Integration of Environmental Impact Metrics into Wind Farm Design, Analysis and Optimization

SET3901: Thesis Project

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Integration of Environmental Impact Metrics into Wind Farm Design, Analysis and Optimization

How to quantify?
Is there only one metric?
How to use the metric?
How to compare wind farm designs using the metric?

by

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Preface

After working in a coal power plant located beside a coal mine, I began to realize the problems humans are creating for future generations by exploiting resources to meet immediate needs. After studying conventional energy generation methods, I felt the need to equip myself with sustainable energy generation methods to work along the lines of developing cleaner solutions to the ever increasing energy demands. Hence, I chose MSc. Sustainable Energy Technology program at Delft University of Technology.

During this journey, I needed support in various ways. I am grateful to have Mrinal Chaudhury with me during the journey as I never felt homesick even after being so far from India for she is the home. Not only did I get a partner for everything, but I got to share my feelings and grow with her and I thank her for being in my life.

I have been a restless person and to calm my nerves, I played football, enjoyed the beautiful game, and appreciated every moment on the field. I thank all my teammates, friends, and the sport for keeping me motivated to look forward to the next day games. I could not pay much attention to my guitar and I apologize for that. I hope to soon get back to playing music more.

I thank all my friends for sharing stress together, teaching me new things, organizing birthdays, dinners, games, barbecues, movie nights, and creating memories. I hope we stay in touch beyond the master's program. I hope to see you all often.

Finances are a nightmare for most international students and I am no exception. I greatly thank my father for supporting my journey in this regard. I also thank Cafe X for providing me with ample opportunity to work and cover my living expenses. I also thank all the funny but smart furry friends who came to our place temporarily and gave me not only money, but also a serotonin boost.

Good sleep is not very common in student life, but a cup of coffee is. I again thank Cafe X for providing me with a ”business card” that helped me not only start my day, but also enjoy and appreciate coffee and hot chocolates.

Some people say that an MSc thesis is the last big project you do during your student life. I disagree because you never know what life has for you. May be a Ph.D. or perhaps another masters? However, the time during thesis is heavily dependent on supervision, and I have been very lucky to have Prof. Axellé Vire as my supervisor. I am very grateful for her time and guidance every week, which allowed me to have continuous progress in a structured way. I also thank Dr. Mihir Mehta and Dr. Matteo Baudino Bessone who took the time to guide me, provide me with their frameworks, and answer all my questions. This thesis would not have been possible without them. I also thank Dr. Gianfranco la Rocca and Dr. Julie Teuwen for being part of my thesis committee and evaluating my work, providing me with valuable insights and ways to improve it.

It has been an amazing experience and I do not regret any part of it.

Thank You!

Rishabh Pal
Delft, August 2025

Summary

Since the global mean temperatures are increasing due to greenhouse gas emissions, the world is moving toward more sustainable products and processes. The energy industry plays an important role in global warming, as conventional energy generation methods contribute a large fraction of greenhouse gas emissions. Energy is a topic of concern because with the increasing population and development of countries, the demand for energy will increase with time. Renewable energy sources such as solar and wind are potential alternatives to coal and gas-fired power plants. Wind turbines have been seen as a method of harnessing clean energy, but the biggest hurdle in transitioning to wind power, like other renewable sources, is the cost of energy. The wind energy industry is moving towards decreasing the levelized cost of electricity from wind farms. However, contrary to the belief, wind turbines also emit a lot of greenhouse gases during their entire lifetime. This occurs during manufacturing, transportation, commissioning, maintenance, decommissioning, and end-of-life practices. In addition to emissions, there are also several impacts on wildlife as a result of the presence of the wind turbine, such as the probability of birds colliding with the blades, entanglement of sea mammals with mooring lines and cables, displacement and alteration of the natural habitat in the wind farm area, to name a few.

This thesis investigates the impacts and how they can be measured or quantified. It also explores if they can be quantified and used as a metric, then how can the metric be used in the wind farm design process to have the least environmental impact. Currently, a Multidisciplinary Design, Analysis and Optimization (MDAO) framework is used to design wind farms with the lowest levelized cost of electricity, one of the most important drivers of the wind energy industry's innovation and development. The thesis will investigate whether the metric can be incorporated into the framework or not and, if done so, how it changes the design of wind farms.

From the research, it has been found that the most important risk is the impact of greenhouse gas emissions during the life cycle of the wind farm. The direct impacts on wildlife due to the physical presence of wind turbines are still under study and the impacts observed so far are not conclusive or consistent with different species or even with all individuals of the same species. Consequently, the focus has been given in the lifetime emissions from a wind farm. From life cycle assessments of several wind farms, a correlation has been developed between the emissions and the amount of materials used in the wind turbine/farm. Using this method, different wind farm designs have been compared to each other, based on the emissions and the cost of electricity. Four different sizes, and three different types of turbines have been tested, keeping the wind farm capacity constant.

For most of the comparisons, it was found that using a fewer number of bigger turbines resulted in lower emissions compared to more number of smaller turbines. This is also seen in the direction in which the industry is progressing. In terms of cost of electricity, there are different results in different cases. The method of including the most important environmental impact of wind turbines, so far, in the wind farm design process has been described and used. The future scope of work and improvements in the framework have been discussed at the end of the thesis.

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Nomenclature

Abbreviations

Abbreviation	Definition
AC	Alternating Current
AEP	Annual Energy Production
CAPEX	Capital Expenditure
DC	Direct Current
DCB	Dichlorobenzene
EOL	End of Life
GHG	Greenhouse Gases
GWP	Global Warming Potential
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCOE	Levelized Cost of Electricity
MDAO	Multidisciplinary Design Analysis and Optimization
MP	Monopile
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
OPEX	Operational Expenditure
RNA	Rotor Nacelle Assembly
TP	Transition Piece
UHC	Ultimate Holding Capacity

1
Introduction

1.1. Global Warming

Global warming is a phenomenon that has been the subject of concern for quite some time now. It can be defined as the increase in combined surface air and sea surface temperatures averaged across the world over a 30 year period [1]. Global warming is referred to relative to the period of 1850-1900 which is considered as the pre-industrial era [1]. The increase in global mean temperature means that glaciers will melt, which will result in rising sea levels and many land areas being submerged in water. There will also be irregularities in harvesting, extreme temperatures in different parts of the Earth, and more frequent storms and other natural calamities. Researchers and climate scientists have conducted studies and recorded various weather phenomena such as temperature, precipitation, storms, etc. over the years to come to the conclusion that the Earth's climate has changed since geological times. However, since the beginning of the industrial revolution, the pace and extent of climate change have increased. According to the Intergovermental Panel on Climate Change (IPCC), the increase in global mean temperature should be well below 2 °C and ideally be limited to a maximum of 1.5 °C. This will prevent or reduce the risk of frequent and adverse weather conditions, such as droughts, wildfires, floods, and heatwaves. Exceeding global mean temperatures by more than 1.5 °C compared to pre-industrial times can also lead to irreversible damages to the Earth such as breakdowns in major ocean circulation systems and collapse of tropical reef systems, and loss and extinction of species. The rise in global mean temperature can be seen in Figure 1.1.

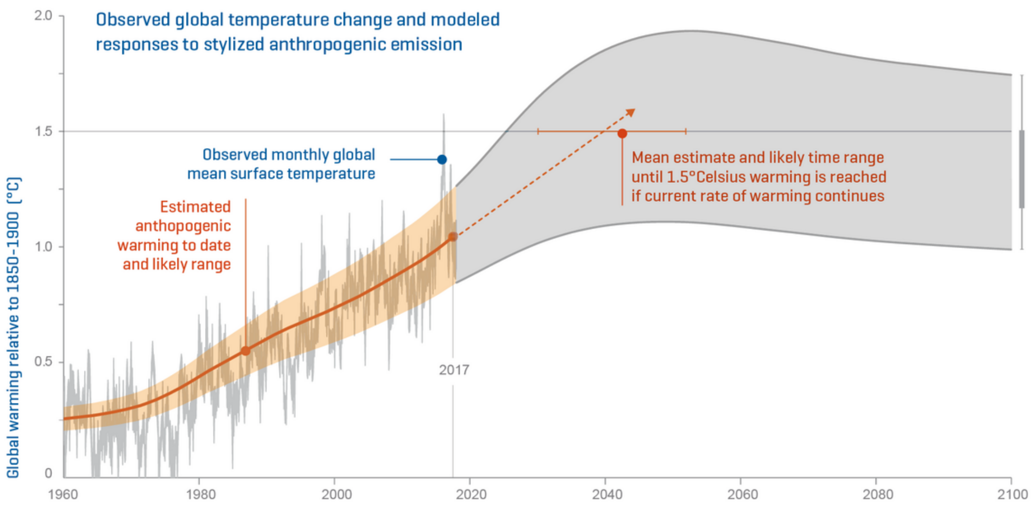


Figure 1.1: Observed global temperature change and modeled responses to stylized pathways [1].

1.2. Energy Sector In Global Warming

Of all contributing factors, carbon dioxide emissions are among the most significant. The burning of coal and other fossil fuels has led to increased emissions of carbon dioxide and other hydrocarbons. These fuels are burned to produce energy for industrial processes, electricity generation, transportation, and other purposes. The world emits around 50 billion tons of greenhouse gases every year [2]. Of all greenhouse gas emissions, a significant portion comes from the energy sector. It is responsible for 73.2% of greenhouse gas emissions [2]. Figure 1.2 can be referred to for all the sectors. Due to the increasing population and development of the countries, the energy requirement is increasing. The developed countries have a higher energy demand compared to developing countries where access to electricity and energy security, in general, is a problem. So, the demand for electricity in developing countries will increase significantly in the coming decades. Moreover, developed countries still use coal, natural gas, and oil for energy generation, which indicates that developing countries will take more time to move to cleaner energy generation methods. One of the reasons for this is the cost of clean energy generation. Over the years, several renewable energy harnessing methods have been developed, which are much cleaner than producing energy from fossil fuels. Harnessing solar energy, tidal energy, geothermal energy, and wind energy are among many others. Wind energy is harnessed by converting the kinetic energy of wind into rotational energy for wind turbines, which, in turn, rotates the generator. It completely depends on the wind climate of the location and hence, some places are more suitable for energy harnessing through wind.

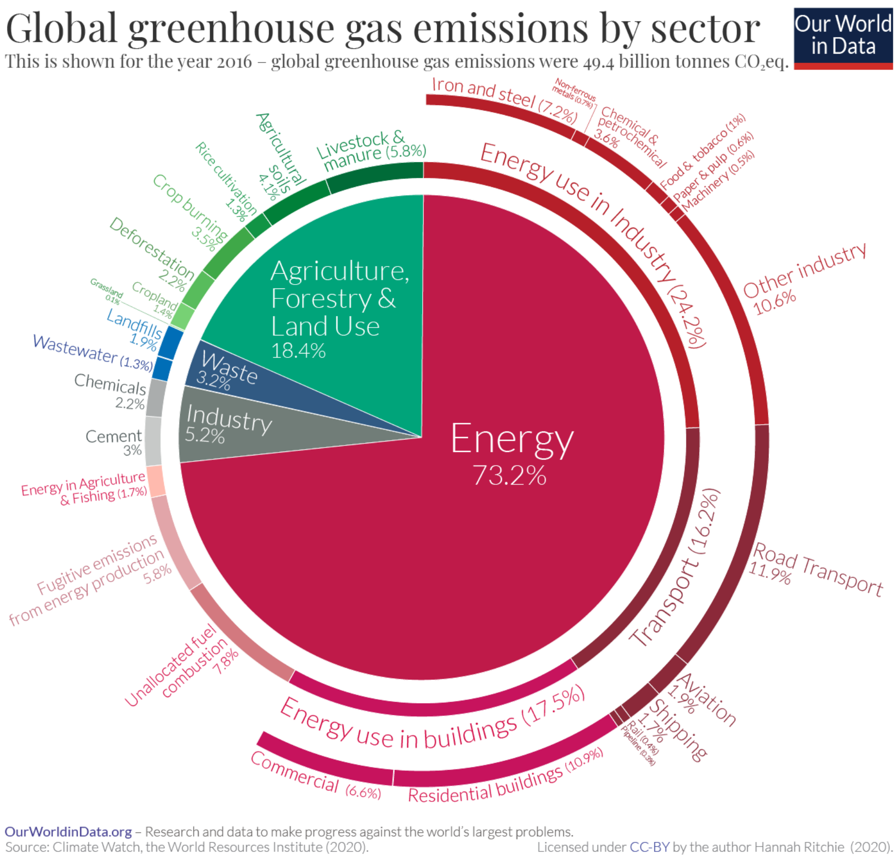


Figure 1.2: Greenhouse gas emissions from different sectors [2].

1.3. Environmental Impacts Of Wind Turbine

Wind energy has a history that dates back several centuries. The turbines since then have grown both in size and capacity and the technology improved making them more efficient. Modern wind turbines can be as large as 236 m in diameter and as tall as 143 m (Vestas V236-15). The bigger the wind turbines are, the more wind is captured, and the higher the power output. Wind turbines rotate because of the incoming wind. There is no burning of fossil fuels in the process, and hence the energy produced is clean. However, even though the energy produced seems to be clean, there is more to it. The production of wind turbines is energy and material intensive. Modern wind turbines are made of steel, cast iron, concrete, epoxy resin, glass fibers, adhesives, etc. Carbon dioxide and other greenhouse gases are emitted during the production of these materials. The mining of metal ores and processing them to obtain pure metal or alloys require a lot of energy in the form of heat and electricity. These processes use fossil fuels to attain such high temperatures, and hence there are emissions of greenhouse gases. More carbon dioxide is produced when the material is fabricated into parts of wind turbines. The transportation of parts to the assembly site and to the final location uses transport vehicles that use diesel. The operation and maintenance activities of the turbines also require the movement of personnel and spare parts using some means of transport that require energy. Decommissioning the turbines when they have served their life requires the transportation of material back from the site and uses diesel powered transportation vehicles. After the life of a wind turbine is over, some of the materials used are recycled and the rest are either incinerated or used as landfill. Incineration and landfills further impact the environment. All of these processes consume fossil fuels during the lifetime of a turbine and contribute to greenhouse gas emissions.

In addition to carbon dioxide, there are other chemicals that are released into the environment during the lifetime of a turbine. These chemicals can cause acid rain, eutrophication, increase the impact on humans and marine animals due to toxicity, etc. These chemicals are released into the environment in the same way as carbon dioxide has been described above. Several processes contribute to it. Moreover, there are some impacts that are directly due to the installation of the turbine. A turbine can cause obstruction to birds and marine animals (in case of offshore turbines), birds can collide to the blades, turbine can deteriorate the health of seabed and organisms thriving in it, the power cables can emit electromagnetic radiation around it, which can disturb the marine animals, the installation of monopile into the seabed can produce a lot of sound in the sea and the sound of the wind turbines can cause disturbance to humans and animals living in nearby area. Some people also object to turbine installation because it deteriorates the view of the landscape. There are several studies that identify these impacts and are described in more detail in Chapter 2. Depending on the type of wind turbine, the impact on the environment vary and it is important to know the types that are studied in this research. The types are described briefly in the next section.

1.4. Types Of Wind Turbines

Wind turbine can be categorized in several ways, such as axis of rotation, turbine location, type of foundation, etc. For the current topic, it is important to consider the turbines that are commercially popular and have an increasing demand in future. Modern 3-bladed horizontal axis wind turbines are installed in most of the wind farms. Among these, the foundation of turbines may vary significantly depending on the location where the turbines are installed. Because of the thrust from wind, and very high towers of turbines, there is a large moment of force acting on the foundation [3]. Thus, foundations play an important role in safe design of turbines and has a lot of weight to counter the moment. For onshore turbines, the foundations can be of the following types [3]:

1. **Spread foundation** - Spreads the load coming from the turbine to the soil. It is like a slab and has a large surface area to distribute the load. The material used for construction is concrete. They can, broadly, be of the following two types:
    (a) **Shallow foundation** - When the spread foundation is placed on the ground or just beneath it.
    (b) **Gravity foundation** - When the spread foundation is placed some depth below the ground by excavating soil.
2. **Pile foundation** - When the soil is weak or soft, then pile foundations are used. The pile goes deep into the soil and is connected to a steel or concrete plate.

For offshore turbines, there are many new designs and concepts of foundations. All designs and types have their own advantages and disadvantages and are suitable for different water depths. Water depths are classified as shallow water (0-30 m), transitional water (30 m - 50 m) and deep water (greater than 50 m) [3]. Some sources also consider 60 m as the lower limit of deep water. For shallow and transitional waters, fixed-bottom turbines are employed. As the name suggests, the bottom/base of the turbine in these cases is not fixed on the seabed. For deeper waters, the base of the turbine can be floating and to keep them in position the base is anchored to the seabed. Offshore wind turbines can be categorized as follows [3]:

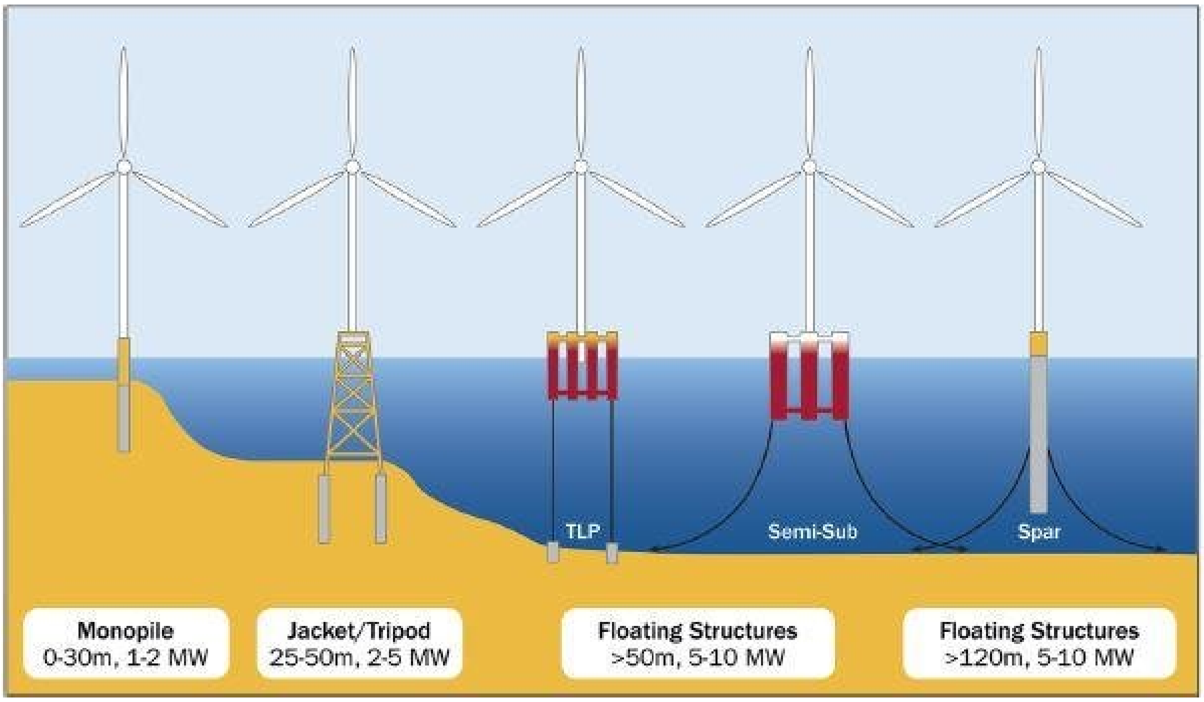


Figure 1.3: Types of foundation used in offshore wind turbines [4].

1. **Gravity based foundation** - derives stability from its own weight. It has a large circular pile with a concrete plate structure resting on the seabed
2. **Monopile type foundation** - a large pile is driven into the seabed where water depths are less than 30 m.
3. **Suction Caisson** - has a pile with an inverted bucket shaped base which goes into the seabed.
4. **Multi-pod (Tripod and Jacket)** - Useful for turbines in transitional water depths. It consists of a substructure which can provide the required strength and stiffness at relatively shorter penetration in the seabed
5. **Floating substructures** - has to be anchored to the seabed for fixing location of the turbine. They are also called floaters, and they use the concept of hydrostatic and hydrodynamic stability. There are several floater designs available but semi-submersible type, barge type, tension-leg platform type, and spar buoy type floaters are the most commonly installed. Figure 1.3 shows some of the common floater designs, and foundation types of offshore wind turbines.

For the current work, only offshore wind turbines are considered during the study.

1.5. Using Environmental Impacts In Wind Farm Design

The impacts of the wind turbines, mentioned in Section 1.3 are not easy to quantify and calculate. Research is still underway to find the intensity of these impacts and other impacts, if any. Some studies show that some of the impacts are significant and others conclude otherwise. Several researchers use the tool, Life Cycle Assessment (LCA), to evaluate the environmental performance of the wind farm design. LCA provides a baseline of all the chemicals and elements going into the environment and provides a metric which can be used to compare 2 or more designs. Several companies assess the impacts of wind turbines using LCA and try to minimize or limit it. However, LCA does not quantify all the impacts precisely like the impact of sound on marine animals, impacts of obstruction in migratory routes, etc. The impacts play an important role in deciding locations of the wind farms, distance from port, logistical routes, etc. Consequently, it is necessary to quantify them and compare the various wind farm designs.

This thesis revolves around this knowledge gap and investigates how environmental impacts can be quantified and used in the wind farm design process. Since there are many parameters of wind turbines that need to be optimized at the same time, a Multidisciplinary Design, Analysis, and Optimization (MDAO) framework is used in the process of wind farm design. Optimization is subject to several constraints, and the objective is to minimize the cost of the wind farm. More precisely, the levelized cost of electricity (LCOE) produced by the farm is minimized. LCOE of wind energy can be reduced in several ways such as reducing capital expenditure and operational expenditure, making the turbines stronger so that they last longer, reducing maintenance requirements, optimizing logistics, and reusing materials used in the turbines. In the process, MDAO is often used. This is essential to make wind energy a more lucrative option compared to fossil fuel energy. The cost of electricity from oil and coal is lower than or comparable. LCOE of hydropower is also lower than that of wind energy [5]. However, in addition to the LCOE, the lifetime Greenhouse Gas (GHG) emissions are also considered to be an important parameter because it is the reason behind the transition. Wind energy has significantly lower emissions than other fossil fuel electricity, but it is not zero. In order to calculate and minimize it during the design process, it will be useful to have a number associated with the impacts. Figure 1.4 can be referred to for information on other energy sources. In this thesis, it will be investigated how environmental impacts can be included in the MDAO framework and, when used as a metric, how the farm design changes. The MDAO framework used in this work is developed at Delft University of Technology.

Since the MDAO framework is used extensively for this research, it is important to explain its basic concepts, as is done in Section 1.6.

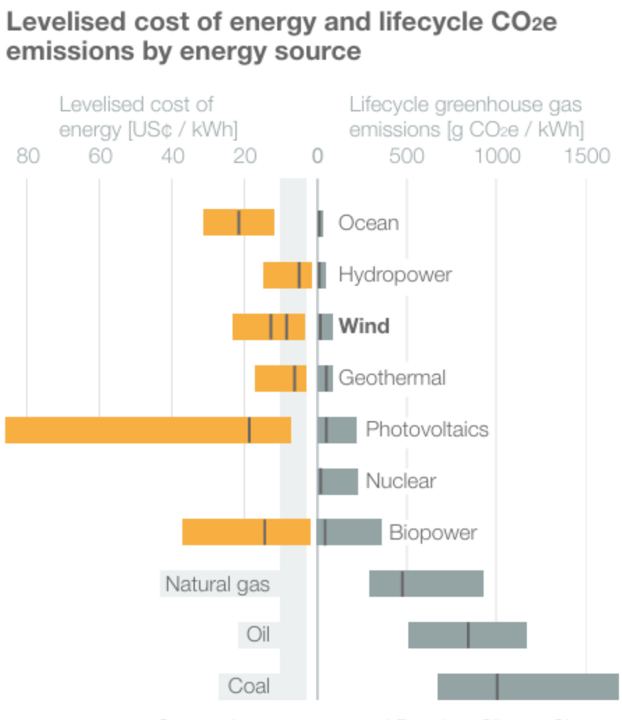


Figure 1.4: Life cycle greenhouse gas emissions of different energy sources [5].

1.6. MDAO Framework

MDAO was developed in the aerospace industry, where the design of the aircraft was strongly influenced by factors from various disciplines. With time, MDAO was introduced to other industries, such as the automotive and civil industries [5]. MDAO is a workflow where different components are optimized and coupled together to simulate the entire system. Optimization problems for different components are termed analysis blocks. In addition, there are drivers that connect these analysis blocks and control which block should be executed in which sequence. The function of the framework is termed the use case and is the objective of the optimization. In the case of wind farms, it can be to maximize the annual energy production or to minimize the levelized cost of electricity. The drivers are used to implement the optimization algorithms in the analysis blocks, and the algorithms explore the design space bound by constraints.

MDAO is a multilevel framework with several analysis blocks in the inner level, optimizing smaller components, and on the outer levels, the system is built and optimized. It can be imagined that the inner layers optimize the components of a wind turbine such as floaters, mooring lines, etc., and when the driver moves to the outer layer, system-level components like turbine spacing, orientation, etc. are optimized.

