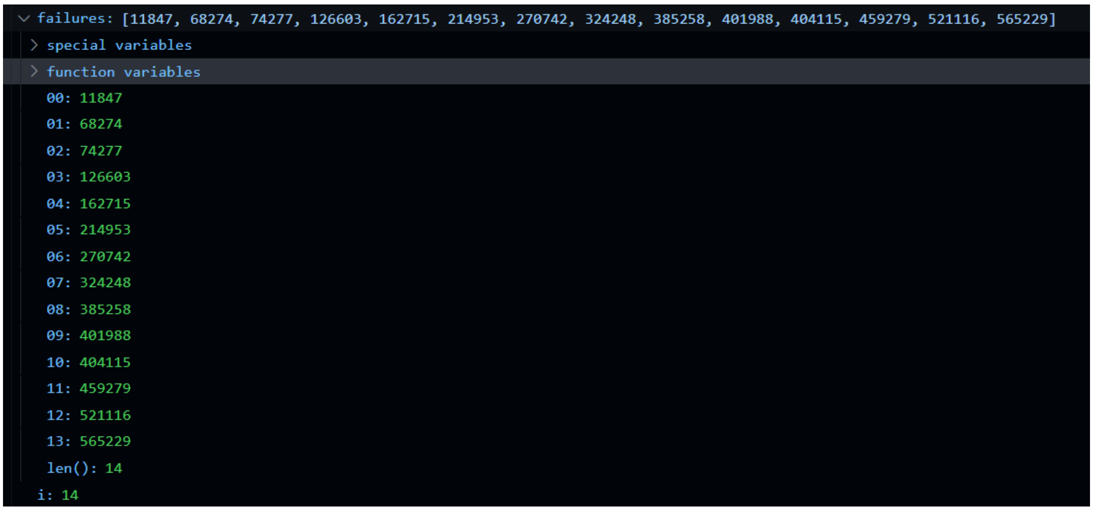
The next step is to run simulations with real data and compare results.

The solutions provided the optimization model are substantially influenced by the costs on the objective function. This requires the model to possess accurate data on this matter. The same can be said for weather data, as it influences both vessel decisions, and Energy production. Better data collection should be a point of emphasis in future work.

The model could also be improved upon. The repairability problem could be explored more deeply. Effectivity of a component without maintenance could also be a variable to be taken into account. For example, the cleanliness of the surface of solar panel. The model also grouped the nodes in clusters randomly. For future work, clusters can be organized by distance, and with optimized size. Another idea for this model, is to have a Checkpoint Center, between shore and the farm. Its purpose is to minimize transit times of vessels and their costs. This center could be used for refueling, personnel change, repair parts storage. Another direction that can be interesting to explore is the possibility of hazardous events. Human accidents can happen, vessels can malfunction.

Appendix A

Appendix



```
failures: [11847, 68274, 74277, 126603, 162715, 214953, 270742, 324248, 385258, 401988, 404115, 459279, 521116, 565229]
  special variables
  function variables
  00: 11847
  01: 68274
  02: 74277
  03: 126603
  04: 162715
  05: 214953
  06: 270742
  07: 324248
  08: 385258
  09: 401988
  10: 404115
  11: 459279
  12: 521116
  13: 565229
  len(): 14
i: 14
```

Figure A.1: Simulation of failures on a OWT in a year

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