1.7. Research Questions

As mentioned above, the current research aims to investigate how environmental impacts can be quantified and used as a metric in the MDAO framework to compare wind farm designs based on environmental impacts and with the lowest LCOE of the farm. This leads to the following research questions:

1. What are the environmental impacts of a wind turbine and how can they be quantified in the form of a metric?
2. Is there only one metric that can capture all the environmental impacts, or would it be better to have multiple metrics?
3. How can the metric(s), capturing the environmental impact, be used in the MDAO framework - to obtain the wind farm design with lowest environmental impact or to compare designs optimized for lowest cost?
4. How do wind farm designs change when environmental metric(s) is also considered in optimization?

1.8. Structure Of The Report

The thesis begins with the pressing concern of increasing the global mean temperature, global warming. Addressing the effects of unchecked human activities on the living conditions of the Earth, the major reasons are mentioned, and a sectoral distribution is shown to direct the thesis into the topic of energy transition. With the energy transition in the picture it is essential to mention the growing demand of energy and renewable energy. The importance of wind turbines in the transition is shown with an emphasis on the fact that these technologies are not completely clean, as expected from their operation procedure. Various environmental impacts of wind turbines are briefly mentioned to open one of the main questions of the thesis, how they can be quantified and used. A small description of the MDAO framework is mentioned, where the importance of it in wind farm design is emphasized. This is followed by the research questions of the thesis and the structure of the report.

Thereafter, the impacts of wind turbines are described in detail in Chapter 2, as found from existing research work. Both positive and negative impacts are covered in this chapter, and different metrics used in LCA and other research works are described. Chapter 3 describes the methodology of the work and highlights the assumptions made in formulating the model to estimate the impacts. Chapter 4 shows the results obtained after running the model with different turbine sizes, types, water depths, etc. which shows how the emissions vary changing design variable. It also shows comparison of farms based on the metric developed.

The report ends with a conclusion made from the results obtained, future scope of work and a list of all references used in the work. The appendix of the report contains results and plots from the model and can be referred to for a better understanding of the results and trends.

2
Literature Review

Wind energy has the potential to contribute significantly to the energy transition. With the increasing world's energy demands, the number of wind turbines is increasing. With improvement in technology and production processes, the cost of wind turbines is decreasing. There have also been many policy changes and subsidies to promote the growth of wind turbines. Due to these changes, the LCOE is decreasing. It is necessary to reduce it at least in the range of energy from fossil fuels. Furthermore, the wind energy industry is also exploring its potential in the ocean due to higher wind speeds and a more regular wind climate. However, the cost of building a wind farm deep in the ocean is more expensive than that of wind farms onshore. This raises the LCOE and to reduce it, the industry is focusing its research and development on minimizing it. In addition to LCOE, the environmental impacts of wind turbines must be studied in detail to ensure that the purpose of the energy transition is not defeated in the process of making wind energy cheaper. During the development of the wind farm plan, the interaction between devices and processes with the environment and living beings in the environment is considered a risk because there is still a considerable gap in scientific knowledge about the impacts [6]. Studies have mentioned that there is not only a lack of data, but also uncertainty in it, which makes it difficult to scale the impacts.

2.1. Indirect Impacts of Wind Turbines

2.1.1. Greenhouse Gas Emissions

Although the energy produced by wind turbines appears to be clean, there are a lot of carbon dioxide emissions during their lifetime, starting from the extraction of materials for the turbine until its decommissioning. The best way to estimate CO_2 emissions is to perform a Life Cycle Assessment (LCA). With LCA all emissions can be captured and calculated, but the calculations are done based on certain assumptions which will be described later in the section. In general, the LCA of any product or system consists of a scope in which the LCA is performed. It can start anywhere from the extraction of materials, production of parts, etc. and last until decommissioning, disposal, reuse, etc. For wind turbines, most of the LCAs start from the extraction of materials and end at the decommissioning of the turbines with a separate segment which takes into account the amount of materials that are recycled. Most often, there are 8 stages in the lifetime of a wind turbine [7], that is,

1. Stage 1: Raw Material Extraction and Processing
2. Stage 2: Transportation of Materials
3. Stage 3: Manufacturing of Components
4. Stage 4: Transportation of Components
5. Stage 5: Installation
6. Stage 6: Operation and Maintenance (O& M)
7. Stage 7: Decommissioning
8. Stage 8: End-of-Life (EOL)

Before starting the LCA of a wind turbine, it is checked which elements or materials are used by the turbine and in what quantities. The detailed bill of material prepared allows the LCA specialist to select the appropriate library and process. In Stage 1, all metals and materials are extracted by mining. Metals like iron, aluminum, copper, etc. require a lot of energy to be mined. The metal ores are in the form of rocks which are broken into smaller pieces, washed, mixed with reductants (mostly coal and hydrogen), and heated to convert the oxides into pure metals. The processing of these metals to increase its purity or to make alloys such as steel is also carbon-intensive. Production of steel requires temperatures of around 1500°C and to reach these temperatures a lot of energy is required. It is obtained by burning coal, which releases CO_2. Aluminum and copper require relatively lower temperatures, but they are still quite high and carbon intensive. On average, 1.931 tons of CO_2 are emitted during the production of 1 ton of steel [8]. For aluminum, it is 23.96 tons of CO_2 for 1 ton of aluminum [9].

Similarly, the production of glass, used as glass fibers in wind turbine blades, also requires a lot of energy and releases a lot of CO_2. On average, 1 ton of glass fiber emits 2 to 3 tons of CO_2 [10]. Some manufacturers also blend carbon fiber with glass fiber to make the blades stronger, but emissions from carbon fiber manufacturing are significantly higher than that of glass fiber. 1 ton of carbon fiber emits 24 tons of CO_2 [10]. Concrete is another example, which is a highly carbon intensive material and has a significant proportion in inland wind turbines and fixed-bottom offshore wind turbines. Cement, an important constituent of concrete, requires very high temperatures for its production and 1 ton of cement produces between 0.79 and 0.9 tons of CO_2 [11]. The other aggregates also add up to carbon emissions. Consequently, it can be concluded that the extraction and processing of metals and other materials are highly carbon intensive.

In reality, it is not just carbon dioxide that is emitted during the extraction and processing of the materials. Other gases like methane, nitrous oxide, sulfur hexa-fluoride are also emitted in some of the processes. Some of these gases have a higher greenhouse effect than carbon dioxide. This is measured by calculating the radiative forcing, measured in W/m^2, which shows how the energy is balanced at the top of the atmosphere. If radiative forcing is positive, then more energy is arriving at the top than energy leaving from the top. This means that the energy inside the atmosphere is increasing, which in turn means that the temperature will rise. All GHGs have positive radiative forcing, but some have higher than the others. To have a common metric or reference point, the radiative forcing of GHGs is converted into equivalents of CO_2, as it is one of the most studied and documented GHG. So even if it is mentioned that CO_2 is being emitted, it must be understood that the cumulative emission of all different types of GHGs is converted into equivalents of CO_2.

In stage 2, the transportation of raw materials to the manufacturing site is considered. The raw materials are finished metallic and non-metallic products. For example, processed steel at the end of stage 1 can be rolled steel sheets or bars. These finished products are transported to the manufacturing sites where they are converted or fabricated into turbine components. The transportation of raw materials can be via road, rail, or water bodies. During transportation, the vehicle uses energy and releases CO_2. Generally, in an LCA, the transportation of the raw materials to the fabrication/manufacturing hub is assumed to be fixed. For example, 500 km by truck, 100 km by ship, etc. For site-specific LCA, the transport is calculated in detail with the exact distance between the raw material processing site and the manufacturing hub, the mode of transport, and the emissions of that mode of transport. On average, a truck emits 307 g of CO_2 per 1000 km of travel [12]. The number of trucks that transport materials depends on the amount of material, which, in turn, depends on the size and number of turbines in a wind farm.

In stage 3, the manufacturing of wind turbine components from raw materials is considered. It emits GHG directly and indirectly, as in stage 1 [7]. It requires energy for the fabrication, welding, and heating of metallic raw materials to shape them to the desired shape and size. Different processes have different carbon emissions and are generally extracted from an LCA database to obtain standardized results. Stage 4 is similar to stage 2 where the finished turbine components are transported to the wind farm sites. In this stage, the only difference is the distance between the manufacturing hub and the site, which can be much larger than the distance in Stage 2. In addition, ships and trucks can be involved depending on the location and accessibility.

Stage 5 consists of the assembly and installation of the turbine at the site. Wind turbine parts are brought to the site and assembled one by one. In case of onshore turbines, the foundation is installed first, followed by the erection of the tower. The nacelle, which consists of the generator, is lifted to the top of the tower. After that, the hub and the blades are assembled. Some companies may tweak the process to some extent, but the overall steps remain similar. All of these steps require machines to lift and install the components, and they consume energy. So, there are indirect carbon emissions from the wind turbine installation process. The site-specific LCA of wind farms considers the actual time these installation equipment are used and computes the GHG emissions during their operation. Generic LCAs use a fixed value for the operating time of the equipment. For example, in [7], the installation is considered to be done by a hydraulic crane and it is operated for 16 hours to install 1 turbine. For floating wind turbines, the installation process is a bit different. The turbine and floater are assembled in a port closest to the wind farm site and then the assembly is towed by smaller vessels. This is done because the assembly of the turbine requires stability and is not achievable in oceans or seas due to waves.

Stage 6 is the longest of all stages. In this stage, the operation and maintenance of the turbine are considered. Turbines and generators are rotating equipment and they require lubrication. Wind turbines which have gearboxes also require lubricant in the gearboxes. In general, there is a fixed schedule in which the lubricants are topped up or changed. The production of lubricants emits GHG, similar to Stage 1. In addition, in this stage, inspection is performed periodically. For onshore turbines, the emissions from a vehicle from the nearest operation center to the site is considered, and for offshore turbines, the emissions from a vessel, used to transport the crew from the nearest port to the wind farm site, is considered. There can also be usage of crane for maintenance and certain parts of the wind turbine can also be replaced. It is considered that one whole blade, one whole gearbox, 50% of the pitch system and bearings, and 15% of the power converter and the nacelle require replacement over the lifetime of a turbine [7]. All of it result in emission of GHGs.

Stage 7 is the stage where the operating life of the turbine is over and it would not be financially feasible to maintain it and operate it for more years. During the end of its operating lifetime, the expense of turbine maintenance exceeds the revenue generated from the sale of energy. Consequently, the turbine is disassembled and brought back to the site for the next steps. This stage is similar to Stages 4 and 5, combined. Disassembly requires the use of hydraulic cranes, and the transport of parts to the site is via shipping vessels or trucks. Similar to the installation phase, 16 hours of crane operation can be considered for LCA and the same transportation distances as in Stage 4 [7].

Stage 8 is one of the important stages in the life of the wind turbine as it is still uncertain about the amount of materials that can be recycled. It is called the End-of-Life (EOL) stage and represents the next steps that can be taken to make the turbine as circular as possible. By circular, it means that the materials or parts of the turbines can be reused or recycled in some other applications or in the manufacturing of the new generation of wind turbines. For example, the steel in the turbine tower can be recycled into the production of new steel, since steel manufacturing uses scrap steel during its production. 90% of the metallic components can be recycled, and the rest 10% are used as landfills [7]. However, there is no mature large-scale technology for recycling thermoset glass-fiber reinforced polymer (GFRP) composite blades. It is still a practice to either use the turbine blade materials as a landfill or incinerate it. Both of these processes significantly increase the GHG emissions. Recycling materials can be considered negative GHG emissions because new materials are not extracted due to recycling. Similarly, rubber and PVC are incinerated, and electronics and concrete parts are used as landfill [7].

Some LCAs can have a slightly different structure, where one or more stages are merged with another stage to represent a larger part of the life. However, the consideration of different inputs and outputs, in terms of both material and energy, is kept the same. The overall results vary due to the different assumptions in the inputs. The stage that impacts the GWP the most is generally kept separate, as it is one of the most important stages. Combining it with other stages will also make it difficult to analyze and conclude the results. A pictorial representation of the LCA system boundary is shown in Figure 2.1.

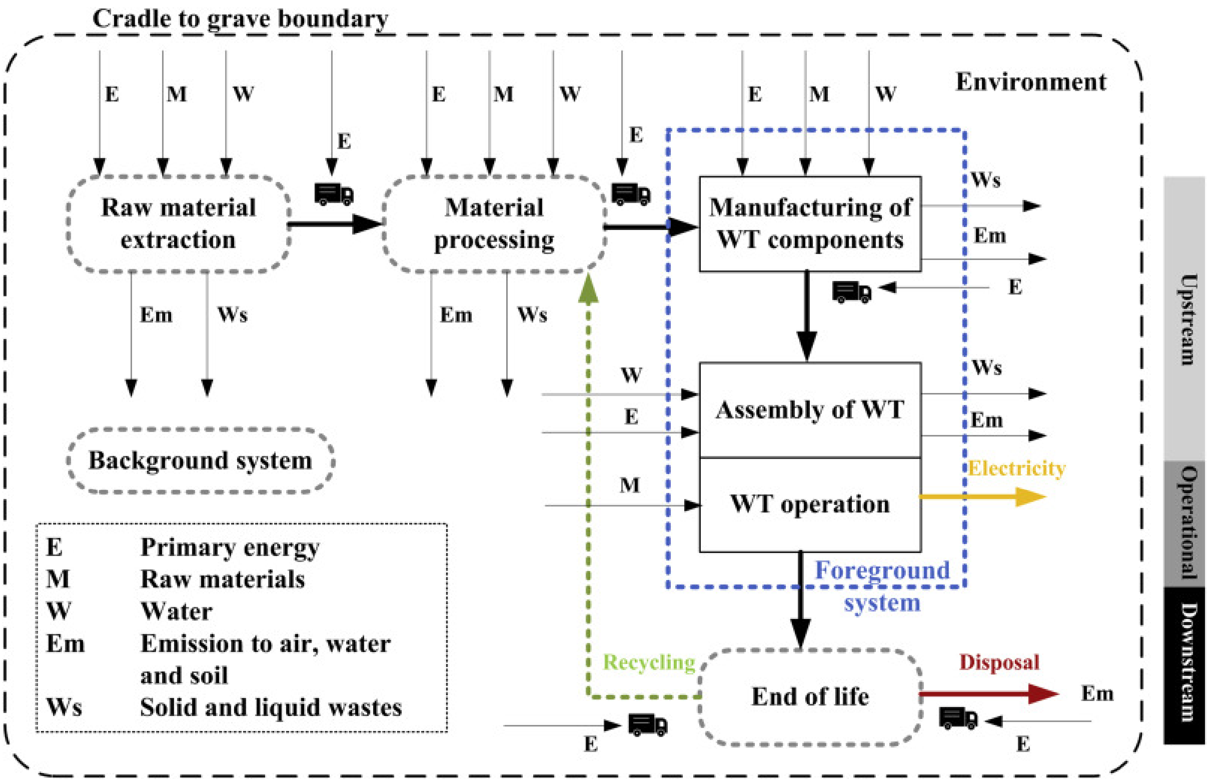


Figure 2.1: System boundary of an LCA study of a wind turbine showing different stages in the life of a wind turbine [13].

2.1.2. Analysis of GHG Emissions

From the analysis of GHG emissions from LCAs, it can be observed which stages in the life cycle of a wind turbine produce the highest GHGs. An automated LCA for turbines of any size is developed in [7]. For testing the LCA model, a study has been performed on a 3.35 MW turbine, and it shows that the highest emissions are from Stage 1 and Stage 3, the extraction of materials and the manufacturing of turbine components. Stage 6, the operation and maintenance of the turbines also have a significant value but is much less compared to Stage 1 and Stage 3. Stage 8 has a negative impact considering the recycling of materials. Figure 2.2 shows the emissions from all stages and components of the wind farm. In the figure, the vertical axis shows the Impact of Energy (IOE), which is the amount of equivalents of CO_2 per unit of energy produced by the wind turbine. So, the total life cycle emissions are divided by the total energy produced by the turbine during its lifetime.

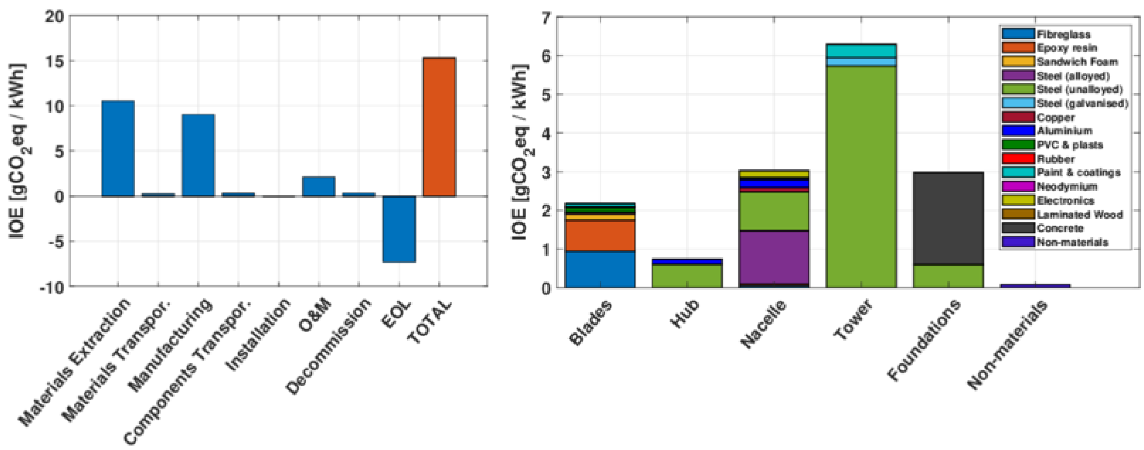


Figure 2.2: Impact of Energy (carbon dioxide equivalents emissions) from different stages of a wind turbine's life cycle [7].

It can also be seen on the right side of Figure 2.2 that a significant portion of the emissions come from a few components and materials in the turbine. It can be observed that the turbine tower produces the highest amount of GHG emissions (41% of the total) followed by the nacelle and foundations (around 20% each). The most important materials in these components are steel and concrete. The turbine blades also have a significant IOE, and the important materials in the blade that cause these emissions are fiberglass and epoxy resin. Steel is a very carbon intensive material that increases its IOE even though around 95% of it can be recycled [7]. Concrete is not the most carbon intensive material by mass, but very large amounts are used for the foundation, and therefore a significant portion of the emissions are from concrete [7]. Fiberglass and epoxy resin are not carbon intensive, but because it cannot be recycled yet, most of it is used as a landfill. This does not decrease its IOE in Stage 8, and consequently, the blades have high carbon emissions. It can be concluded from Figure 2.2 that the material requirement of the wind farm is one of the important factors contributing to GHG emissions. The bigger the wind turbine, the more emissions it produces. The bigger wind turbines will have larger towers, blades, and foundations, which means more usage of steel, concrete, polymers, resins, glass fibers, etc. This has also been studied and confirmed in [7] where a sensitivity analysis was performed and it was observed that the IOE increases when the rotor diameter or hub height is increased. Alternatively, if the power of the turbine is increased keeping the physical dimensions same then the IOE decreases. This is achieved by technological improvements, reduction of wake effects in the farm, installation of wind farms in areas of higher mean wind speeds (without the requirement of change of class of the turbine), etc.

Other LCAs of wind farms and wind turbines also suggest a similar conclusion. In [14], five different stages have been considered. They are material extraction and manufacturing, transportation, construction and installation, operation, and end-of-life (EoL). From the study, it was concluded that the material extraction and manufacturing stage contributed the most to life cycle GHG emissions. It can be seen in Figure 2.3 that the first stage has emissions much higher than the other stages. In the study, six different scenarios have been considered in which the lifetime of the wind farm and the percentage of metal recovery have been varied. Only four of them are shown in Figure 2.3. The lifetime of the wind farm has been increased from 20 years to 100 years, and the percentage of metal recovery has been increased from 85% to 100 % for steel and from 90% to 100% for copper. In all six scenarios, stage 1 leads in carbon emissions. Another study shown in [15] concludes similar results. In Figure 2.4, it can be seen that the material manufacturing stage of wind farms contributes to climate change more than any other stage. Similarly, the contribution of the tower to climate change is the highest, followed by the generator. The generator requires electrical steel and many other rare earth metals that are highly carbon intensive. In the case of a floating offshore wind farm, the floaters contribute to climate change more than the wind turbine itself because of the large quantities of steel used for its construction.

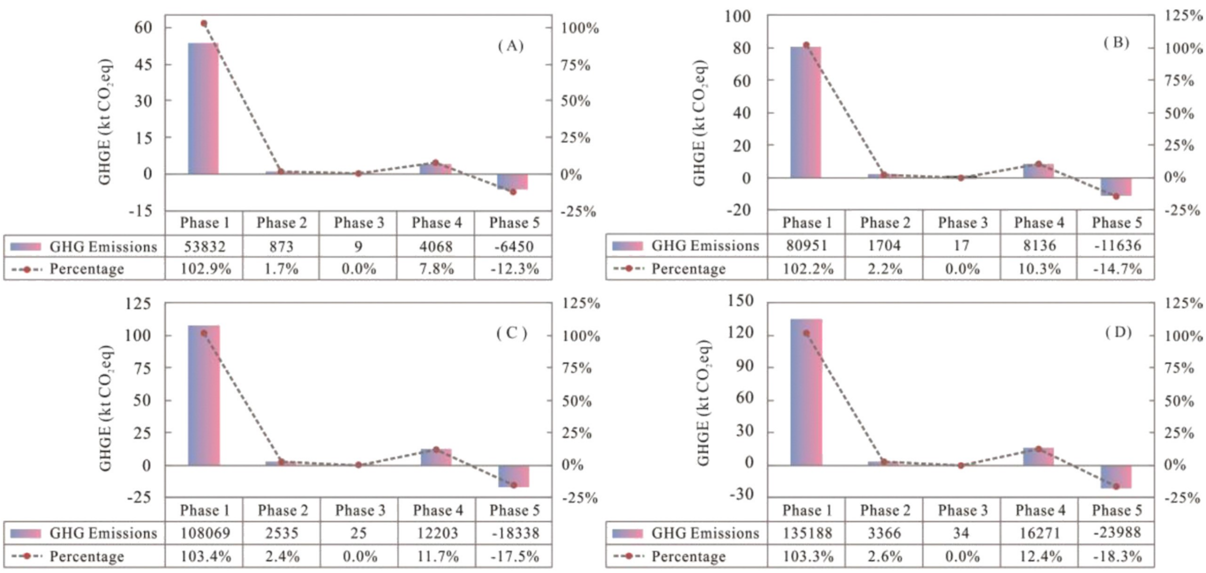


Figure 2.3: Carbon emissions from different stages of wind farm lifetime in different scenarios [14].

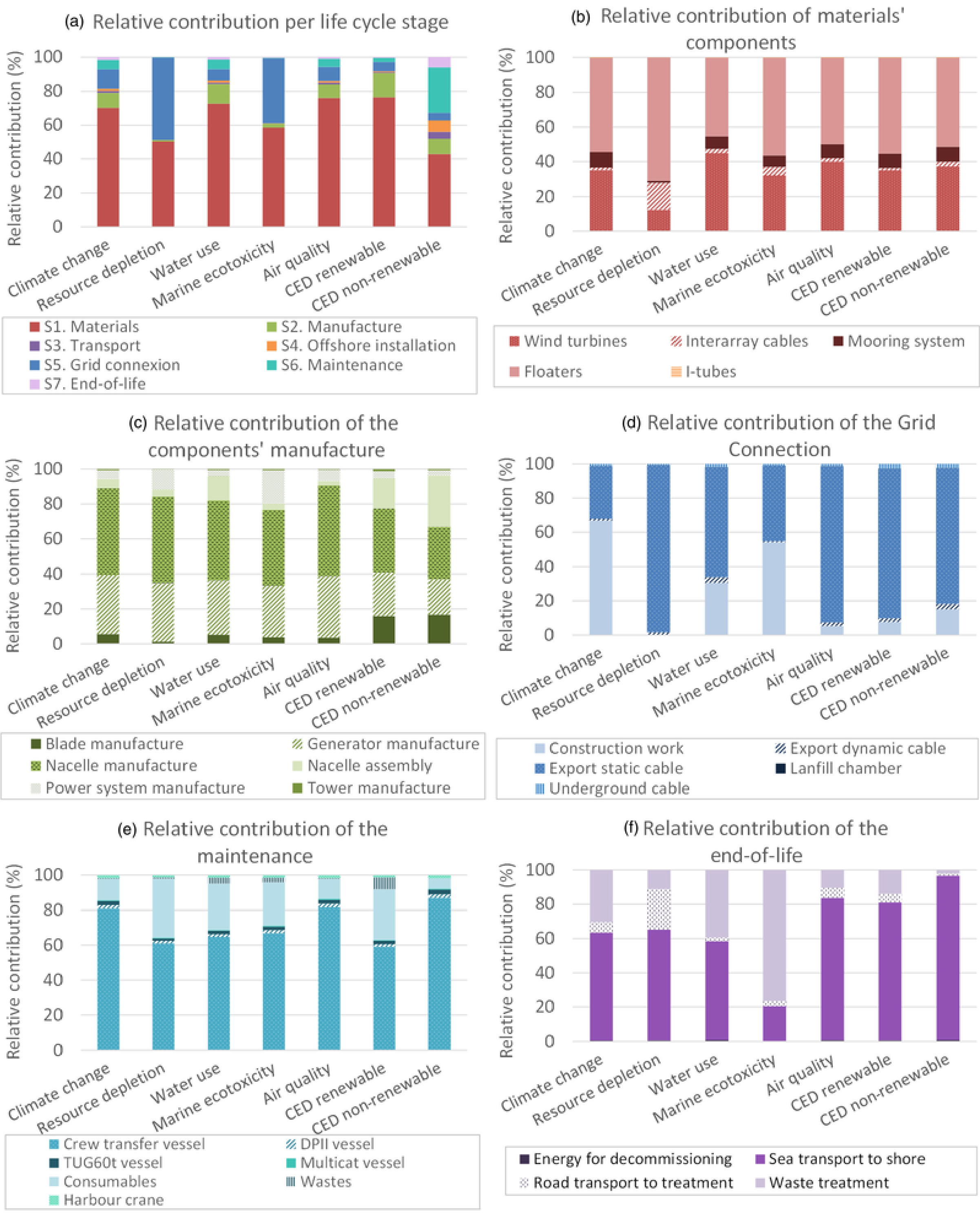


Figure 2.4: Contribution of different stages of lifetime and components of wind farm to the lifetime GHG emissions [15].

Turbine manufacturers also conduct life cycle assessments of their products. LCAs of wind farms, conducted by Vestas, conclude similar results. One such LCA is shown in Figure 2.5, where the 15 MW turbines used in a 990 MW offshore wind farm were assessed, show that material manufacturing has higher emissions than any other stages [16]. Figure 2.6 [16] shows the emissions of different parts of the wind farm. The Global Warming Potential (GWP) in the figure shows that a major part of it is due to foundation, tower, replacements of parts, etc. which also indicates the dependency of emissions on steel and concrete.

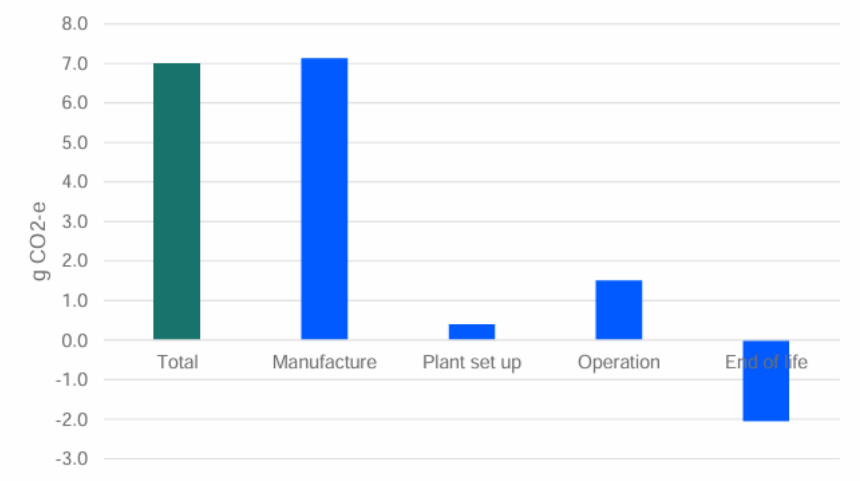


Figure 2.5: GHG emissions from different stages of 15 MW turbines in a 990 MW wind farm [16].

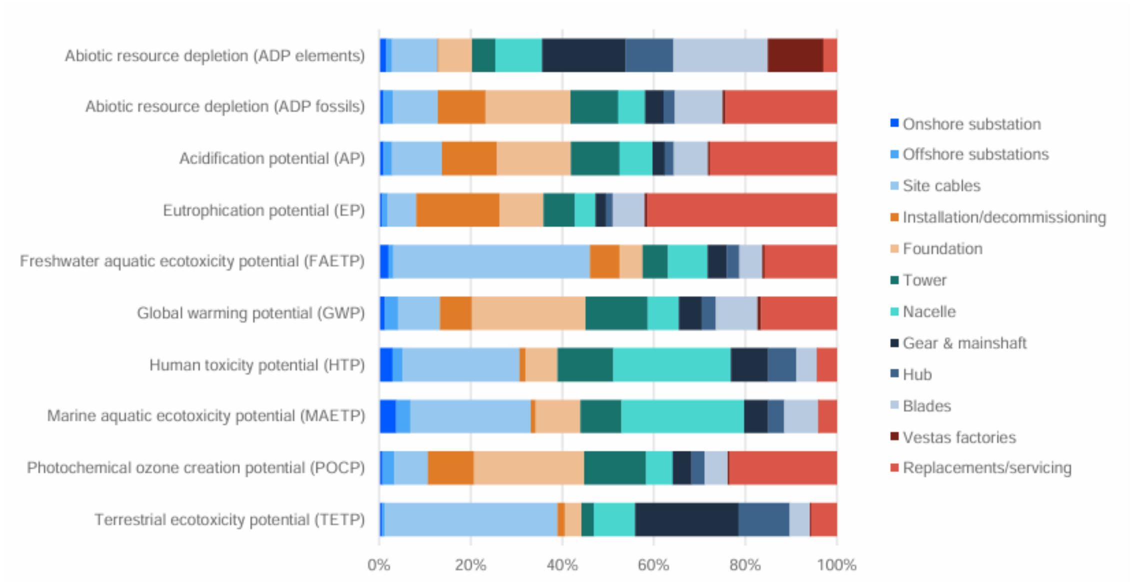


Figure 2.6: Results of Life Cycle Assessment of 15 MW wind turbines by Vestas [16].

From the above assessments, it can be concluded that the GHG emissions are heavily dependent on material consumption and extraction. Carbon-intensive materials, such as metals, concrete, glass, and polymers, play an important role in increasing the GWP. The recycling of materials is limited to only a percentage of certain materials, and hence it cannot decrease the emissions in the EoL stage of the wind farm. Consequently, it raises one of the questions of the thesis. Is using more number of small turbines better than using fewer number of larger turbines in terms of environmental impact?

2.1.3. Non GHG Emissions

In addition to CO_2 emissions, there are other compounds that also impact environmental health. Certain compounds, when released into the environment, can cause acid rain. Nitrogen oxides, sulfur dioxide, hydrogen chloride, non-methane volatile organic compounds, etc. are some of the compounds that cause acid rain [17]. These oxides are converted into acids when they react with water in the atmosphere, and when there is precipitation, the acid, formed in the atmosphere, is precipitated along with rain. Acids in rain or acid rain can decrease soil quality, increase the acidity of ground and surface water bodies, react with nutrients in the soil such as calcium and magnesium salts, and make trees weaker and more susceptible to damage from extreme cold, droughts, and pests. They can also release toxic

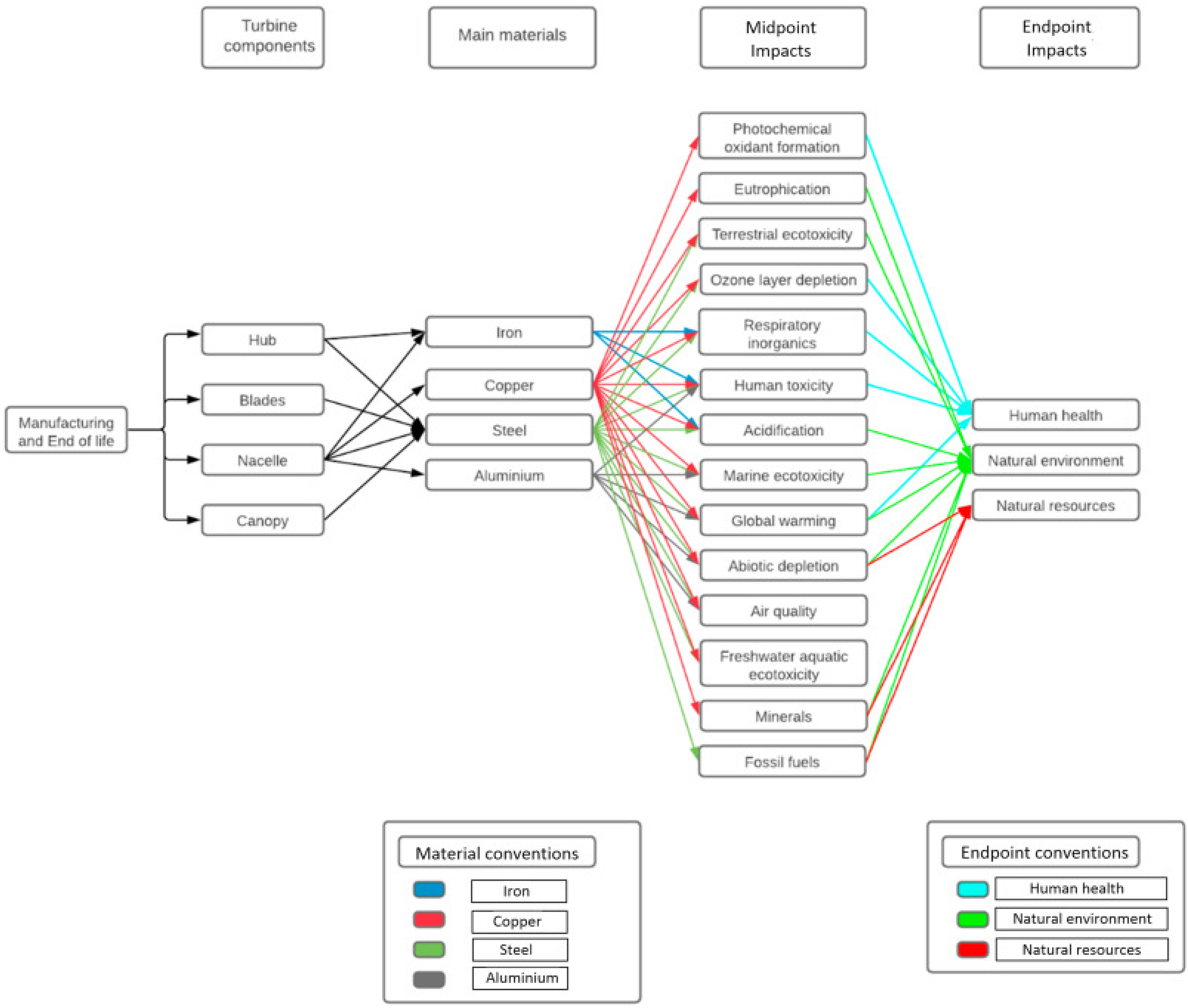


Figure 2.7: Relation among metals in Rotor-Nacelle Assembly (RNA) and impact parameters in LCA of wind turbine [18].

aluminum compounds by reacting with rocks rich in aluminum salts, corrode buildings and monuments made of marble and limestone, and kill marine animals and plants in the region where acid rain occurs. Compounds causing acid rain are emitted during the burning of fossil fuels. As mentioned above, the manufacturing of metals and concrete requires large amounts of energy and high temperatures that are obtained by burning coal and oil. The production of iron, copper, and steel also releases a lot of acid rain, which causes compounds to enter the environment. In addition to metals and alloys, the production of glass fibers and plastics is also responsible for these emissions [18]. Figures 2.7 and 2.8 can be referred to to understand how the emission of different metals and non-metals contribute to different impacts on the environment (including acidification). Consequently, these compounds are emitted during the manufacturing of wind turbine components, transportation of the components, movement of vessels for wind turbine installation (burning of diesel) , maintenance, decommissioning, etc. This impact on the environment is calculated by measuring the emissions of each compound and converting them into equivalents of sulfur dioxide (SO_2) [17].

Furthermore, certain compounds, when released into the environment, increase the growth of organisms in water bodies, which, in turn, decrease the oxygen levels in water, thus making it harder for other marine animals to survive. This process of accumulation of nutrients resulting in the growth of organisms that deplete oxygen in water bodies is called eutrophication. The compounds that cause this process are generally phosphates and nitrates [18]. An excess amount of these salts in water bodies create conditions for the growth of algae, phytoplanktons, and bacteria. Eutrophication can also occur naturally, but it is much faster when salts are added in a shorter time period. Due to the growth of these organisms and the decrease in oxygen levels in water, the aquatic ecosystem is disturbed, leading to the decrease in population of aquatic animals and plants, increase or introduction of new invasive species, increase

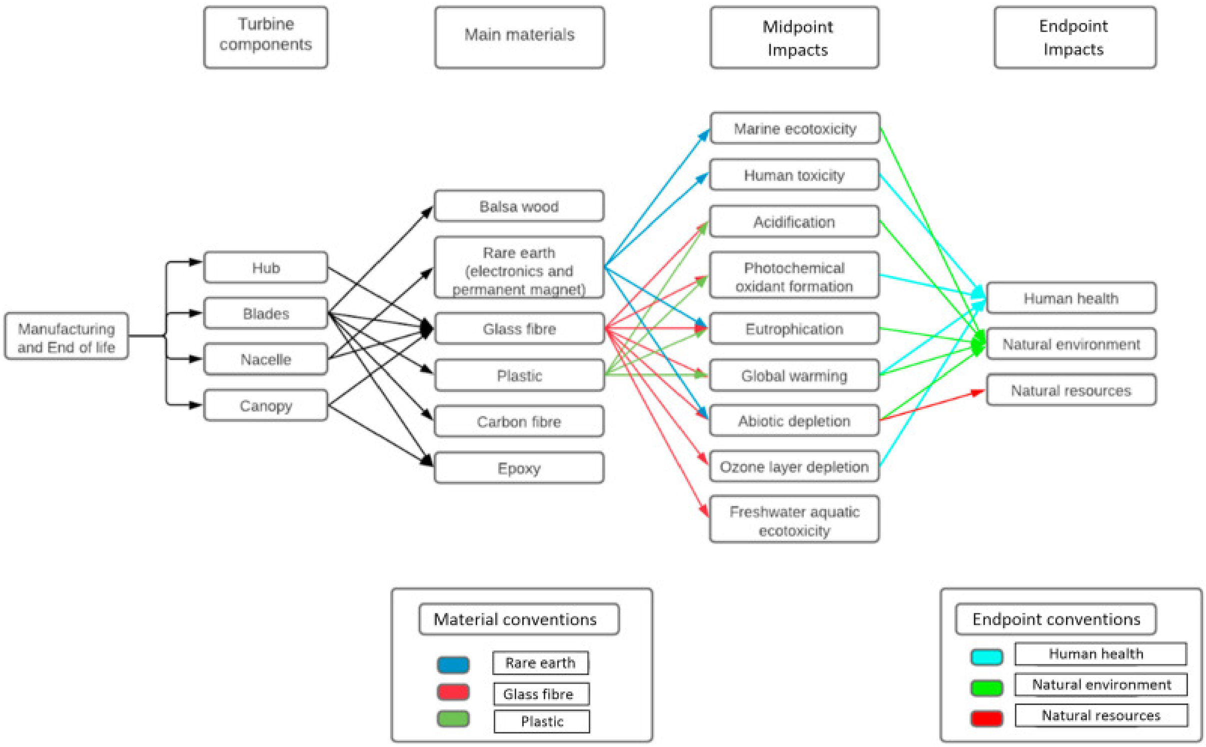


Figure 2.8: Relation among non-metals in Rotor-Nacelle Assembly (RNA) and impact parameters in LCA of wind turbine [18].

toxicity of the water when the organisms die (releasing toxic compounds into the water), etc. Water rich in nitrates and phosphates can lead to degradation of human health when consumed, and some water bodies or coastal water are used for consumption by humans. The production of concrete, copper, plastics, rare earth elements (used in electronics), etc. is responsible for the emission of phosphates and nitrates into the environment and hence contributes to the eutrophication caused by wind turbines [18]. The emissions of different compounds are converted into equivalents of phosphates to have one unit for calculation [17].

In addition, certain compounds are toxic in nature for different species of plants, animals, birds, and marine animals. Compounds of metals, polycyclic aromatic hydrocarbons, surfactants, microplastics, polychlorinated biphenyls, pesticides, dichlorobenzene, etc. are some of many compounds that are toxic to living organisms in general [19]. Some compounds are more toxic to certain organisms and less toxic to others. Consequently, toxicity is divided into marine eco-toxicity, human toxicity, terrestrial eco-toxicity, and freshwater aquatic eco-toxicity. The compounds mentioned above are released into the environment through several industrial processes during the manufacturing of components, processing of coal, packaging, preserving, combustion of natural gas, production of polymers, etc. They enter the environment in the form of particulate matter, aerosols, colloids, or solutions [19]. When it comes to wind turbines, production of glass fibers, processing of rare-earth elements, aluminum, steel, copper, etc. causes toxic substances to be released into the environment [18]. High levels of these compounds in the body can lead to deterioration of health or even death. Similarly to the previous methods, the emission of different compounds is converted into equivalents of 1,4-dichlorobenzene (1,4-DCB) [17].

2.2. Direct Impacts of Wind Turbines

Although the life cycle assessment of wind turbines is a good way to assess and measure environmental impacts, it only gives a measure of the amount of materials that are going into and out of the system and the effects of these materials on the environment. It is an indirect way of calculating the impacts. However, a wind turbine can potentially directly impact living organisms by physically interacting with them. Here, the behavior of animals, plants, birds, and marine animals may be affected due to the presence of wind turbines. There can be loss or change of the seabed / soil due to foundations [6]. There are several potential impacts identified by different researchers and organizations. A review of the impacts presented in [20] and shown in Figure 2.9 categorizes them into the following categories:

1. Atmospheric and oceanographic dynamics
2. Habitat alteration
3. Electromagnetic field effects
4. Noise effects
5. Structural impediments
6. Changes to water quality

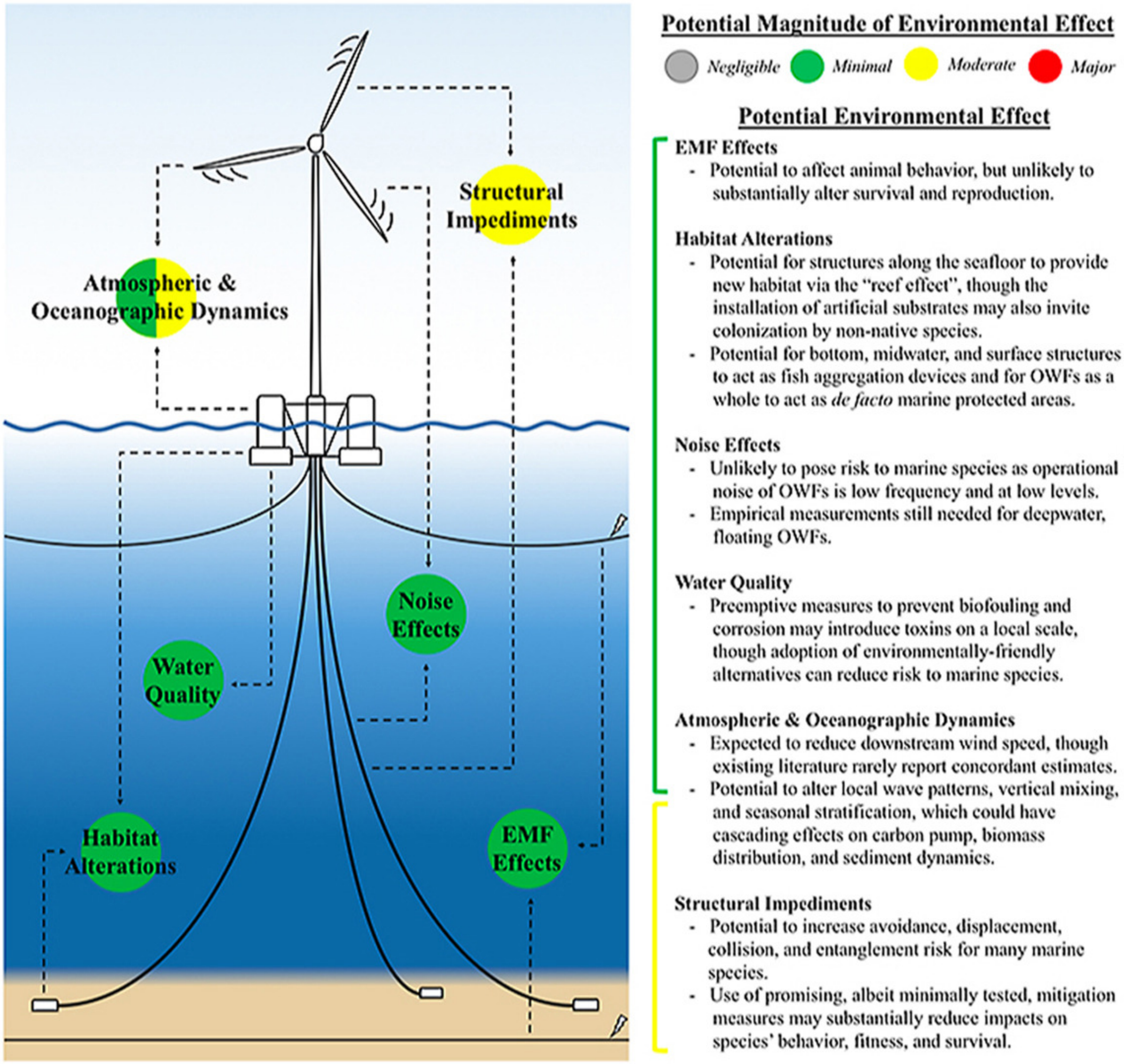


Figure 2.9: Potential environmental impacts of wind turbines [20].

2.2.1. Atmospheric and Oceanographic Dynamics

Wind turbines extract energy from the wind and hence the wind speed after crossing the turbine is less than the speed of wind before the turbine. This effect is known as the wake effect and severely affects the performance of downstream turbines. However, when a farm is considered, the wind conditions after the wind farm can be different, which leads to different weather conditions altogether. Research done on studying the effect of climate change in areas which are in the downstream of large-scale wind farms, using climate models, shows that precipitation can increase due to farms [20]. Wind speeds measured by satellite synthetic aperture radar (SAR) near Horns Rev in the North Sea and Nysted in the Baltic Sea revealed that the average wind speed deficit ranged from 8% to 9% immediately after the wind farm and recovered to a deficit of 2% within 5 km to 20 km downstream [20]. For deep water offshore wind farms the effect on regional climate is likely to be minor to moderate and compared to other anthropogenic climate forcings, such as GHG emissions, it is negligible [20].

There is also an effect of wind turbines and farms on ocean dynamics, but current understanding and knowledge about it is, however, limited and uncertain. Offshore wind turbines, especially fixed-bottom turbines, can change wave propagation shoreward due to reflection and diffraction of waves from the turbines. Consequently, there is an increase in vertical mixing of the water, altered seasonal stratification, and nutrient transport [20]. This can have cascading effects on the natural biological carbon pump, which is a process in which inorganic carbon is fixed to organic matter via photosynthesis at the surface and subsequent sinking and sequestration at depths. There may also be effects on biomass distribution and sediment dynamics that can scale with the footprint of wind farm. Although floating deep-water wind turbines have a lesser footprint on the seabed, which indicates a lesser effect on oceanographic dynamics, it still requires further exploration and research [20].

2.2.2. Habitat Alteration

The deployment of new structures in the environment always has the potential to alter behavior and induce physical changes in habitats. It may also induce changes in the local composition of species. For offshore wind turbines, the foundation, scour protections, mooring anchors, and sub-sea cables act as artificial reefs by introducing a hard substrate that can be colonized by vertebrates and reef-associated fishes [20]. This phenomenon is popularly known as the ”reef effect” and is well documented in studies on oil and gas platforms, and sub-sea pipelines. Evidence of offshore wind farms functioning as both artificial reefs and fish aggregation devices for demersal fishes has been found [20]. However, with support to one kind of species also leads to invitation of other species looking for food. Non-native species, also called invasive species, are higher up in the food chain and can affect the marine biodiversity and have far-reaching ecological and economic consequences. For example, marine structures near the coast of the north Adriatic Sea facilitated the growth and spread of non-indigenous green algae (Codium fragile) [20]. This is also an example of the eutrophication described above. Mid-water and surface structures act as fish aggregation devices and settlement surfaces for invertebrates and algae, and consequently fishes of many species are attracted. Fishing activities and the movement of boats and ships are restricted in and around wind farms as a safety measure. Consequently, the wind farm area becomes a protected area for marine species, creating refuges for some species, increasing the abundances of local species, and generating spillover effects to adjacent areas [20]. Although the investigation on these impacts is still in progress, no study to date has reported significant negative habitat alteration due to offshore wind farms [20].

2.2.3. Electromagnetic Field Effects

As wind turbines and farms are growing in size and moving into deeper waters, the cables, used for transporting energy from the farm to the shore, are carrying more energy than before. Floating wind farms have sub-sea cables, carrying current, which are in the vicinity of fishes. Fixed-bottom wind farms have the advantage of cables laid along sea floor, but for floating wind farms the cables are suspended in the sea. Three-phase alternating current (AC) cables produce both electric and magnetic fields. Magnetic fields produced from inter-array cables are typically low, whereas the fields produced by export cables can be higher. Moreover, the usage of high voltage direct current (HVDC) cables makes it a bit more difficult because they have a higher intensity of the magnetic field around them [20]. HVDC cables are becoming more popular for floating offshore farms as these farms are moving further into deep sea, and transportation losses are lower in HVDC cables than in HVAC cables over long distances. Several species of marine animals, such as bony fish, marine turtles, cetacea, etc. are sensitive to electric and/or magnetic fields [20]. Most likely impacts on these species are physiological impacts such as altered development, and behavioral impacts such as attraction, avoidance, impaired navigation, and orientation, etc. Research about it to date is limited and studies have shown that the response is species-specific and sometimes individual-specific. This means that some species are affected by the electromagnetic fields and some are not and within a species not all individual show the same response as others. Thus, the effect cannot be generalized. For example, Little skate (Leucoraja erinacia) exhibited a strong behavioral response, where as the American lobster (Homarus americanus) exhibited only a subtle change [20]. Similarly, a study was conducted on caged rock crabs (Metacarcinus anthonyi and Cancer productus) where they were placed beside an un-energized, and an energized sub-sea cable and there were no significant differences in response or behavior [20]. The swimming speed of European eels (Anguilla anguilla) in the Baltic Sea was found to be significantly lower near the sub-sea cables, but there was no evidence of cables obstructing their movement or the field affecting their fitness [20]. Overall, studies mention that the behavioral changes and impacts demonstrated in certain species are minor, but there are still large gaps in understanding these interactions.

2.2.4. Noise Effects

Wind turbines are being studied extensively to understand the effects of their noise on living beings. In recent years, there has been an increase in documentation on the impacts of noise on human health. Not only do the study findings vary widely, but also have conflicting conclusions. Typically described as swooshing sound, they are considered similar or worse to some forms of industrial noise or traffic noise [21]. Some studies also conclude that the effects of noise on people living more than 500 m from turbines are minimal, partial, and highly affected by psychological factors. People living in the vicinity of turbines voice the problem of sleep disturbances [21]. During planning/designing a wind farm at an onshore location or a location close to human locality, noise levels regulations are followed strictly. However, these regulations are based on thresholds beyond which humans are not comfortable. But for animals, birds, or marine life, such regulations are not properly developed or are largely ignored [21]. Wind turbine noise can range from frequencies that are audible to the human ear to low frequencies that are inaudible to the human ear. However, many birds and animals are sensitive to low-frequency sounds, and some use them to communicate and navigate. Some of the potential impacts identified from wind turbine noise include [21]:

1. physiological damage such as chronic high levels of stress hormones
2. partial or complete hearing loss
3. use of anti-predatory measures at the expense of foraging or fleeing the area leading to habitat loss as the noise can be perceived as threat
4. reduced efficiency of finding and handling food
5. hindered animal communication and hence, coordination and reproduction

The number of studies on noise pollution is increasing, but studies specifically on wind turbine noise are not abundant. Some studies focus more on traffic noise than on wind turbine noise. Some studies also focus on noise from both traffic and wind turbines and conclude that the combination of the two can create a greater disturbance to certain species than individual noise [21]. In the case of offshore wind turbines, the impact of noise on marine animals is similar but far less in magnitude. Wind turbines offshore are designed to have a greater tip speed ratio than turbines near shore or inland. This leads to offshore turbines making more noise than onshore turbines. However, the tip speed ratio cannot be significantly increased as it increases the erosion of the blades. Consequently, the noise from offshore turbines is not much higher than that from onshore turbines. Onshore turbines have a regulatory limit and are designed to have noise within limits. Therefore, marine species and migratory birds experience more noise from offshore turbines than they would from an onshore turbine. Although the number of studies on the effect of wind turbine noise on marine animals is very low, the conclusion so far is that the impacts are not significant. Monitoring at Horns Rev in the North Sea revealed that wind turbine noise had no detectable effect on harbor porpoise abundance [20]. Analysis of the noise of two Danish (Middelgrunden and Vindeby) and one Swedish (Bockstigen-Valar) fixed-bottom offshore wind farms concluded that operational noise is unlikely to harm or hinder communication in harbor seals (Phoca vitulina) and harbor porpoises [20]. For fixed-bottom offshore turbines, monopiles are embedded in the seabed by hydraulic impacts, which creates a lot of noise. Some organizations are also looking into alternative monopile installation methods such as drill-drive installation which causes less noise. Overall, with the limited knowledge on the impacts of noise on wildlife and marine life, it is uncertain to conclude, but to date the impacts seem to be minor compared to the larger impacts like the emissions.

2.2.5. Structural Impediments

The physical presence of large structures such as wind turbines always poses a threat to birds and marine species. Wind turbines pose a greater threat because of their rotating blades and mooring lines, in the case of floating turbines. For marine species, they can benefit them by the reef effect as mentioned above, or they can pose as an obstacle. For birds and bats, they are never an advantage. Wind farms exhibit barrier effects for them. Birds may try to avoid wind farms and take a more circuitous route, which can cause them to expend more energy [20]. Although the consequences of such barrier effects are largely unknown, a comparison of pre-construction and post-construction data from the Nysted wind farm in the North Sea suggests that birds show avoidance behavior, but the energy expended to circumvent the wind farm remains insignificant [20]. Monitoring bird behavior at the Thanet offshore wind farm in the UK showed that 96.8% of the recorded seabirds avoided turbines by flying between turbine rows and the rest 3.2% adjusted their flight height to fly below the rotor swept zone, suggesting that changing routes is not necessarily done by all birds [20]. Some species of birds show avoidance more than other species. For example, flocks of ducks and geese entering the Nysted wind farm area decreased by a factor of 4.5 between pre-construction and initial operational periods.

Avian collision risk remains one of the most publicized concerns regarding wind turbine facilities despite estimates of avian mortality from wind turbines remaining much lower than that from other anthropogenic sources. Sources of avian mortality include buildings, power cables, cats, automobiles, pesticides, communication towers, wind turbines, etc. [22]. Among these sources, wind turbines are responsible for only 0.003% of avian deaths, whereas buildings comprise 58.2%, power lines comprise 13.7%, cats comprise 10.6%, etc. [22]. It can be seen in Figure 2.10 that the deaths from wind turbines are relatively very small compared to other sources. In addition to that, wind turbines are growing in size every year, but their rotational speed decreases with size. This means that the probability of collision decreases as the lower speed gives the birds more time to react. Hence, deaths are expected to decrease with increasing size [23].

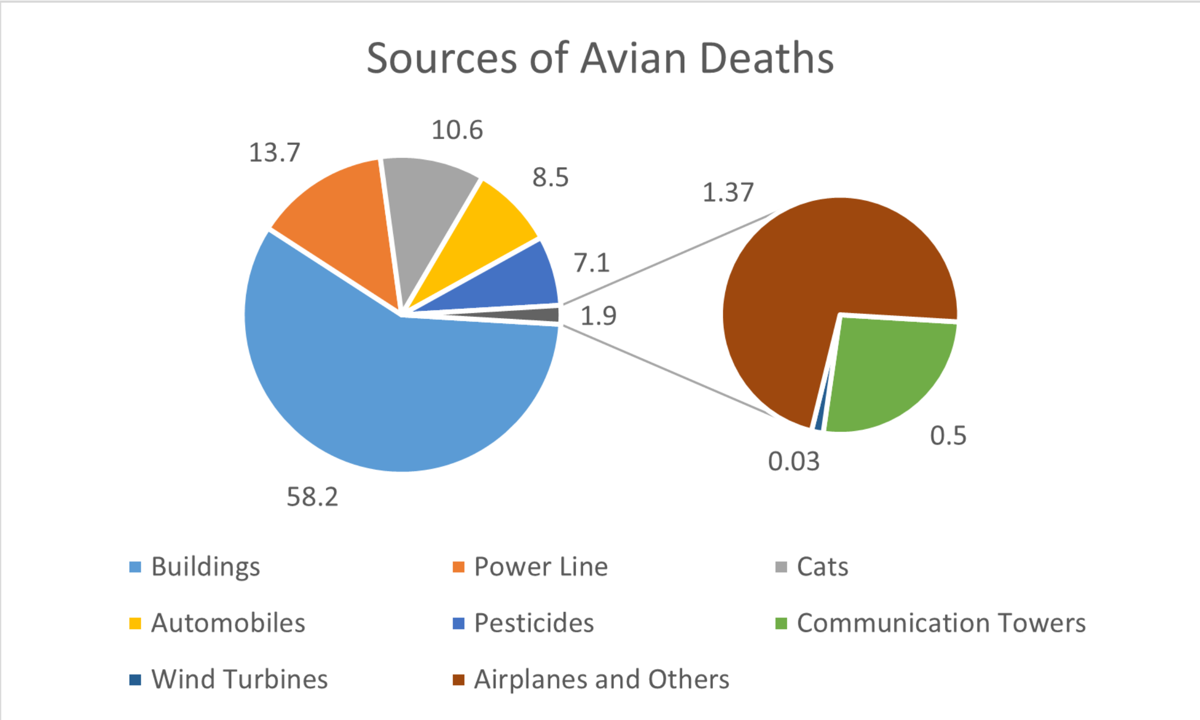


Figure 2.10: Percentage distribution of sources of avian mortality [22]

Similarly, bat mortality rates from wind turbine collisions show that weather, season, and habitat type are key factors that influence it. For seabirds, the collision risk is species dependent, and the risk decreases when the wind farms move away from the shore. Wind speed and direction, blade height, visibility, and lighting also play an important role in affecting the risk of collision. Facility-specific parameters like inter-row and inter-column spacing, and number of rows and columns also influence the probability of collision, and hence the risk. The wind industry is actively deploying measures such as painting the turbine blades and tower and installing lights on the nacelle to prevent avian collision. Figure 2.11 shows an example of a concept proposed in [24]. Some energy companies also stop turbines during a specific time of the year when migratory birds migrate from the area. Although the collision of birds is not as minor as the electromagnetic field impacts, it still needs to be understood more so that strategies to prevent it can be developed and implemented. So far, it has been concluded that building a wind farm away from migratory routes of birds and in areas with a lower population of birds is the best way to prevent avian deaths [20].

Floating offshore wind farms are less risky for birds, but they create another risk, risk of entanglement

Figure 2.11: Concept of using different colors on turbine to increase its visibility [24].

of marine mammals and fishes with mooring lines and power cables. Entanglement depends on the mooring characteristics, the physical dimensions of the lines, and the configuration of the turbine array. It also depends on the relative size of marine mammals and fishes. Catenary mooring provides greater risk compared to taut mooring due to larger footprint, greater line curvature, and less rigid behavior. Baleen whales are at highest risk of entanglement due to their relative size and foraging habits [20]. Although the relative risk among the mooring systems differs, the absolute risk of entanglement is much less than expected. The mooring system typically uses chains and polyethylene ropes of diameter 100 mm to 240 mm. Fishing gear, which has been identified as a major entanglement risk for whales and other marine mammals and fishes, is typically 1 mm to 7 mm in diameter. Instead of getting entangled with the mooring lines and cables, also known as primary entanglement, the risk of secondary entanglement is higher for marine species. In secondary entanglement, the fishing gear is entangled in mooring lines, and then the marine species get entangled with it. There is also a risk of tertiary entanglement in which the fish or the marine mammal, already wrapped or entangled in fishing gear, swims through the wind turbine facility and gets stuck on the mooring lines or cables. Entanglement with cables has not been reported since 1959 and is considered a rare event. This is possible due to improvements in cable installation and features [20]. The impacts on marine animals seems to be minor but they are not yet studied extensively. It is still considered that constructing wind farms that do not intersect with biologically important areas, such as feeding grounds and migration corridors, is the most effective way to prevent entanglement and collision [20].

2.2.6. Changes To Water Quality

Changes in water quality are predominantly a risk for offshore wind turbines. Offshore conditions are not favorable for iron and steel products. Corrosion followed by erosion is very high in offshore environment due to humid air, salty water, and high wind speeds. Wind turbine blades that are made of glass fibers are also subjected to harsh conditions that lead to erosion. Wind turbine manufacturers use several corrosion protection measures to prevent corrosion and reduce maintenance. Some of the measures include epoxy-based coating, cathodic protection, and polyurethane topcoat [20]. These corrosion protection measures are a direct source of contamination, releasing chemicals into the environment (sea water). Chemicals such as bisphenol A and metals such as aluminum, zinc, cadmium, and indium. Bisphenol A is released from epoxy resin-based anticorrosion coatings, and zinc and cadmium are released from galvanic (cathodic) protections. Mussels (Mytilus galloprovincialis) from offshore gas platforms in the Adriatic Sea were studied and it was found that the levels of cadmium and zinc were high in them. Galvanic anodes were hypothesized to be the reason behind it [20]. Data from offshore wind farms are scarce, but they do not report any significant changes in water quality. Since 2008, organotin-based antifouling paints have been banned and the use of tributylin has been stopped. Tributylin is a highly toxic chemical that was used heavily by the shipping industry, but its ban on all industries also helped to make turbines cleaner and less harmful. Although the use of alternative chemicals in corrosion protection poses a risk of contamination, the impact on water quality and toxicity will be minor, nevertheless. However, these challenges are not new to the wind turbine industry as they have also been explored by other marine industries. With stricter regulations, the impacts will decrease with time in the future [20]. For onshore turbines, the risk of releasing harmful chemicals into the environment is less because of the lesser use of corrosion protection and the lesser presence of water bodies.

From the above-mentioned impacts, it can be concluded that the impacts on the behavior of animals are still not extensively studied and understood. Hypotheses are made based on certain individuals of a species that may or may not be applicable to other individuals or other species. Some of the impacts are not even negative, which means that turbines actually help wildlife. This makes it difficult to generalize the impacts and measure them. Among all the behavioral impacts, collision of birds and noise from the turbines are the most researched topics. In addition, the impacts, understood from current levels of research and data, are not as significant as the impacts from emissions of greenhouse gases, phosphates, sulfur and nitrogen oxides, and toxic compounds.

2.3. Metrics Used

Measurement of impact on animal behavior is a very difficult task, as it is difficult to define a unit or metric. Several organizations such as the Marine Strategy Framework Directive attempted to give a structure to ”pressures” on the environment [6]. Pressures are defined as the stresses put on the environment by wind turbines, and the magnitudes of the pressures are scaled as low, medium, and high. Similarly, the impacts due to these stresses or pressures are further classified as positive, negative, both positive and negative, unknown, and not significant [6]. The magnitude of pressures are scaled as high, medium, low, not significant, and unknown [6]. However, in this attempt, the scales are not defined with numbers. These parameters are subjective and cannot be used in wind farm optimization problems. In this regard, the results from an LCA prove to be useful as they provide results with a unit. LCA considers the impacts that are well studied and documented and that are considered to be more harmful than the behavioral impacts mentioned above.

To measure the impact of wind turbines in terms of greenhouse gas emissions, all greenhouse gases emitted during the entire lifetime of the wind turbine are converted into equivalents of carbon dioxide. **Global warming potential (GWP)** is the term used to measure how much energy is absorbed over a certain period when 1 tonne of a specific gas is released into the atmosphere relative to the amount of energy absorbed by 1 tonne of CO_2 over the same period. Generally, the time period used is 100 years. Equation 2.1 shows a simplified expression of calculating GWP, where X_{GWP} is the actual GHG emissions for a period of 100 years, $X_{GWP(T)}$ is the target value for the same period and Y_{GWP} is the GWP score [17].

$$Y_{GWP} = \frac{X_{GWP(T)}}{X_{GWP}} \tag{2.1}$$

Similarly, to measure the **acidification potential (AP)**, the amount of acid rain causing gases is measured and converted into equivalents of SO_2^-. Equation 2.2 shows a simplified expression of calculating the acidification potential, where X_{AP} is given by Equation 2.3 and $X_{AP(T)}$ is a standard set by the Environmental Protection Agency (EPA) for the ambient air quality, which is 190 μ g/m^3. In Equation 2.3, $SO_{2,0}$, SO_2, τ_{SO2} and MH_{SO2} refer to the background concentration, annualized life cycle emissions, residence time, and vertical mixing height of SO_2, respectively [17].

$$Y_{AP} = \frac{X_{AP(T)}}{X_{AP}} \tag{2.2}$$

$$X_{AP} = SO_{2,0} + \frac{SO_2}{Area_{Community} \cdot MH_{SO_2}} \cdot \frac{\tau_{SO_2}}{8760} \tag{2.3}$$

The **eutrophication potential (EP)** is also calculated by measuring the emissions and converting them into phosphate equivalents. Equation 2.4 shows the expression to calculate the eutrophication potential, where X_{EP} represents the actual life cycle emissions of phosphates per year and $X_{EP(T)}$ represents the target value calculated using Equation 2.5. EP_{ref} is the reference eutrophication potential which is equal to global annual phosphate emissions and α_{EP} is the adjustment factor [17].

$$Y_{EP} = \frac{X_{EP(T)}}{X_{EP}} \tag{2.4}$$

$$X_{EP(T)} = EP_{ref} \cdot \alpha_{EP} \tag{2.5}$$

The **marine aquatic eco-toxicity potential (MAEP)** is also calculated in a similar way with the reference compound being 1,4-dichlorobenzene (1,4-DCB). All compounds released into the environment that are toxic to living organisms are converted to equivalents of 1,4-DCB. This substance is used as raw material for the production of insecticides, deodorants, pigments, and solvents in industry [25]. Since its use is very common in industries, it is used as a reference in LCAs. Equation 2.6 shows the expression used to calculate the eco-toxicity potential where X_{WE} represents the actual life cycle emissions of 1,4-DCB per year and $X_{WE(T)}$ represents the target value which is calculated using Equation 2.7. WE being the acronym for water eco-toxicity in [17]. WE_{ref} is the reference eco-toxicity potential that is equal to the global annual 1,4-DCB emissions and α_{WE} is the adjustment factor [17]. Other toxicity potentials, like human toxicity potential and the terrestrial eco-toxicity potential, are also calculated similarly.

$$Y_{WE} = \frac{X_{WE(T)}}{X_{WE}} \tag{2.6}$$

$$X_{WE(T)} = WE_{ref} \cdot \alpha_{WE} \tag{2.7}$$

All of these parameters mentioned above are calculated by the LCA studies and are obtained as an output when the manufacturing processes and quantities of raw material are given as input. LCA software also has several databases where different processes and assumptions are stored. Based on the product (in the present case it is a wind farm) different databases can be selected for assessment.

After assessing all impacts and the potential ways to quantify the important ones, it is necessary to explain the methodology to convert the impacts into a metric, estimate the impact of a wind farm design, and integrate it into the MDAO framework. The next chapter explains this methodology in detail.

3
Methodology

In this chapter, the methodology for converting the environmental impacts of wind turbines into a metric is described. The chapter starts with the idea of finding a relation between the amount of material used in the turbine and the amount of GHGs emitted into the environment. Two relations are developed using which the amount of emissions from turbines can be estimated. Following the relations, the general workflow and the MDAO framework are described. Thereafter, the parameters of wind turbines and wind farms that are varied are described in detail. This sets the foundation for all the steps that are taken during the simulations and design process.

3.1. Correlation Between Emissions And Materials

Given the maturity of research on the impacts of wind turbines on animal behavior, it is not easy to have a metric. The impacts that are more significant with the current maturity of research are the emissions of different compounds during the life cycle of a wind turbine. In this regard, the life cycle assessments (LCAs) conducted by various companies and researchers set a good foundation for developing an estimation of the emissions. Vestas, one of the wind turbine manufacturers, conducts the LCA of the wind turbines. Although farm sizes and turbine specifications are different, they serve as a reliable baseline for the global warming potential (GWP). Data of turbine LCAs of sizes ranging from 1.8 to 15 MW have been compiled to find the relationship between the amount of materials and the total greenhouse gas emissions. This has been done because in Chapter 2, it was observed that the amount of material used in a turbine/farm determines the amount of emissions. It must be noted that the farm size varied for different farms, ranging from 50 MW to 102 MW. The lifetime of the turbine was set to 20 years and the energy output of the farm, based on the location, was calculated by Vestas. The data from the LCAs of Vestas that is used to estimate GHG emissions is shown in Table A.2 in Appendix A. LCAs also contain data on the amount of materials used, for example, the amount of steel, concrete, iron, polymer, etc. Iron and steel were combined as steel because the carbon intensities of both materials are similar. Consequently, the variation of the GHG emissions and the amount of different materials used in the wind farm were plotted against the various wind farms. This was done to have a visual representation of the correlation between GHG emissions and the amount of materials used in the turbines. Figure 3.1 shows the relationship between the total amount of material used in the wind farm construction and the total GHG emissions over its lifetime. Figure 3.2 shows how the total GHG varies with different materials like steel, concrete, and polymer composites. It can be concluded that emissions follow the trend of total material use very closely. Similar trend is also seen for individual materials like steel and concrete. To verify the correlation between these parameters, the correlation coefficients were calculated and shown in Table 3.1. It can be observed that the correlation coefficient between total GHG emissions and steel and concrete is very high, 0.92 and 0.91 respectively. Between emissions and polymer composites, it is quite low and with respect to total amount of materials used, it is again quite high. The correlation between polymers and GHG emissions is low because they are lighter compared to metals and the amount of polymers used in the turbine is much lower compared to metals. This suppresses the influence of polymers on the emissions. This is in line with the research carried out previously, which has been mentioned in Chapter 2.

A relationship was developed between the individual materials and the total emissions. This was done to

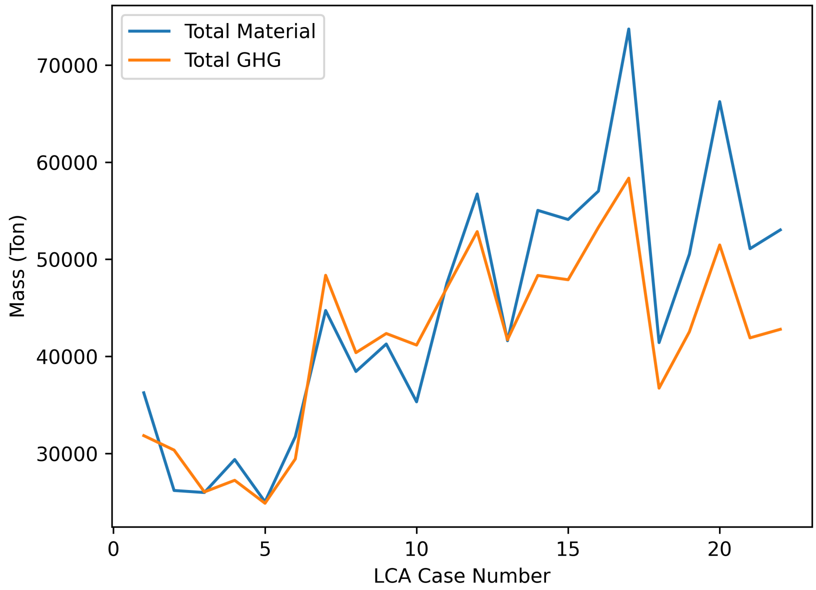


Figure 3.1: Variation of total GHG emissions (ton) of a wind farm and the variation of total amount of material (ton) used in it, for different wind farm life cycle assessments.

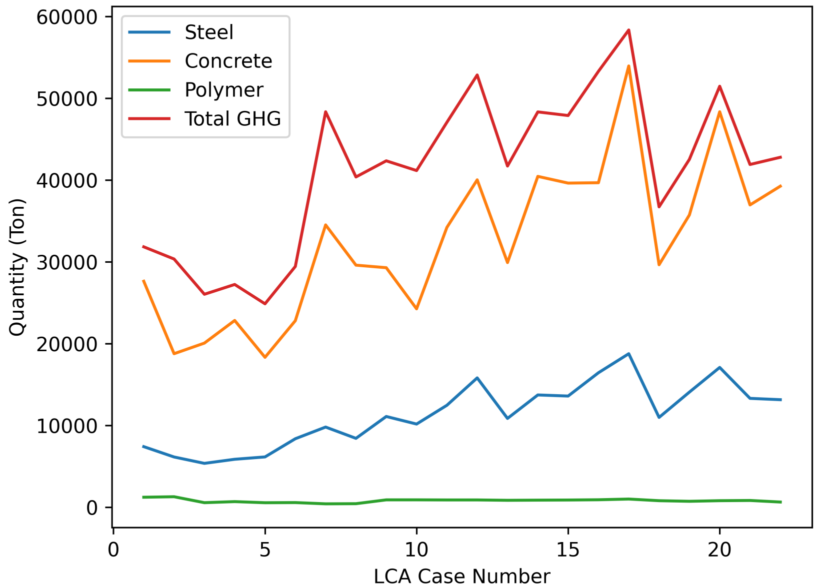


Figure 3.2: Variation of total GHG emissions (ton) of a wind farm and the variation of amount of different material used in it, for different wind farm life cycle assessments.

estimate the emissions based on the materials used in the wind farms. A simple linear regression model was used to create a polynomial function of degree 2 that incorporated different materials as variables. A polynomial function of degree 3 was also tested, but the coefficients were 0 or negligible for 3rd degree variables. The second-degree polynomial function was validated with reference values and satisfactory results were obtained. The relationship can be seen in Equation 3.1 and Equation 3.2. Equation 3.1 is the polynomial function in which concrete is also considered, but in the case of offshore wind turbines, concrete is used in small quantities and Equation 3.2 becomes more useful. Although there are concrete floaters available on the market that are cheaper and more environmentally friendly (owing to lower emissions) than their steel counterparts [26], the market is occupied primarily by steel floaters [27] and only steel floaters are considered in the frameworks. In case concrete floaters are considered, then 3.1 must be used. In these equations, Y is the total GHG emissions in tons from the wind farm during its lifetime, X_1 is the total amount of steel (tons) used in the wind farm, X_2 is the total amount of concrete (tons) and X_3 is the total amount of composite polymers (tons) used in the wind farm.

Table 3.1: Correlation coefficients between different material and total GHG emissions.

	Steel	Concrete	Polymer Composites	Total Material
Total GHG Emissions	0.92	0.91	0.17	0.92

$$\text{Y} = 13179.89 - 2.26 \cdot X_1 + 2.16 \cdot X_2 - 40.54 \cdot X_3 + 0.01 \cdot X_1 \cdot X_3 + 0.02 \cdot (X_3)^2 \tag{3.1}$$

$$\text{Y} = 50878.94 + 3.75 \cdot X_1 - 124.52 \cdot X_3 + 0.06 \cdot (X_3)^2 \tag{3.2}$$

3.2. Workflow

Calculating the amount of material used on the wind farm can be a challenging task and involves design optimization. For this purpose, the MDAO framework is used to obtain the masses of different components such as mooring lines, anchors, monopile (MP), transition piece (TP), floater, etc. For the turbine tower and rotor-nacelle assembly (RNA), the weight of the components has been obtained from turbine design reports by the National Renewable Energy Laboratory (NREL) and the International Energy Agency (IEA). Four turbine sizes have been tested and evaluated, and they are 5 MW, 10 MW, 15 MW, and 22 MW in capacity. The 5 MW, 10 MW, 15 MW, and 22 MW turbines are mentioned in detail in [28], [29], [30] and [31], respectively. In addition, important turbine properties are mentioned in Table 3.2. When the total weight of a single turbine has been calculated, an estimate of the amount of different materials can be made using the average proportions by the NREL [32]. According to current technology, a land-based wind turbine consists of 9% steel and 0.8% cast iron resulting in a total of 9.8% of iron and steel, if considered together. 87% of it is made of concrete and road aggregates that make up the foundation mass. Composites and polymers constitute up to 2% of the mass. However, in the case of floating wind turbines and offshore fixed-bottom turbines the proportions are very different. Steel constitutes around 87% of the mass, and cast iron constitute around 3%, which adds up to 90% of the mass made of iron and steel. Polymers and composites constitute 4% of the turbine mass. A visual representation of the distribution is shown in Figure 3.3 [32]. In this thesis only the present scenario is considered as the design variables are optimized based on the current technological advancements and resource availability.

Table 3.2: Important parameters of turbines used in the wind farms.

Parameters	5 MW	10 MW	15 MW	22 MW
Rated Power (MW)	5	10	15	22
Rotor Diameter (m)	126	178.3	240	184
RNA Mass (ton)	350	675	1017	1215.6
Tower Mass (ton)	347.46	605	860	1574.04
Hub Height (m)	90	119	150	170

After obtaining the mass of steel and composites, Equation 3.2 can be used to obtain the estimated value of GHG emissions from one turbine. To calculate GWP, the total GHG emissions from the wind farm over its lifetime must be divided by a functional unit, which is generally the units of electrical energy produced. Most LCAs use kilo-Watt-hour (kWh) as the functional unit. So, the amount of energy produced over the lifetime must be calculated, and the MDAO framework calculates the annual energy production (AEP) of the wind farm. To keep the calculation simple, the AEP is multiplied by the lifetime of the wind farm to obtain the total energy production, as shown in Equation 3.3. In Equation 3.3, GHG_{Farm} is the total GHG emissions of the farm over its lifetime. It must be noted here that the AEP depends on the turbine, its availability, layout, and spacing between the turbines in the farm and site conditions. Similarly, GHG_{Farm} depends on the amount of different materials used in the turbine. The lifetime of the wind farm also depends on the site conditions, maintenance strategies, the robustness of the design, and

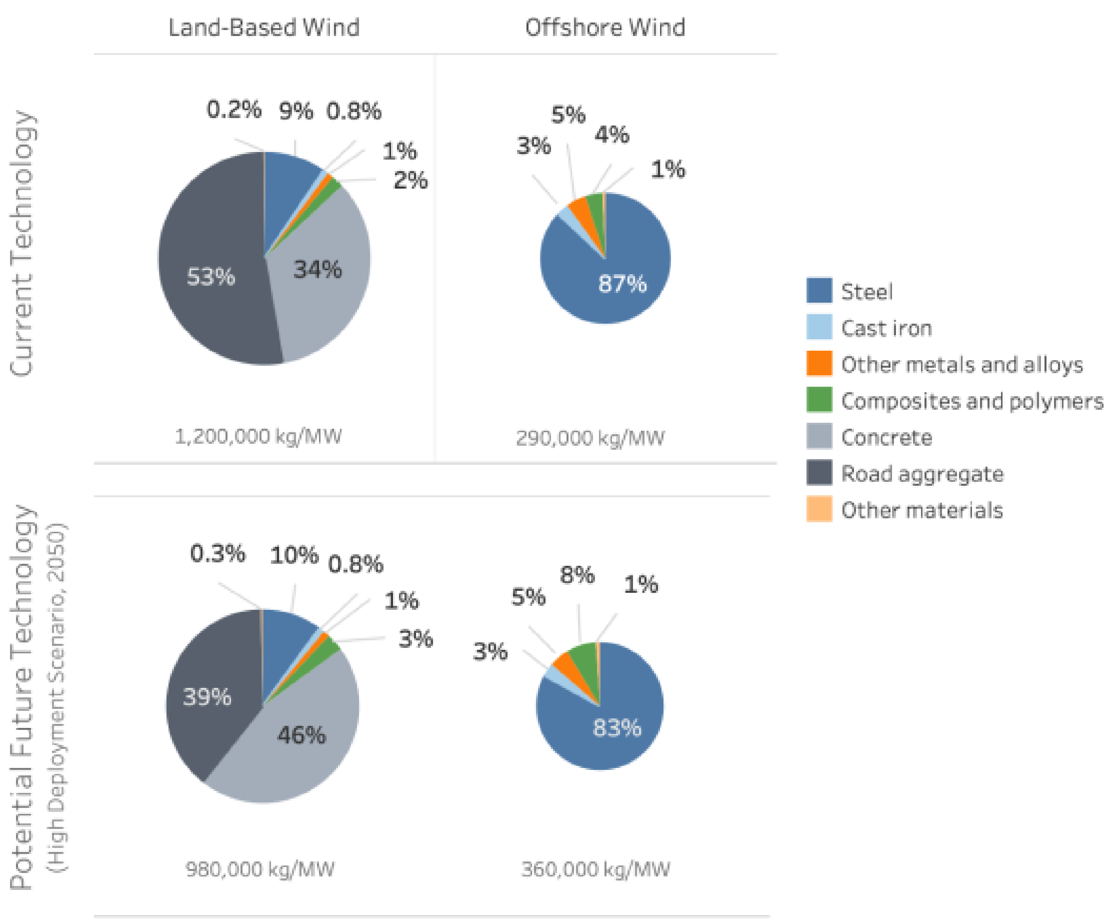


Figure 3.3: Proportion of different material used in current wind turbines and in potential future wind turbines [32].

materials used, but for a simplified model, only maintenance strategies are considered. Tables 3.3 and 3.4 summarize all the important parameters and bounds, respectively, that are varied during the study.

$$\text{GWP} = \frac{\text{GHG}_{\text{Farm}}}{\text{AEP} \times Lifetime} \tag{3.3}$$

Table 3.3: Important parameters varied in the MDAO frameworks

Parameter	Values
Turbine Size	5 MW, 10 MW, 15 MW, 22 MW
Wind Farm Size	400 MW to 800 MW
Water Depth	40 m to 400 m
Lifetime	25 years to 40 years
Construction Time	3 years
Number of Installations/year	6 to 54 depending on farm and turbine size
Layout	6x3 to 16x10 depending on farm and turbine size
Floater Type	Semi-submersible and Spar buoy
Turbine Footprint Constraint	3×Rotor Diameter to 8×Rotor Diameter

Wind farms with different turbine capacities are studied and compared, keeping the wind farm capacity nearly the same. The wind farm capacity cannot be exactly matched as the turbine capacities do not divide evenly into the total farm capacity. When comparing wind farm configurations with different wind turbine capacities, it is also necessary to compare the LCOE of the farm. LCOE is also obtained from the

Table 3.4: Bounds of design variables used in floating wind farm design.

Parameters	5 MW	10 MW	15 MW	22 MW
Semi-sub outer column radius lower bound	3	3	3	3
Semi-sub outer column radius upper bound	10	10	10	10
Semi-sub offset radius lower bound	30	40	40	40
Semi-sub offset radius upper bound	60	65	70	75
Semi-sub draft lower bound	8	12	12	12
Semi-sub draft upper bound	40	45	45	50
Semi-sub freeboard lower bound	5	6	6	6
Semi-sub freeboard upper bound	45	50	50	50
Semi-sub fairlead-anchor distance lower bound	1.5xD	3xD	2xD	2xD
Semi-sub fairlead-anchor distance upper bound	10xD	8xD	8xD	8xD
Layout spacing lower bound (Semi-sub)	4xD	6xD	6xD	5xD
Layout spacing upper bound (Semi-sub)	14xD	14xD	14xD	14xD
Spar buoy radius lower bound	3	3	3	3
Spar buoy radius upper bound	10	12	15	20
Spar buoy draft lower bound	40	50	50	50
Spar buoy draft upper bound	100	150	175	200
Spar buoy freeboard lower bound	5	5	5	5
Spar buoy freeboard upper bound	100	100	130	150
Spar buoy fairlead-anchor distance lower bound	1.5xD	1.5xD	1.5xD	1.5xD
Spar buoy fairlead-anchor distance upper bound	10xD	10xD	10xD	10xD
Layout spacing lower bound (Spar buoy)	5xD	5xD	5xD	5xD
Layout spacing upper bound (Spar buoy)	14xD	14xD	14xD	14xD

*D = Turbine Rotor Diameter

MDAO framework. It must be noted that the framework optimizes the farm design to minimize the LCOE. As an additional feature, the GWP is calculated. This gives a metric for comparing wind farm designs based not only on LCOE but also on environmental impact. A flow chart of the workflow is shown in Figure 3.4 for visualizing it.

3.3. Framework

As mentioned in Chapter 1, MDAO is a multilevel optimization framework, and the optimization problem is subject to several constraints at different levels. The components of wind turbines are optimized in the inner layers with constraints on their dimensions, physics, and mechanics (depending on the component). For example, the draft of the floater is subjected to a minimum and a maximum limit, and this is used while designing the floater, which in turn is optimized with the objective of having minimum cost. In the outer layers, other parameters are optimized with the objective of minimizing LCOE. For example, the distance between the turbines is optimized to minimize the LCOE by increasing AEP and reducing wake losses. A visualization of the framework is shown in Figure 3.5. X_i are the design variables which are optimized by the optimizer and for each variable the corresponding component cost is calculated and compared to the previous calculation. If a lower value is obtained, then the new value is used. This process continues in a nested fashion until the design values converge. The coupling variable is the variable that enables different variables to be optimized with the same objective. For example, when the electrical system is designed, the design variables associated with it are given an initial value. These variables are optimized by the optimizer in the inner layer to minimize the cost of electrical components. The cost of electrical components is optimized and sent to an analyzer, which computes the overall LCOE and sends it to the optimizer in the outer layer. If the variables can be improved, then the outer layer optimizer executes the inner layer optimizer again with new values of the design variables. This process continues until all variables do not change by a significant value (that is, when they converge).

There are different types of optimizers available, but for the framework discussed in this thesis, COBYLA optimizer, a part of SciPy optimizer library in Python, is used. It is the default optimizer in the framework and has not been changed since it is out of the scope of the research work. COBYLA stands for Constrained Optimization BY Linear Approximations and finds the local optima based on the initial input. Different values of input variables have been tested and the best value has been chosen.

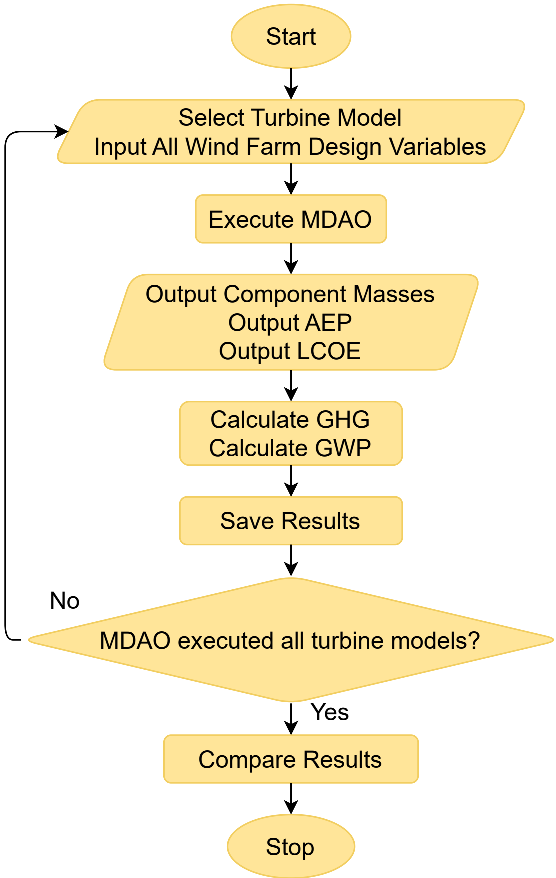


Figure 3.4: Workflow of the using the MDAO framework to estimate GHG emissions and compare wind farm designs based on LCOE and environmental impact.

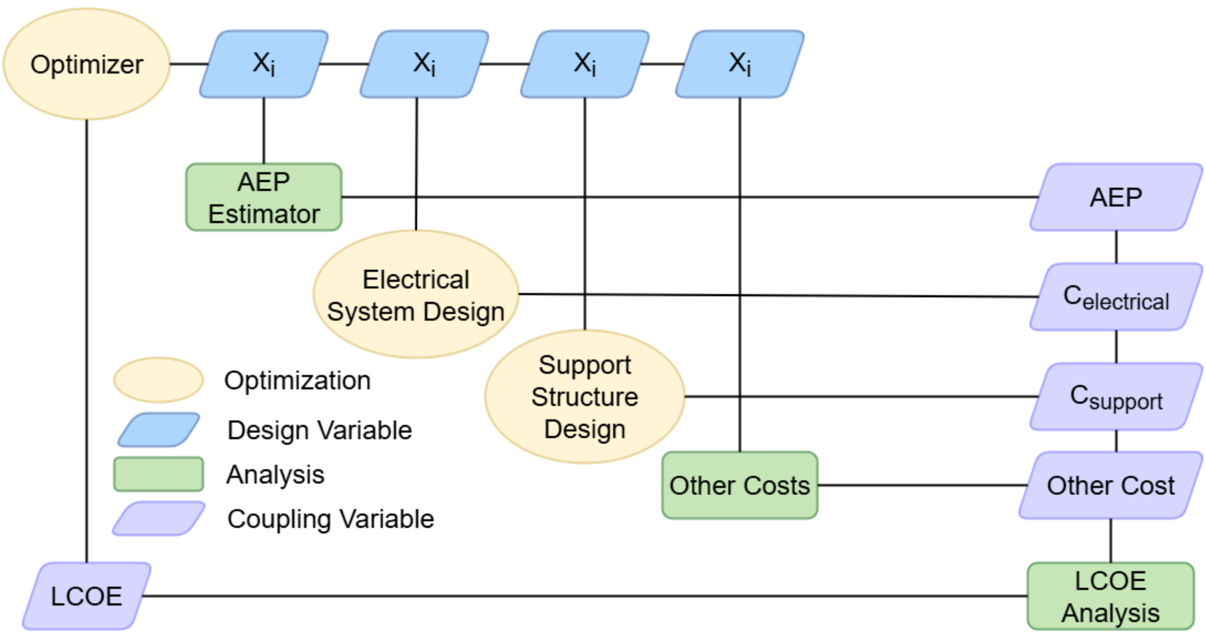


Figure 3.5: MDAO framework used for fixed-bottom wind farm design [5]

3.4. Variation of Test Parameters

3.4.1. Installation And Maintenance

To maintain consistency in test conditions, the input parameters are carefully changed. For example, the number of years required to construct a specific farm size is kept the same for all turbine sizes. This assumption is made because larger wind turbines will be more difficult to transport and install but the number of larger wind turbines is smaller, and vice versa for smaller turbines.

The installation process for floating wind turbines on semi-submersibles is taken from [33]. It consists of five sequential phases, operating around the clock without any parallel activities:

1. The floaters are transported from the fabrication shipyard to the port where turbines are assembled on the floaters. The floaters are floated out and then towed to the port one by one.
2. The assembly of the wind turbines is done at the quayside.
3. Mechanical completion and verification of the assembly (pre-commissioning) is carried out at the quayside.
4. The turbine assembly is then towed to the site one by one and then mooring lines and anchors are attached at the site.
5. A final check is performed after the installation and then the turbine is commissioned.

A deterministic cost model is used to compute installation logistics-related costs [33]. It includes:

- Vessel charter costs (for example, tugboats, AHTS, CLV).
- Quayside crane operation.
- Storage costs at the shipyard and port.
- Quayside berthing cost for turbine-substructure assemblies.

The first phase of the installation procedure incurs costs associated with the chartering of one large tugboat and two small tugboats, which support the float-out operations and tow the semi-submersibles from the fabrication yard to the port. Additionally, the cost of using the slipway for float-out is included and is assumed to be equivalent to the cost of one quayside crane lift. In the second phase, a mobile crane is deployed at the quayside for the assembly of wind turbine components onto the semi-submersibles. Each turbine requires seven lifting operations: three for the tower sections, one for the pre-assembled nacelle and hub, and three for the rotor blades. During the pre-commissioning phase, a small tugboat provides assistance. For subsequent towing and installation of the turbine–substructure assemblies at the site, two anchor handling tug supply (AHTS) vessels and two small tugboats are chartered. These vessels also support the hook-up of mooring lines to the substructure. The connection of the dynamic cable is performed by a dedicated cable-laying vessel. Finally, the commissioning operations at the offshore site are supported by a small tugboat. The cost and duration of the activities used in the framework related to the installation is summarized in Table 3.5 [33].

Table 3.5: Logistics and vessel rate assumptions used in the MDAO framework for floating wind turbines [33].

Description	Value
Time to float-out semi-submersible	3 h
Time to prepare for towing operations	2 h
Time to lift and assemble a turbine component	3 h
Mechanical completion at quayside	24 h
Installation time at site	14 h
Final installation check at site	12 h
Daily rate of small tugboat	€4,135
Daily rate of large tugboat	€28,321
Daily rate of AHTS	€39,891
Daily rate of cable laying vessel	€101,232
Hourly rate of quayside crane	€833
Daily storage rate at shipyard/port	€0.18 per m^2
Daily rate for quayside berth	€300

For spar-buoy type wind turbines, the process is slightly different compared to the semi-submersible counterparts. The floater is towed from the shipyard to a sheltered area and for this purpose 1 large and 1 small tugboats are used. For filling up the ballast, 1 cargo vessel is used. For the mating of turbine components, 1 heavy life vessel (HLV) and 3 small tugboats are used, and for towing the mated turbine to the site, 2 large AHTS and 2 small tugboats are used. For quayside pre-commissioning, 1 small tugboat is used, for commissioning, 1 commissioning vessel is used, and for cable laying, 1 cable laying vessel is used.

For floating turbines, this installation method is not changed though it would be interesting to see how the increase in turbine size would change the installation cost when different type and number of vessels are used. However, the installation costs at the shipyard, port, and quayside are scaled up or down linearly with the number of floating units, the area occupied by the unit, and the time period for which it is stored. Furthermore, a workability factor is also multiplied to account for weather delays, non-ideal sea conditions, and idle time of vessels [33].

For fixed-bottom turbines, a different framework is used and the daily rate of the vessels in it is scaled up or down with the size of the turbine. The installation cost in general scales linearly with the number of turbines, size of turbines, and the distance of the farm from the shore. The rate of the vessels and the transit speed of the vessels are taken from [34] and are mentioned in Table 3.6. The distance of the site from the shore is fixed at 40 km to achieve consistent test conditions.

For floating wind turbines, the probability of major failure is 0.119 failures per turbine per year, and for fixed-bottom wind turbines it is 0.3 failures per turbine per year.

Table 3.6: Vessel data used for installation and O&M cost modeling [34].

Vessel type	Purpose	Day rate (EUR)	Transit speed (km/h)	Mobilization costs (EUR)
WTIV	Installation: foundation, turbine, O&M	200,000	10	500,000
HLV	Installation: substation	500,000	7	500,000
CLV	Installation: cable lay	110,000	6	550,000
CBV	Installation: cable burial	140,000	6	550,000
CTV	Crew transfer	3,000	40	–
DSV	O&M: scour repair	75,000	6	225,000

3.4.2. Farm Size And Layout

To check the variation in emissions and GWP with increasing farm sizes, the capacity of the wind farm is changed, and the framework is run with different turbine sizes. For example, the wind farm capacity is varied from 400 MW to 800 MW. Each of the farms is tested with different sizes of turbines (5 MW to 22 MW) in it. To do this, the layout of the turbine is changed in the framework. The layout of the wind farm is manually input, and other combinations can also be tried, but the idea behind selecting a combination is to keep the sides of a rectangle as equal as possible. The layout changes the LCOE significantly as the cable cost changes when the layout is changed and the LCOE of the farm is very sensitive to the cable cost. For floating wind turbines, only a rectangular layout is possible. For example, if 41 turbines are required, then only the combination is 41 rows and 1 column, or vice versa. There is no provision to have a layout consisting of 8 rows and 5 columns and 1 turbine at the end of either a row or a column. LCOE changes because it depends on the AEP of the farm and AEP, in turn, is heavily dependent on the layout, as wake interactions are determined by the turbine placement. However, it can be changed in the framework, but it is out of the scope of this project. However, this is not the case in the framework for fixed bottom wind turbines. In case of fixed bottom wind turbines, a manual layout is given as an input to the framework, and it consists of the coordinates of the turbines. Hence, an odd layout can also be used. In such cases, the capacity of the farm is slightly changed to have the nearest whole number multiple of the turbine capacity. The reason for keeping the layout as square as possible is to minimize the effect of changing wind conditions and water depths. The layouts used for floating wind farms are shown in Table 3.7.

Table 3.7: Farm Layouts for different turbine and farm sizes (floating wind farms)

Farm Size	5 MW	10 MW	15 MW	22 MW
400 MW	10x8	8x5	9x3	6x3
500 MW	10x10	10x5	11x3	11x2
600 MW	12x10	10x6	8x5	9x3
700 MW	14x10	10x7	23x2	8x4
800 MW	16x10	10x8	9x6	9x4

3.4.3. Other Models And Algorithms

The MDAO framework also considers the wake effect in the calculation of AEP. For floating wind turbines, the Bastankhah Gaussian wake model [35] is used, and for fixed bottom wind turbines, the Jensen wake model [36] is used. These are the default wake models incorporated in the MDAO frameworks. Similarly, the electrical cable topology is also optimized, and the Esau Williams algorithm is used for this purpose. Esau-Williams algorithm [37] is a heuristic algorithm commonly used in topology optimization. In the framework a set of cables is mentioned with their capacities and price per unit length, and the algorithm selects the cheapest combination among the options. For the selection, the user has to input how many turbines must be connected to a cable. Once the maximum number is reached, a higher capacity cable must be selected which is also given as an input by the user, and so on. Based on these inputs, the algorithm has to select the best combination.

3.4.4. Mooring Lines And Anchors

Similarly, different mooring lines are mentioned in the framework in the form of a catalog. The catalog consists of mooring lines with different diameters, and the cost of the mooring is based on the cost of steel used to manufacture it and the cost of its fabrication.

For anchor design, a slightly different approach is used. The anchor mass and traction depend on the type of anchor used, and there are six types. The types are as follows [38]:

1. dead weight
2. driven pile
3. drag anchor
4. suction pile
5. gravity-installed (drop) anchor
6. vertical load anchor

Figure 3.6 shows the different types of anchors mentioned above. Drag anchors are the most commonly used anchors [38], and they are also the anchor used in the MDAO framework for floating wind turbines. They are partially or fully submerged in the sea bed, and the friction of the soil in front of the anchor determines the holding capacity. Drag anchors are good for resisting horizontal forces and hence are used in a catenary type of mooring. Since the catenary type of mooring is the most commonly used mooring drag anchors become the most common type as well. There are several types of drag anchors based on the ultimate holding capacity (UHC) of the anchor and the design criteria of the anchors are mentioned in Table A.1, Figure A.1 and Figure A.2 in Appendix A. The UHC is determined by Equation 3.4, where the UHC is in kN, W is the weight of the anchor in (tons) and a and b are the anchor coefficients. The weight of the anchor should be between 1 to 50 tons, or else a higher or lower capacity anchor has to be selected. Stevin MK3 and Stevpris MK5 are two types of drag anchors used in the framework. For 5 MW to 15 MW turbines, Stevin MK3 anchors are used, but for 22 MW turbines the UHC increases further, and Stevin MK3 anchors cannot be used anymore. For this reason, the 22 MW turbine uses a Stevpris MK5 anchor and the coefficients a and b change from 229.19 and 0.92 to 552.53 and 0.92, respectively. It must be noted that anchor type also depends on soil type of seabed and ”medium clay” type soil is assumed for all the cases. This is because the medium harness of soil is commonly found. Consequently, the anchor mass is expected to drop abruptly in the case of the 22 MW turbine, which will be discussed in Chapter 4.

$$\text{UHC} = a \cdot W^b \tag{3.4}$$

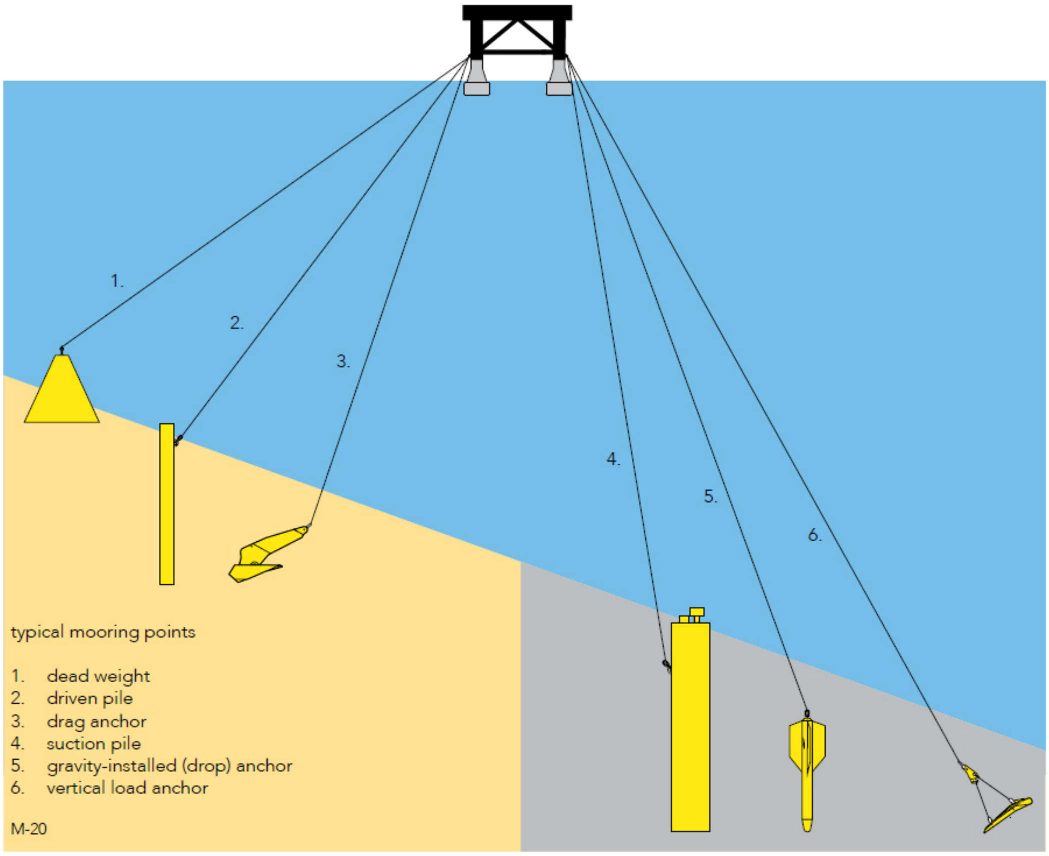


Figure 3.6: Different types of anchors used floating wind turbines [38]

3.4.5. Construction Time And Floater Type

For higher-capacity wind farms, the number of turbines is increased accordingly. For example, when the farm capacity is changed from 400 MW to 500 MW, the number of 10 MW turbines is changed from 40 to 50. In this case, the total installation time is kept constant at 3 years. The total number of turbines to be installed in the farm is equally distributed among three years. In case the number of turbines is not divisible by 3, then the nearest multiple of 3 is chosen, and the extra turbines are added to the first and second year. The floating wind turbine floater is also changed from semi-submersible to spar-type, and in this case a different framework/script is used for optimizing the spar-type floater. It also requires different input files dedicated for spar-type floater.

3.4.6. Water Depth And Lifetime Of Farm

The depth of water and the lifetime of the farm are also changed to observe their effect on GWP and LCOE. For floating wind turbines, the depth is changed in the framework, whereas for fixed-bottom turbines, a bathymetry file is used as an input, and the water depth is changed in the input file. The depth is varied to compare a floating and fixed-bottom wind farm in transitional water and how the GWP and LCOE change with varying depths. For floating wind turbines, the depth is varied from 50 m to 400 m and for fixed-bottom wind turbines the depth is varied from 30 m to 60 m. The comparison of the two types of turbines at 50 m and 60 m is of interest. Beyond 60 m, the framework for fixed-bottom turbines does not work due to constraints in the tower design process. This will be discussed in detail in Chapter 4. Similarly, the lifetime is also changed in the framework before executing it. Although the lifetime of a wind farm is taken as 20 years by Vestas in their LCAs it is more common to find turbines with an expectancy of 25 years. Recently manufactured turbines such as the Vestas V236-15 are expected to last 30 years. With increasing robustness of design and improved maintenance practices, a hypothetical scenario has been developed where the lifetime is expected to be around 35 years and a very ambitious expectancy of 40 years. In the framework, all wind farms are expected to last 25 years, except when the lifetime is varied from 25 years to 40 years to see how much the GWP and emissions change.

After describing the research methodology, it is important to execute the model, obtain the results, validate them, and find conclusions from them. The next chapter describes the results obtained from the framework and the reasons for them.

4 Results And Discussion

The previous chapters focused on the foundation of the research, the existing literature, and the method of answering the proposed research questions. This chapter focuses on the results obtained from the tests conducted using the MDAO framework to assess the environmental impacts of wind turbines and on how the design variables of a wind farm change with changing input parameters. It starts with validation of results to know that the method used is accurate and realistic, and then various sections and subsections focus on changes in the environmental and economic parameters as a result of changing turbine and farm variables.

4.1. Validation Of Results

It is important to validate the results obtained using the estimation models. To do this, the results are compared to the LCAs performed by researchers and organizations other than Vestas (since Vestas' LCAs were used as the foundation of the estimation models). A compilation of LCAs is presented in [39] where different sizes of turbines are studied and compared. Offshore floating, fixed-bottom, and onshore turbines have been compared. Table 4.1 shows the compiled data that was used to validate the results of the model. Although different studies have different conditions, results can be compared considering relevant variables, the most important being the turbine size used for a specific farm size. This means a 400 MW wind farm consisting of 1 MW turbines would not be an ideal design, and hence it cannot be compared to a similar wind farm consisting of 20 MW turbines. From the study, the average value of GWP for onshore turbines is around 6.8 g CO_2 eq./kWh, the average value of GWP for fixed-bottom wind farms is around 31.5 g CO_2 eq./kWh and the average for floating wind turbines is around 25.9 g CO_2 eq./kWh [39]. From the results obtained from the model, the average GWP of wind farms made of 15 MW semi-submersible type wind turbines is around 37.66 g CO_2 eq./kWh, for 15 MW spar type wind turbines is 34.64 g CO_2 eq./kWh and for 15 MW fixed-bottom wind turbines is 28.06 g CO_2 eq./kWh. The comparison of the results is shown in Figure 4.1. Since the results obtained are close to the average values found by other researchers, it can be assumed that the results are reasonable.

Table 4.1: GWP of various onshore, offshore floating and fixed-bottom wind farms consisting of different types and sizes of wind turbines [39].

Turbine Size (MW)	GWP (g CO_2/kWh)	Lifetime (Years)	Type
5	12.2	25	Floating Spar Buoy
5	20.9	20	Floating Tension Leg Spar
5	31.4	20	Floating Semi Submersible
5	25.3	20	Floating Spar Buoy
5	19.2	20	Floating Tension Leg Platform
5	18.0	20	Floating Tension Leg Buoy
5	18.9	20	Bottom Fixed OC4 Jacket
3	40.9	20	Gravity Based Foundation
3	28.0	20	Monopile
3	41.7	20	Tripod
3	44.3	20	Tripod

Turbine Size (MW)	GWP (g CO_2/kWh)	Lifetime (Years)	Type
3	38.1	20	Floating
3	25.7	20	Monopile
3	32.9	20	Floating
3	33.0	20	Floating
3	33.8	20	Floating
3	35.5	20	Floating
3	25.6	20	Monopile
3	40.5	20	Tripod
3	33.1	20	Floating
3	33.9	20	Floating
3	35.5	20	Floating
3	33.4	20	Gravity Based Foundation
3	27.7	20	Monopile
3	41.3	20	Tripod
3	42.0	20	Tripod
3	47.3	20	Tripod
1	7.4	20	Onshore
2	7.1	20	Onshore
2.3	5.8	20	Onshore
2	9.5	20	Monopile
2.3	6.5	20	Monopile
2.3	7.9	20	Floating Dutch Tri Floater
5	7.3	20	Floating Dutch Tri Floater
6	22.3	20	Floating Semi Submersible
2	295.2	20	Onshore
2	468.0	20	Floating Spar Buoy

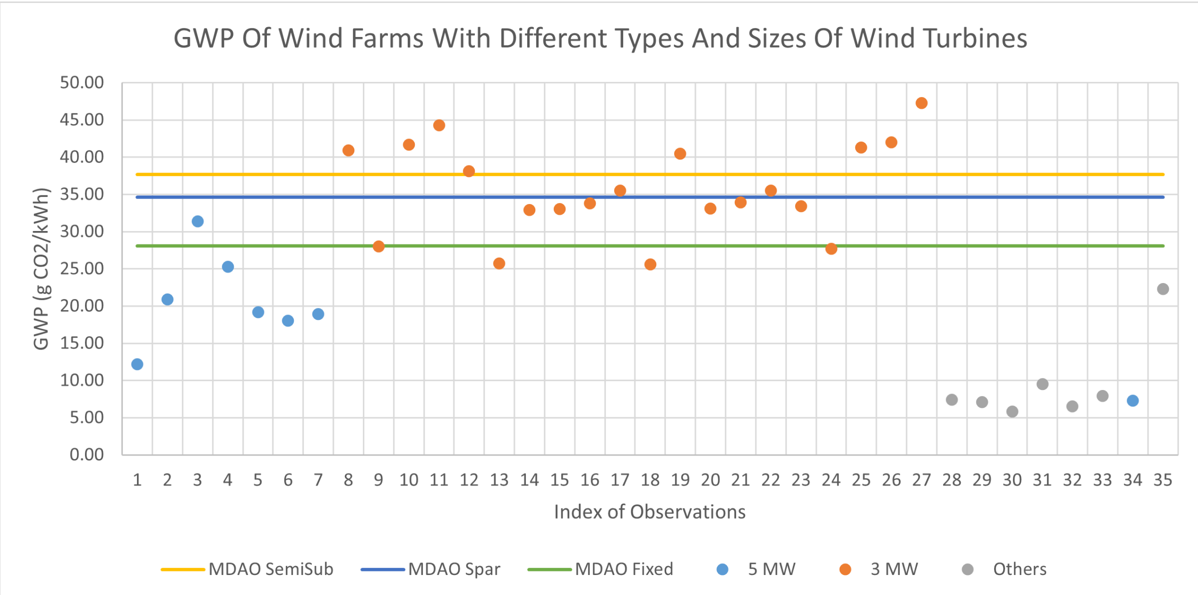


Figure 4.1: GWP of wind farms consisting of turbines of different types and sizes from the various literature (scatter points) and from the model (lines).

Since a different framework is used for fixed-bottom wind turbines, a different set of reference data is required. The framework used by Metha et al., 2024 [34] is used to estimate the environmental impacts of fixed-bottom wind turbines. Since the design variables are optimized by the model and then they are used to estimate the emissions, the LCOE of the framework is used as a reference parameter. From Figures 4.2 and 4.33, it can be seen that the normalized LCOE and the LCOE from the current framework follow the same trend with a minimum around 16 MW [34]. In Figure 4.2, the x-axis labels indicate turbine power (MW) and rotor diameter (m). For example, 14-225 means that the turbine power capacity is 14

MW and has a rotor diameter of 225 m. Since a 16 MW turbine has not been used in the study, the minimum is around 15 MW. In addition, other parameters such as OPEX, CAPEX, etc. also follow a similar trend.

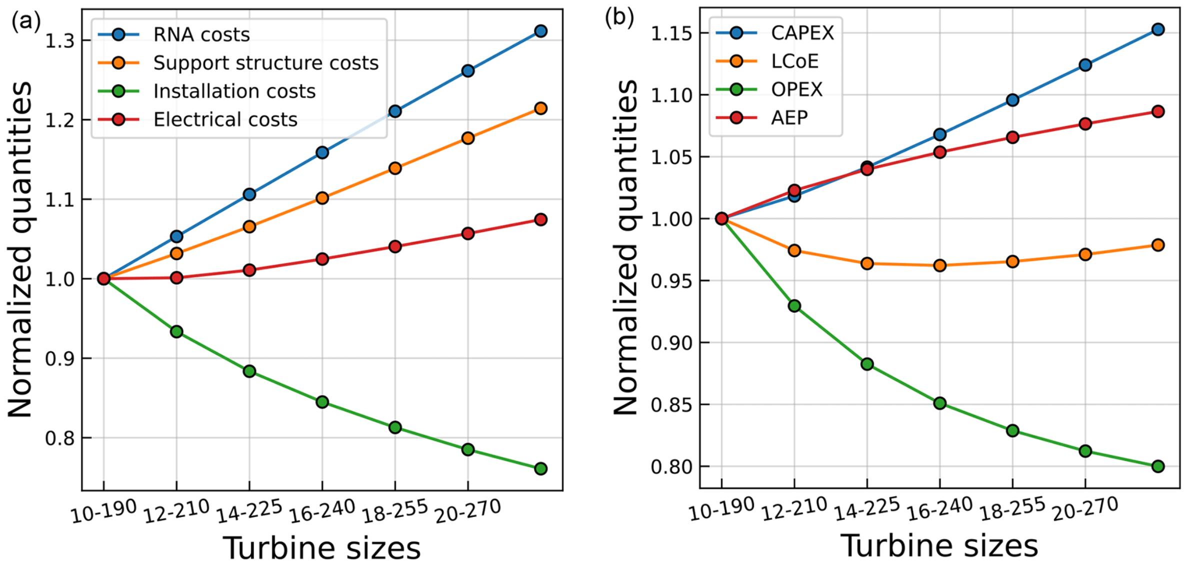


Figure 4.2: Variation in costs and economic parameters with turbine size [34]. The x-axis labels indicate turbine configurations, where the first number denotes turbine power in megawatts (MW) and the second number denotes rotor diameter in meters (m).

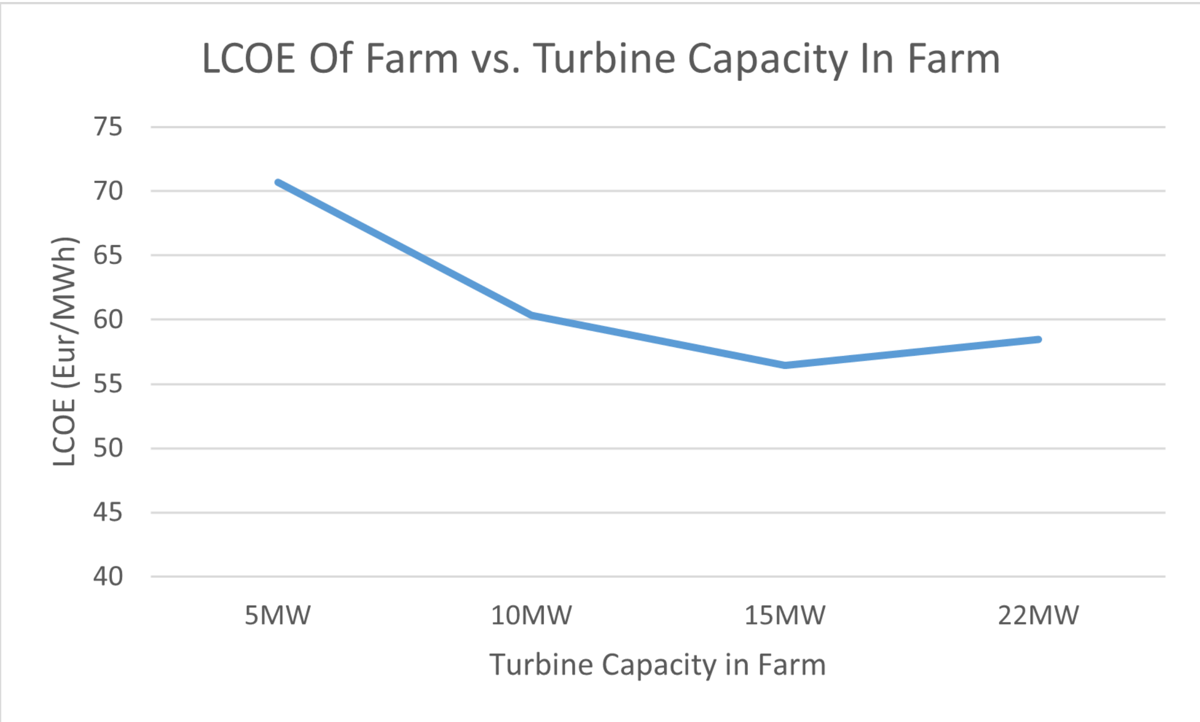


Figure 4.3: Variation in LCOE of a 400 MW wind farm at 30 m water depth, consisting of fixed-bottom wind turbines of varying capacities.

4.2. Floating Wind Turbines

In this section, estimations of the environmental impacts of floating wind turbines are compared and analyzed. The MDAO framework is used to optimize the design of wind farms using different sizes of wind turbines. As mentioned in Chapter 3, 4 turbine sizes are used to study the impacts and GHG emissions, GWPs and LCOEs are compared to understand which size choice is better and why. Among the various types of floating wind turbines, only 2 are studied because they are the most commercially available and used. They are the semi-submersible and spar-types of wind turbines. Although there are restrictions on the spar-type wind turbine it has been included in the results and it will be mentioned where it will not be considered.

4.2.1. Greenhouse Gas Emissions

The most concerning impact of the time is the GHG emissions and is estimated using Equation 3.2, as mentioned in Chapter 3. Consequently, a 5 MW semi-submersible wind turbine at 100 m depth will yield a total GHG emissions of 57117.85 tons over its lifetime. Similarly, wind turbines of 10 MW, 15 MW and 22 MW capacity will yield a total GHG emissions of 62292.08 tons, 68757.46 tons, and 73911.79 tons, respectively. By intuition, a bigger turbine would require more materials for its construction and hence a higher level of emissions. However, this is also proved from the results obtained from the framework. It can be seen from Table 4.2 and Figures 4.4 and 4.5 that the floater mass increases with increasing size and, therefore, the steel mass increases. This is because with increasing turbine size, the mass of turbine components is increasing and, therefore, a heavier floater is required to maintain the hydrostatic and hydrodynamic stability. The mass of moorings and anchors also increases because of higher loads on them, which in turn increases due to larger surface area and hence larger thrust forces. However, for a 22 MW wind turbine, a different type of anchor is required, as explained in Chapter 3. The use of Stevin MK3 anchor requires a mass of more than 50 tons, which violates the design rules. Hence, Stevpris MK5 is used and the mass decreases abruptly. Stevpris MK5 has a higher capacity to resist horizontal forces with a lower mass. Therefore, with increasing masses, material consumption also increases and hence, GHG emissions increase, as shown in Table 4.3 and Figure 4.6. Compared to a 5 MW turbine, a 10 MW turbine has around 9.06% more emissions, a 15 MW turbine has around 20.38% more emissions, and a 22 MW turbine has around 29.4% more emissions.

Table 4.2: Variation of component masses of different turbine sizes in a 400 MW wind farm at 100 m water depth.

Turbine	Tower Mass (Ton)	RNA Mass (Ton)	Floater Mass (Ton)	Anchor Mass (Ton)	Mooring Mass (Ton)
5 MW	347.46	350	1778.97	8.29	37.30
10 MW	605	675	3297.02	19.74	64.48
15 MW	860	1017	5070.96	30.85	105.88
22 MW	1574.04	1215.6	6671.96	14.90	140.26

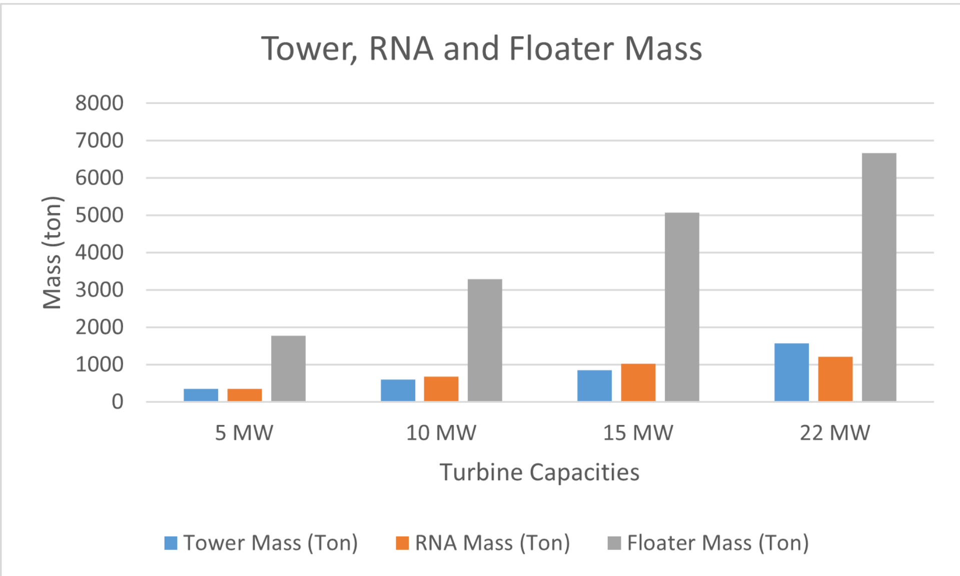


Figure 4.4: Variation of mass of tower, RNA and floater with turbine sizes.

However, this does not necessarily mean that the larger turbines are worse than the smaller ones. Larger turbines have higher energy generating capacity and hence, for a wind farm of a specific capacity, the number of larger turbines required would be less than the number of smaller turbines. Consequently, it is important to compare the GHG emissions of the farm. For a 400 MW wind farm, the number of 5 MW

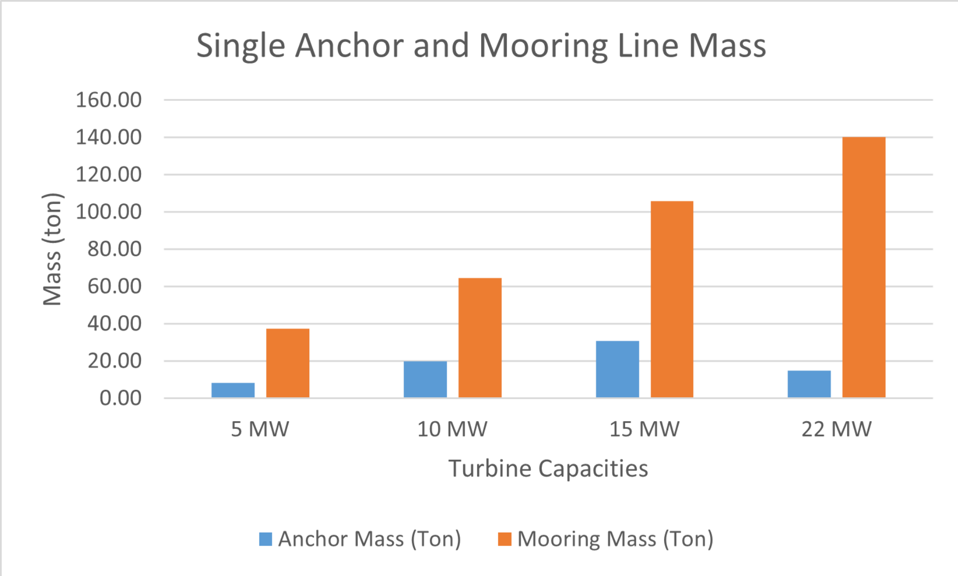


Figure 4.5: Variation of mass of single anchor and mooring line at 100 m water depth with turbine sizes.

turbines required would be 80. Similarly, the number of 10 MW, 15 MW, and 22 MW turbines required for a 400 MW wind farm would be 40, 27 and 18, respectively. The wind farms designed by the framework are shown in Figures A.3 to A.6. The total GHG emissions from the farm using 5 MW, 10 MW, 15 MW and 22 MW turbines are 4569427.60 tons, 249683.24 tons, 1856451.33 tons and 1330412.31 tons, respectively. It can be seen in more detail in Table 4.3 and Figure 4.7. The total GHG emissions from the farm decreases when the turbine size is increased, keeping the farm capacity constant. Compared to a 400 MW wind farm made of 5 MW turbines, a farm made of 10 MW turbines has around 45.47% lesser emissions, a farm made of 15 MW turbines has around 59.37% lesser emissions, and a farm made of 22 MW turbines has around 70.88% lesser emissions.

Table 4.3: Environmental and economic metrics for different ratings of semi-submersible type wind turbines in a 400 MW wind farm at 100 m water depth.

Turbine	Turbine Emissions (Ton)	Farm Emissions (Ton)	Farm GWP (g CO_2 eq./kWh)	Farm LCOE (Eur/MWh)
5 MW	57117.85	4569427.60	108.47	87.25
10 MW	62292.08	2491683.24	53.69	70.05
15 MW	68757.46	1856451.33	37.66	64.51
22 MW	73911.79	1330412.31	28.25	60.47

For spar-type wind turbines, a similar trend can be observed. Turbines with capacity of 5 MW, 10 MW, 15 MW and 22 MW emit a total of 55489.99 tons, 59212.83 tons, 62664.08 tons and 65446.23 tons of CO_2 eq., respectively. Compared to a 5 MW spar-type wind turbine at 100 m water depth, a 10 MW turbine produces 6.71 % more emissions, a 15 MW turbine produces 12.93% more emissions and a 22 MW turbine produces 17.94% more emissions. When a farm is considered, the GHG emissions from a 400 MW wind farm, at 100 m deep water, made of 5 MW, 10 MW, 15 MW and 22 MW spar-type wind turbines are 4439199.50 tons, 2368513.32 tons, 1691930.27 tons, and 1178032.19 tons of CO_2 eq., respectively. Similarly, compared to a 400 MW wind farm made of 5 MW spar-type turbines at 100 m water depth, a farm made of 10 MW wind turbines has 46.64% less emissions, a farm made of 15 MW wind turbines has 61.89% less emissions, and a farm made of 22 MW wind turbines has 73.46% less emissions. The emissions of a single turbine increase as the size increases, but decrease for the farm. The increase in emissions from a single turbine is overcompensated for by the decrease in the number of turbines required. Table 4.4 and Figures 4.6 and 4.7 show the changes in more detail. Note that the ballast mass in the floater is not considered in the calculation. Ballast, in floaters, can be made of gravel, concrete, sand, water, steel, etc. In the framework, the ratio of water to total ballast is 0.3, but the material of the solid ballast is unknown. If it is considered concrete and Equation 3.1 is used, then it

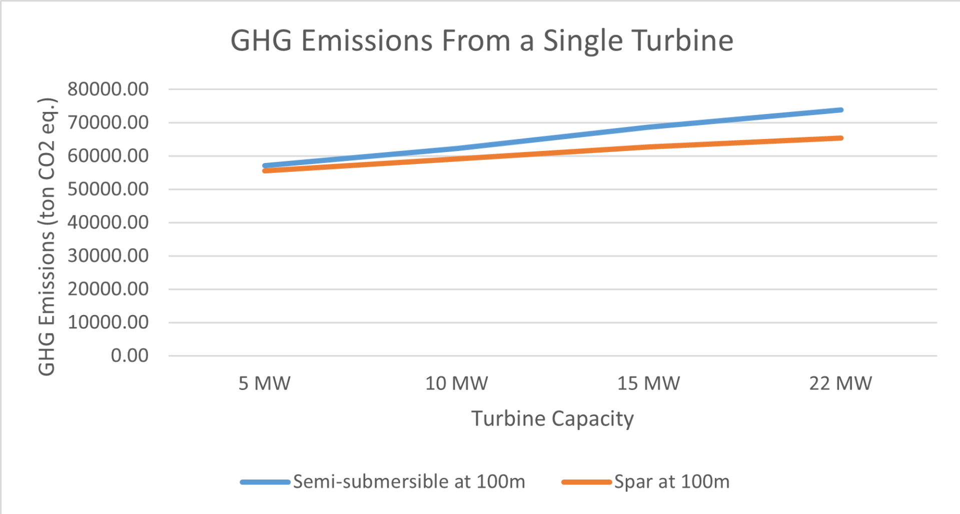


Figure 4.6: Variation of greenhouse gas emissions from a single semi-submersible type turbine at the mentioned water depth with increasing capacity.

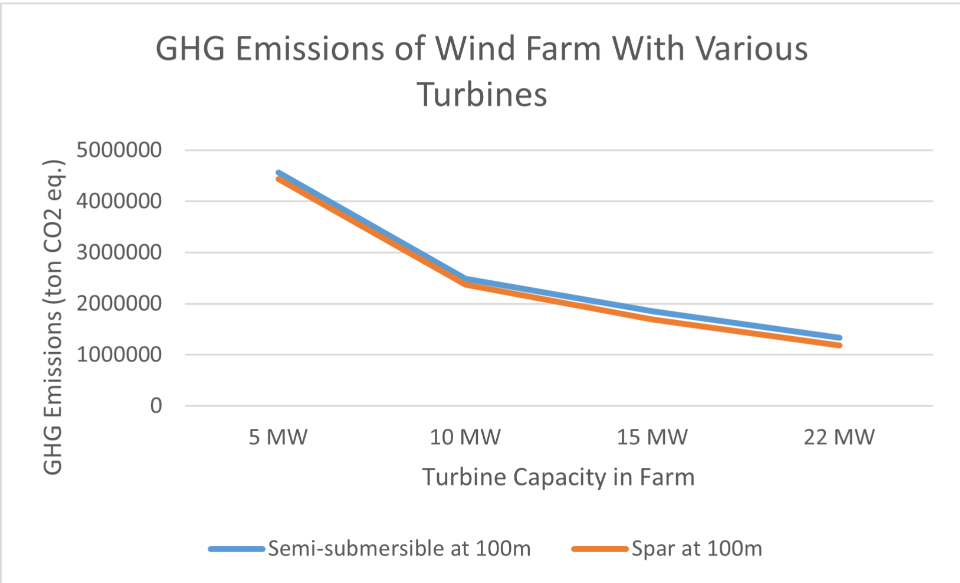


Figure 4.7: GHG Emission variation by turbine capacity in a 400 MW wind farm at the mentioned water depth consisting of semi-submersible type turbines.

results in abnormally high GHG emissions. Consequently, only steel mass is considered.

Table 4.4: Environmental and economic metrics for different ratings of spar type wind turbines in a 400 MW wind farm at 100 m water depth.

Turbine	Turbine Emissions (Ton)	Farm Emissions (Ton)	Farm GWP (g CO_2 eq./kWh)	Farm LCOE (Eur/MWh)
5 MW	55489.99	4439199.50	105.91	81.43
10 MW	59212.83	2368513.32	51.99	63.66
15 MW	62664.08	1691930.28	34.64	55.86
22 MW	65446.23	1178032.19	25.49	52.64

4.2.2. Global Warming Potential

As mentioned in Chapter 3, the global warming potential (GWP) is calculated using Equation 3.3 and depends on the total GHG emissions and the AEP. From the variation of total GHG emissions from the farm, it can be assumed how the GWP will vary. Yet, it is interesting to see the trend in GWP due to the varying AEP of the farm. The AEP changes with increasing turbine size, as shown in Figure 4.8, since larger turbines have higher hub heights and therefore experience stronger and more stable winds. Consequently, the GWP decreases with increasing turbine size for a farm of given capacity. However, the AEP decreases slightly when the size is changed from 15 MW to 22 MW, probably due to the relatively new and suboptimal design of the 22 MW turbine, although this is not confirmed. However, the reduction in GHG emissions is much higher than the drop in AEP, resulting in an overall reduction in GWP. From Table 4.3 and Table 4.4, it can be seen that the GWP decreases significantly when a larger turbine is used in the wind farm, which holds for both types of floaters (Figure 4.9). For semi-submersible turbines, compared to a 5-MW turbine, 10-MW, 15-MW and 22-MW turbines have 50.50%, 65.28% and 73.96% lower GWP, respectively. Similarly, for spar turbines, compared to a 5-MW turbine, 10-MW, 15-MW and 22-MW turbines have 50.91%, 67.29% and 75.93% lower GWP, respectively. Thus, it can be concluded that a farm with larger but fewer turbines is environmentally beneficial. The GWP decreases with increasing turbine size, though the change becomes smaller after a point, in which case other factors such as LCOE can become more significant.

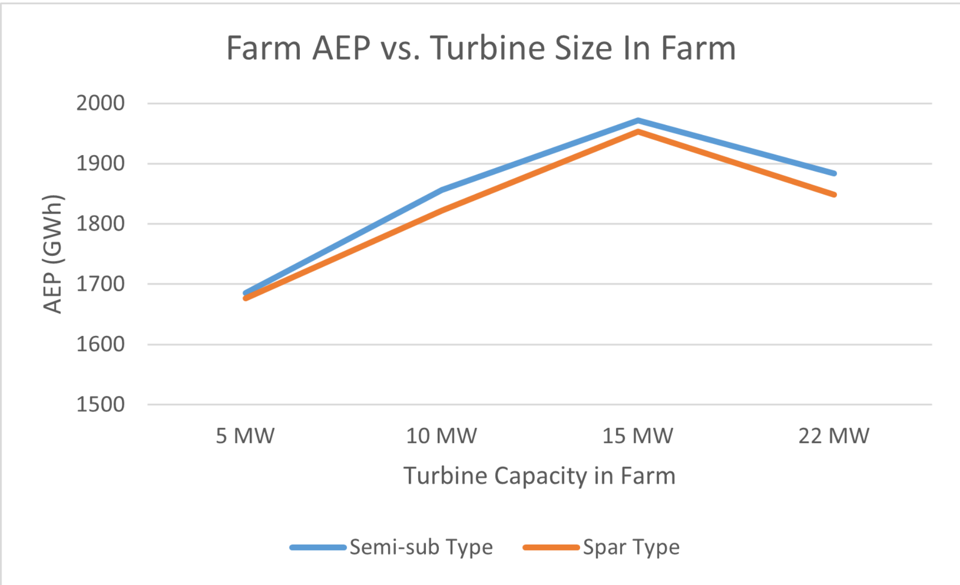


Figure 4.8: Variation in farm AEP with turbine size in a 400 MW wind farm at 100 m water depth and turbine type (floating only).

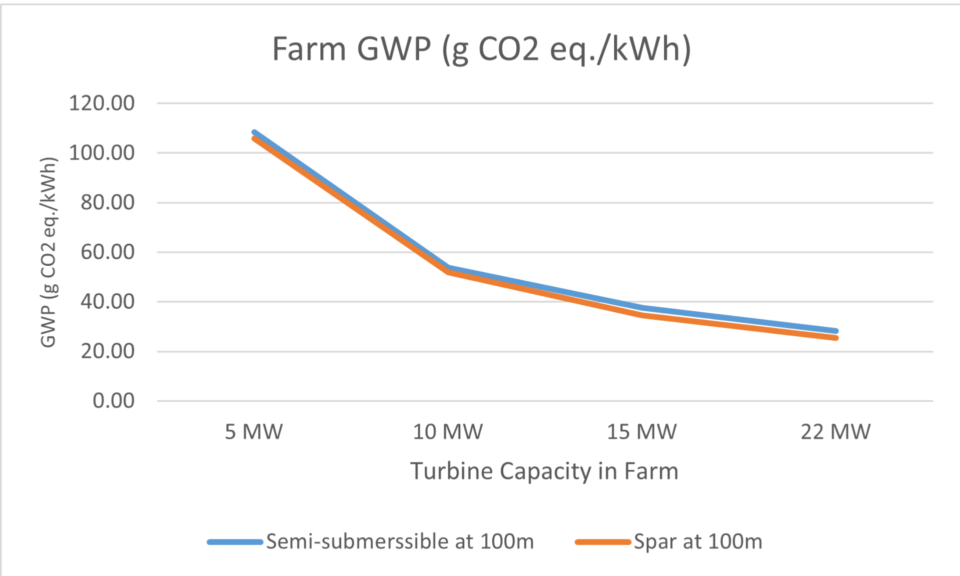


Figure 4.9: Variation of GWP with turbine rating in a 400 MW wind farm at the mentioned water depth and different types of floater.

4.2.3. Levelized Cost of Electricity

Currently, one of the most important drivers for the development of the wind turbine industry is the LCOE of wind farms. The MDAO frameworks also optimize the design to achieve the minimum LCOE of the wind turbine. Hence, it is important to check how the LCOE varies with the turbine ratings for a given wind farm size. From Table 4.3 and 4.4 and Figure 4.10, it can be seen that the LCOE decreases with increasing turbine rating. Compared to a 400 MW wind farm at 100 m water depth consisting of 5-MW semi-submersible type turbines, a farm with 10 MW turbines has 19.71% lower LCOE, a farm with 15 MW turbines has 26.06% lower LCOE, and a farm with 22 MW turbines has 30.69% lower LCOE. Similarly for a similar farm with spar type turbines, compared to a farm with 5 MW turbines, a farm with 10 MW turbines has 21.82% lower LCOE, a farm with 15 MW turbines has 31.4% lower LCOE, and a farm with 22 MW turbines has 35.36% lower LCOE. It can also be noted that the LCOE of spar type turbines is lower than that of semi-submersible type turbines of the same specification. This will be discussed in more detail when both floating wind turbines are compared to each other.

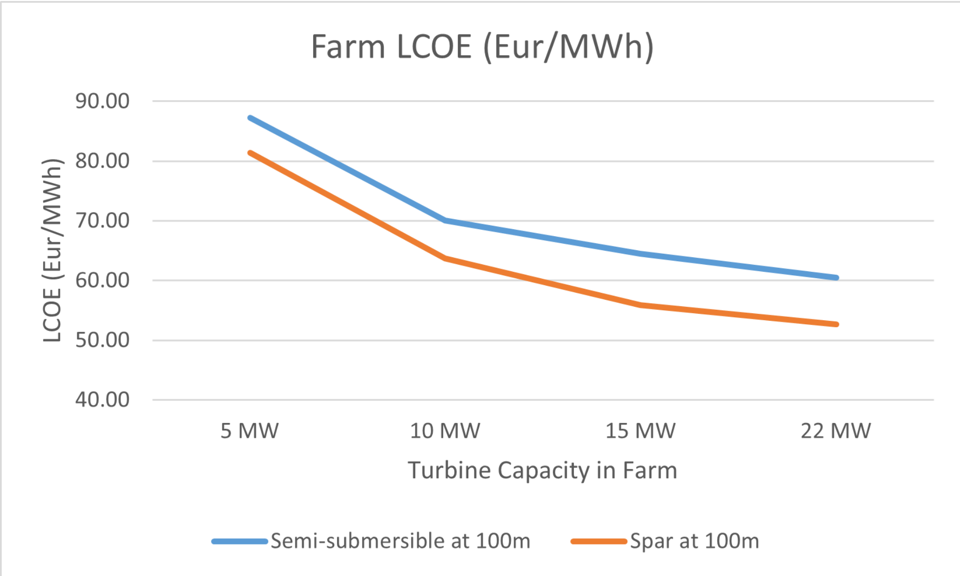


Figure 4.10: Variation of LCOE with wind turbine size in a 400 MW wind farm at the mentioned water depth and different types of floater.

The reduction in LCOE with increasing turbine size can be attributed to the fact that with higher rated turbines the material cost in the farm is significantly lower. In addition, installation and maintenance trips also decrease, which drives down the installation and O&M cost, and hence the LCOE. It can be visualized in Figure 4.11 and a detailed breakdown is mentioned in Table 4.5. Another factor driving the LCOE down is the wind farm capital expenditure (CAPEX). Although the cost of turbines increases with size, the total cost of the wind farm decreases because of the smaller number of turbines. This trend is obtained in all the cases except in the case of the 400 MW farm with 15 MW wind turbine where the CAPEX increases compared to the farm with 10 MW wind turbines.

So far, it can be concluded that larger turbines are better in terms of both the environment and the economy. However, some studies suggest that the LCOE will increase after reaching a minimum when the turbine rating is increased, for example, in the case of fixed-bottom wind turbines in [34]. It depends on the model with which cost estimations are made and, to achieve consistent results, it is necessary to have a single model for estimation. For floating wind turbines, the same cost model is used which scales the cost of turbine with rated capacity, probability of failure, and hence maintenance with the number of turbines, etc. The installation and transportation vessels' costs are constant in the model, but it can be expected to have a higher cost for 15 MW and 22 MW wind turbines and hence a slightly higher LCOE.

4.2.4. Size of Wind Farm

The size of wind farms is increasing every year, and it is possible due to higher-capacity wind turbines. Current wind farms are reaching the gigawatt scale. It is interesting to see whether higher capacity wind farms are more economical and environmentally friendly at the same time or whether there is an opportunity to trade off. In the experiment, the size of wind farm is increased from 400 MW to 800 MW to

Table 4.5: Farm CAPEX, installation cost, and OPEX for various turbine sizes and types for a 400 MW wind farm.

Turbine Type	Turbine Rating	Farm CAPEX (M€)	Farm Installation Cost (M€)	Farm OPEX (M€)
Semi-sub	5 MW	966.38	77.99	95.90
	10 MW	890.76	46.72	59.47
	15 MW	893.69	32.37	43.28
	22 MW	808.79	24.39	32.92
Spar	5 MW	851.57	108.70	137.67
	10 MW	759.81	66.08	90.15
	15 MW	732.87	50.92	71.70
	22 MW	660.10	39.54	59.89
Fixed-bottom	5 MW	880.44	43.23	37.15
	10 MW	880.75	31.61	30.36
	15 MW	1011.99	29.59	29.05
	22 MW	1037.44	24.00	27.93

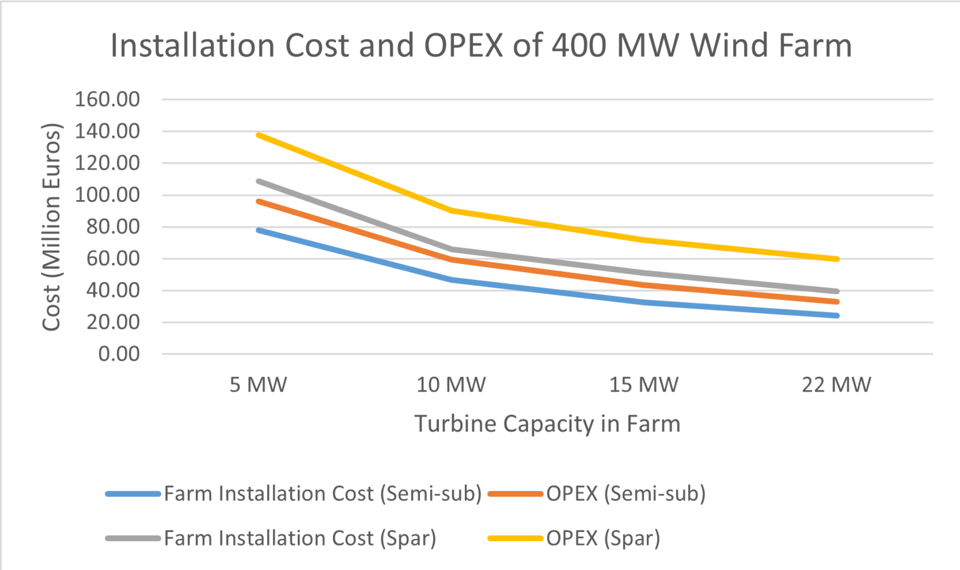


Figure 4.11: Variation in installation cost and OPEX with turbine size and type in a 400-MW wind farm at 100 m water depth.

check the trend of emissions and LCOE but there are certain assumptions made while increasing the size. One of the most important assumptions is the division of the number of turbines installed per year and the total time required to construct the wind farm. As mentioned in Chapter 3, the number of years to construct the farm is fixed at 3 years, and the number of turbines is divided among the years as equally as possible.

The GHG emissions from a single turbine are expected to remain fairly constant with increasing farm size because the turbine design should not change significantly with increasing farm size. This is also obtained from the framework as shown in Figure 4.12. In the figure, various turbine sizes and water depths are mentioned in the legend in a format where the turbine rating, in megawatts, is followed by the water depth in meters. For example, ”05MW 100” means 5 MW turbines at 100 m water depth. However, there are a few exceptions in which the emissions deviate slightly. This is probably due to suboptimal design variables or variables that get stuck at local minima. Although different initial values of design variables have been tried, there is still scope to fine-tune them. Since the difference is not very significant, the current values are used as the final values. In general, it can be assumed that there is no significant change in GHG emissions from a single turbine when the wind farm capacity is changed.

The GHG emissions of the farm increase as the number of turbines increases. For 5 MW turbines on the farm the GHG emissions increase approximately at the rate of 11434.04 ton of CO_2 eq./MW increase in the wind farm capacity. Similarly, the rate of change for 10 MW, 15 MW and 22 MW turbines on the farm are 6235.78 ton of CO_2 eq./MW, 4639.63 ton of CO_2 eq./MW and 3324.61 ton of CO_2 eq./MW, respectively. The variation in farm emissions with farm capacity is shown in Figure 4.13.

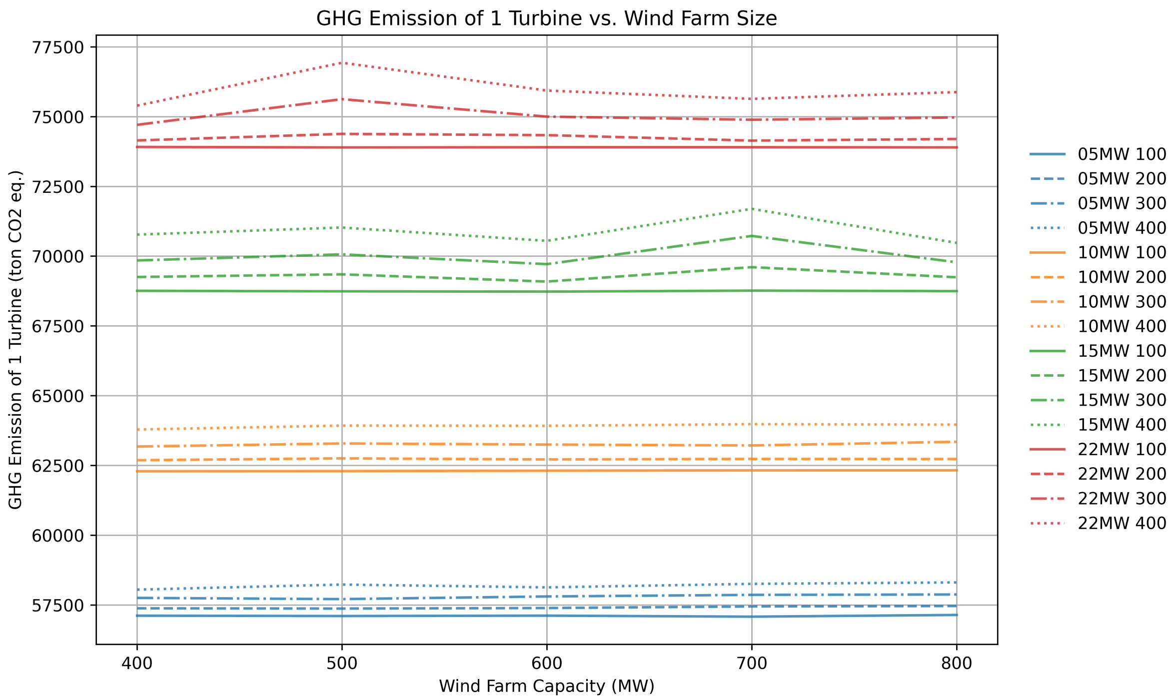


Figure 4.12: Variation in GHG emissions from a single turbine (semi-sub type) when the capacity of wind farm is changed.

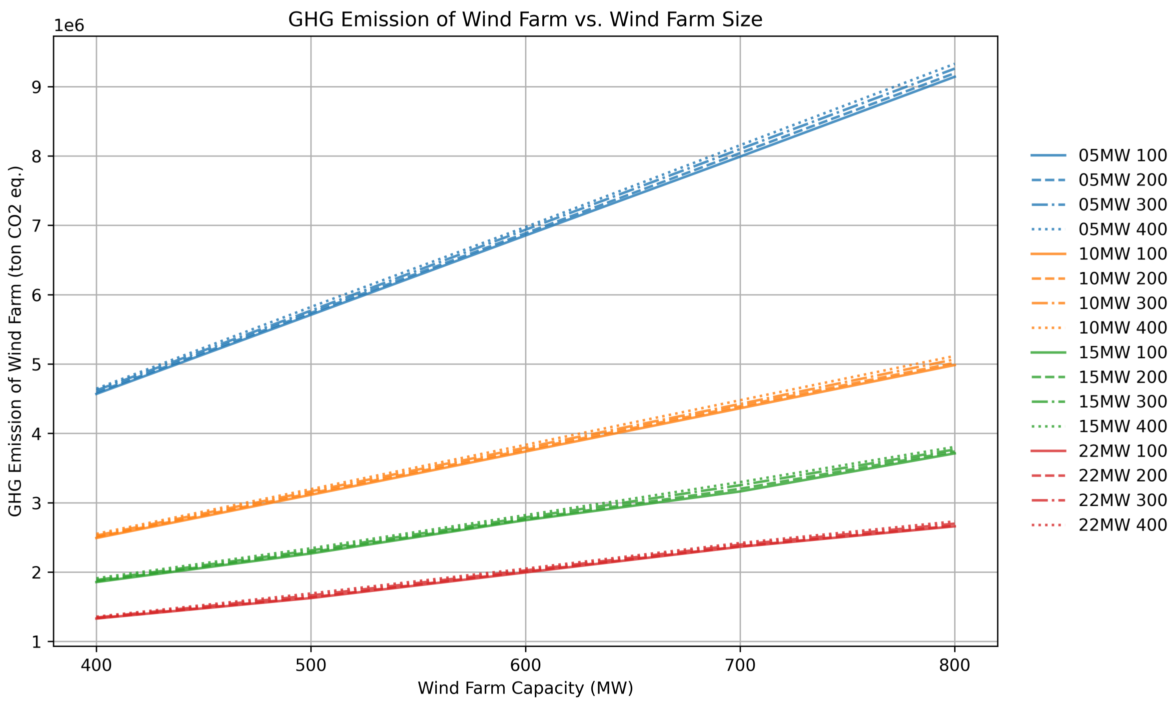


Figure 4.13: Variation in GHG emissions from the wind farm with different turbine (semi-sub type) ratings when the capacity of wind farm is changed.

Although the GHG of the farm increases, the amount of energy produced by the farm also increases. This means the farms can only be compared with a normalized parameter, in this case its the global warming potential. The variation in GWP of the farm with farm capacity is shown in Figure 4.14. The GWP remains fairly constant when the capacity of the wind farm changes. This means that energy production increases in the same way as emissions increase.

The LCOE of the wind farm increases with increasing farm size, as shown in Figure 4.15. This is contrary

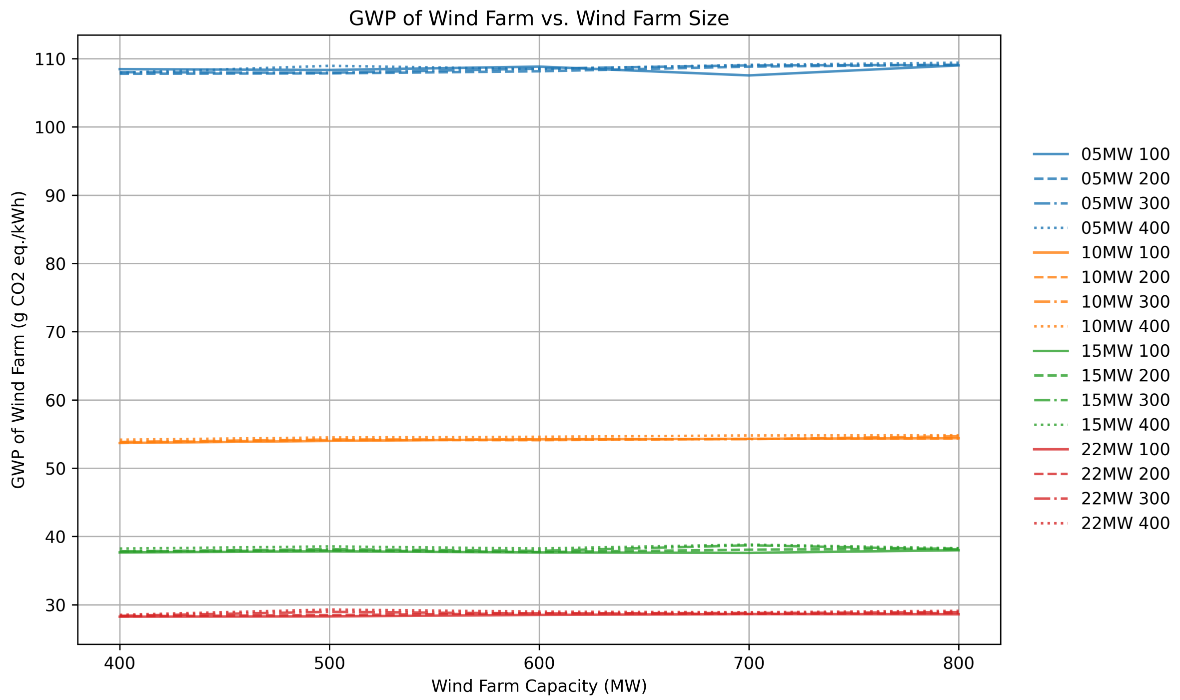


Figure 4.14: Variation in GWP of the wind farm with different turbine (semi-sub type) ratings when the capacity of wind farm is changed.

to the trends seen in the wind industry as it is expected to have a lower LCOE with larger wind farms, and hence the drive for having larger wind farms is present. The opposite trend is due to the assumptions made in the test. Since the time to build a wind farm is kept constant, it may not be realistic to install a very large number of turbines in a year. For example, in an 800 MW wind farm, the number of 5 MW turbines required is 160. This means installing 53 turbines in one year on average. Due to the huge number of turbines, the number of vessels should also increase accordingly, but they are also kept constant, as it would have increased the complexity of the tests. Therefore, the number of hours required by the vessels increases, and therefore the installation cost increases significantly as shown in Figure 4.16.

In Figure 4.15, two jumps can be seen in. This is due to the layout configurations arising from a number (of turbines), which has only two factors, besides one and itself. The first abnormality in the trend can be seen in the 500 MW farm consisting of 22 MW turbines, and the second can be seen in the 700 MW farm consisting of 15 MW turbines. In both cases, the number of turbines is such that the layout is not close to square. In the 500 MW farm, the number of 22 MW turbines is 22, and it leads to the only combination of 11 turbines in a row and 2 columns of such rows or vice versa. Similarly, for 700 MW farm, the number of 15 MW turbines is 46, which leads to the combination of 23 turbines in a row and 2 columns of such rows or vice versa. The other combinations for the above cases can be 23 numbers of 22 MW turbines and 47 numbers of 15 MW turbines. Both of these combinations are close to the specified wind farm capacities, but both are prime numbers. Due to the limitation in the framework, it will lead to a single column or row of turbines, and it will increase the LCOE even further. The LCOE increases as a result of a longer cable layout, which leads to higher cable cost. It must be noted that the layout spacing is optimized by the framework to minimize wake effects, which in turn maximizes AEP and hence minimizes LCOE. However, the coordinates of the wind turbine are dependent on the user and are input in the form of a matrix, as mentioned in Chapter 3. Furthermore, although the wind turbine design variables are optimized, the cost of the wind turbines can be further optimized by changing the layout. This effect can also be seen in other costs such as the installation costs.

Similar results can be observed in the case of spar buoy type turbines. Although the values of the parameters are less than those of semi-submersible type turbines, the trend followed by the parameters of spar turbines is the same. The results are shown in Figures A.11 to A.15. Spar type turbines will be compared to semi-submersible type turbines later in this chapter.

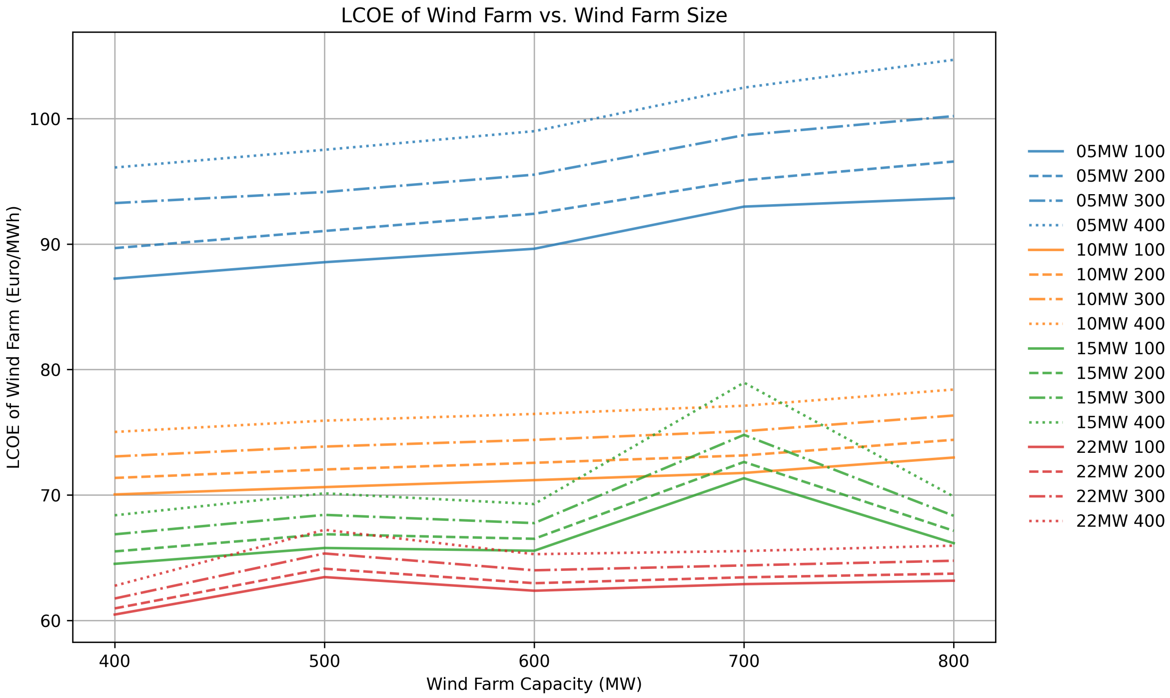


Figure 4.15: Variation in LCOE of the wind farm with different turbine (semi-sub type) ratings when the capacity of wind farm is changed.

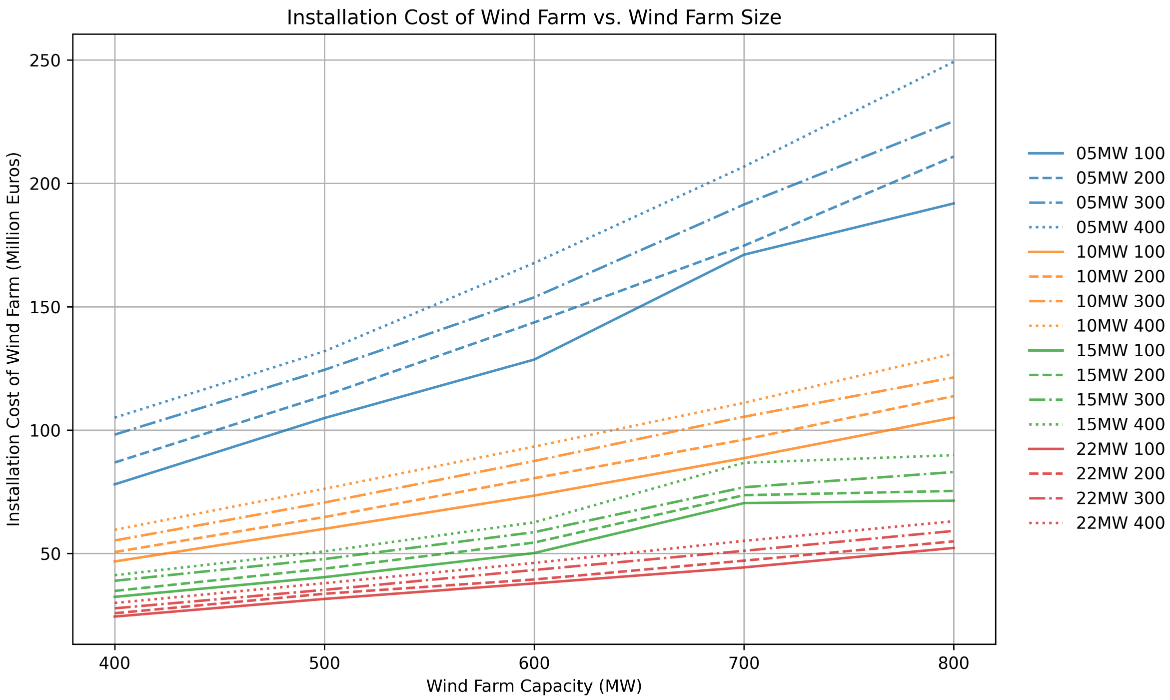


Figure 4.16: Variation in installation cost of the wind farm with different turbine (semi-sub type) ratings when the capacity of wind farm is changed.

4.2.5. Water Depth

Floating wind turbines are suitable for deep waters, where installing monopiles and making transition pieces is not expensive. Deep waters are generally found away from shore and the wind conditions are better for wind turbines. The surface roughness at deep sea is around 0.0002 m, where as for very open landscape it ranges between 0.01 m and 0.03 m. Therefore, a floating wind turbine creates an opportunity to harness stable wind energy with capacity factors considerably higher than those of in-land wind turbines. Consequently, it has been checked what will happen to the wind farms if it is moved to deeper waters. The depth of the water has been varied from 100 m to 400 m in steps of 100 m, and the corresponding emissions and economic parameters have been checked. The depth is assumed to be the same everywhere in the wind farm. With increasing depth, the GHG emissions of a single turbine increase as shown in Figure 4.17. This happens because at higher depths the length of mooring line increases and hence its mass. This increases the total quantity of steel used on the farm, and therefore the GHG emissions of the farm also increase, as shown in Figure 4.18. However, the AEP of the farm also increases with deeper waters, and the GWP of the wind farm remains almost the same as shown in Figure 4.19.

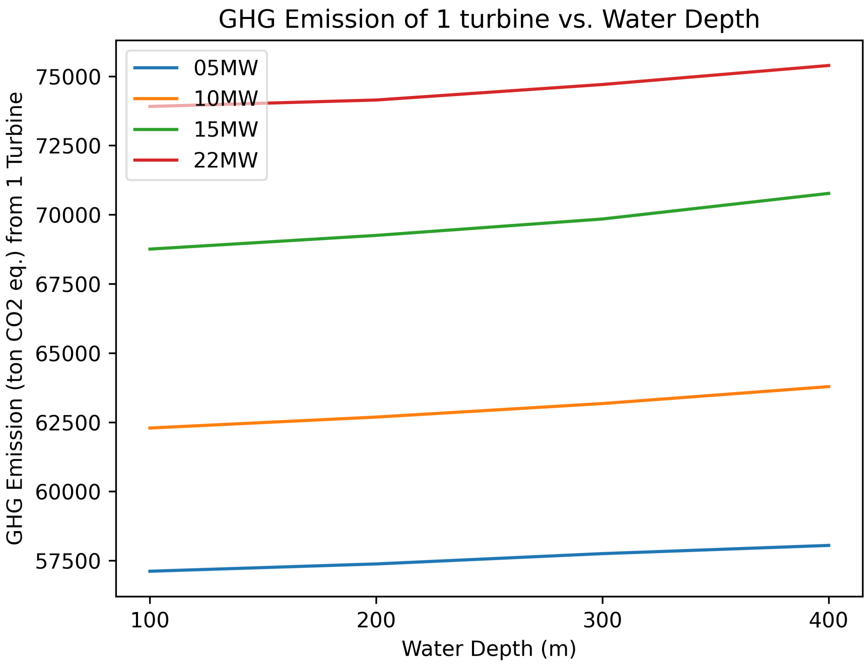


Figure 4.17: Variation in GHG emissions with depth of water for semi-sub type turbines with different ratings.

Since the mooring lines increase in length and mass with increasing depth of water, the cost of the wind turbine, and hence the cost of the farm is expected to increase. This will potentially increase the LCOE unless the increase in AEP compensates for the increase in costs. Figures 4.20 and A.10 show the variation in LCOE and AEP with the depth of water of the farm, respectively. It is clear that the increase in costs is more than the increase in AEP when the depth of water is increased. The increase in the total mooring and anchor mass in the farm is shown in Figures A.7 and A.8, respectively. It must be noted that the anchor mass of 22 MW turbines is much lower than the smaller turbines and the reason behind it is the use of an anchor model which can resist higher horizontal forces while being lighter in weight compared to the model used for smaller turbines. This is explained in more detail in Chapter 3. The floater mass is expected to not change with increasing water depth, but there is a slight decrease in its mass with increasing water depth, and this is probably due to the hydrostatic equilibrium changing from the increased mooring mass at higher water depths. The variation in floater mass with changing water depth is shown in Figure A.9.

Similar results can be observed in the case of spar buoy type turbines. Although the value of the parameters is less than that of semi-submersible type turbines, the trend followed by the parameters of spar turbines is the same. The results are shown in Figures A.16 to A.23. In contrast to the semi-submersible floater, the mass of a spar buoy floater remains fairly constant, as expected. Spar type turbines will be compared to semi-submersible type turbines later in this chapter.

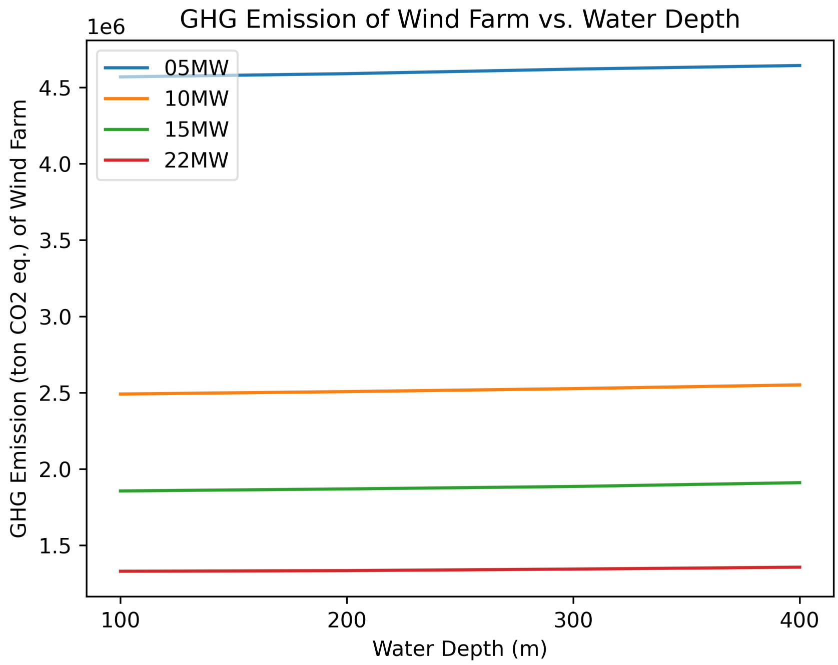


Figure 4.18: Variation in GHG emissions with depth of water for wind farms made of semi-sub type turbines with different ratings.

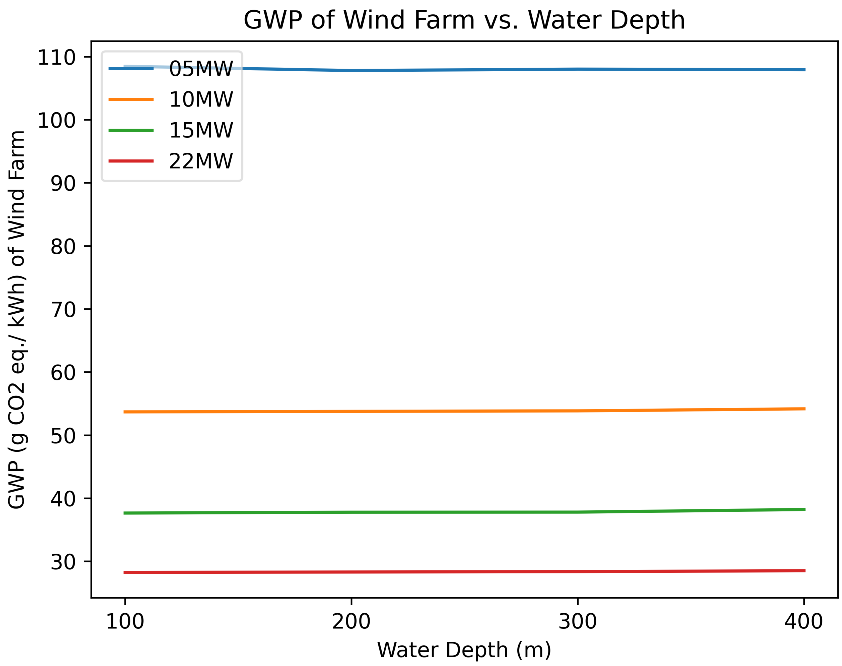


Figure 4.19: Variation in GWP with depth of water for farms made of semi-sub type turbines with different ratings.

4.2.6. Lifetime Of Wind Farm

The life of a wind farm can significantly change the impact of turbines on the environment. If the same amount of material is used for a longer time, then the emissions are distributed over a longer time, and hence the emissions are reduced. With farms lasting longer, lesser farms would be constructed and less material will be used. Wind turbines were expected to last 20 years earlier and with improved technology and maintenance practices, turbines are expected to last 25 years. The turbines manufactured today are expected to last 30 years. As described in Chapter 3, the lifetime of the wind farm has been varied

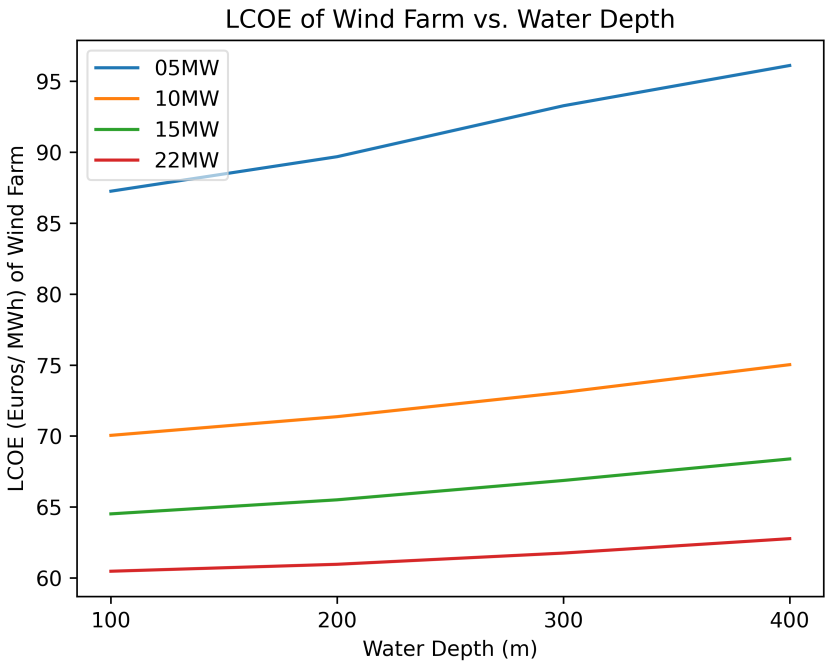


Figure 4.20: Variation in LCOE with depth of water for farms made of semi-sub type turbines with different ratings.

from 25 years (default setting in the framework) to 40 years. Life can be expected to improve further and expectancy can be assumed to be 35 years. An optimistic scenario is considered where the life is up to 40 years. When the lifetime is changed, it is assumed in the model that only maintenance is improved. The failure rates of turbines have been kept unchanged, as mentioned in Chapter 3. The probability of major failures in floating wind turbines is 0.119 failures/turbine/year and in fixed bottom turbines it is 0.3 failures/turbine/year. Changes in materials, technology, or construction method have not been considered.

The GWP, which depends on the lifetime of the wind farm, decreases with increasing life expectancy. For semi-submersible type wind turbines in a wind farm, the reduction in GWP can be as high as 28.81%, as in the case of 5 MW turbines in a 400 MW farm at 100 m water depth. For higher capacity wind turbines the reduction in GWP is less as fewer turbines are used. The variation of GWP with the lifetime of a wind farm is shown in Figure 4.21 and Table 4.6.

Similarly, the LCOE also decreases with increasing lifetime of the farm. This is because the CAPEX of the farm is not increasing with increasing lifetime as changes in technology and material are not considered. However, the maintenance cost increases, which in turn increases the OPEX of the farm. Changes in LCOE and OPEX are shown in Tables 4.7 and 4.8, respectively, and are visualized in Figures 4.22 and 4.23. Similar variation is also observed with spar buoy type turbines and the changes are shown in Tables A.4 to A.6 and Figures A.24 to A.26. It can be concluded from this test that if focus is put more on extending the life of a wind farm, then the impacts on the environment can be significantly reduced.

Table 4.6: Farm GWP (g CO_2 eq./kWh) as a function of turbine (semi-submersible type) rating and operational lifetime of the farm.

Lifetime (years)	5 MW	10 MW	15 MW	22 MW
25	108.47	53.69	37.66	28.25
30	90.46	44.73	31.46	23.48
35	77.22	38.38	26.84	20.14
40	67.48	33.65	23.51	17.62

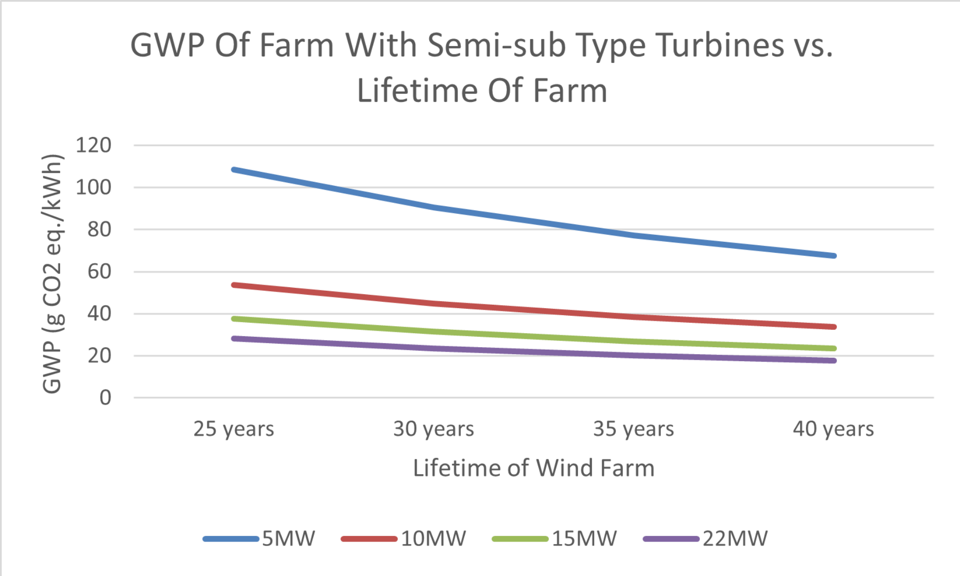


Figure 4.21: Farm GWP (g CO_2 eq./kWh) as a function of turbine (semi-submersible type) rating and operational lifetime of the farm.

Table 4.7: Farm LCOE (€/MWh) as a function of turbine (semi-submersible type) rating and operational lifetime of farm.

Lifetime (years)	5 MW	10 MW	15 MW	22 MW
25	87.25	70.05	64.51	60.47
30	84.33	67.60	62.24	58.17
35	82.71	66.18	60.94	56.90
40	81.67	65.34	60.19	56.14

Table 4.8: Farm OPEX (Million Euros) as a function of turbine (semi-submersible type) rating and operational lifetime of farm.

Lifetime (years)	5 MW	10 MW	15 MW	22 MW
25	95.90	59.47	43.28	32.92
30	99.53	61.81	44.26	34.11
35	103.02	63.03	46.16	34.63
40	104.76	63.45	46.65	35.14

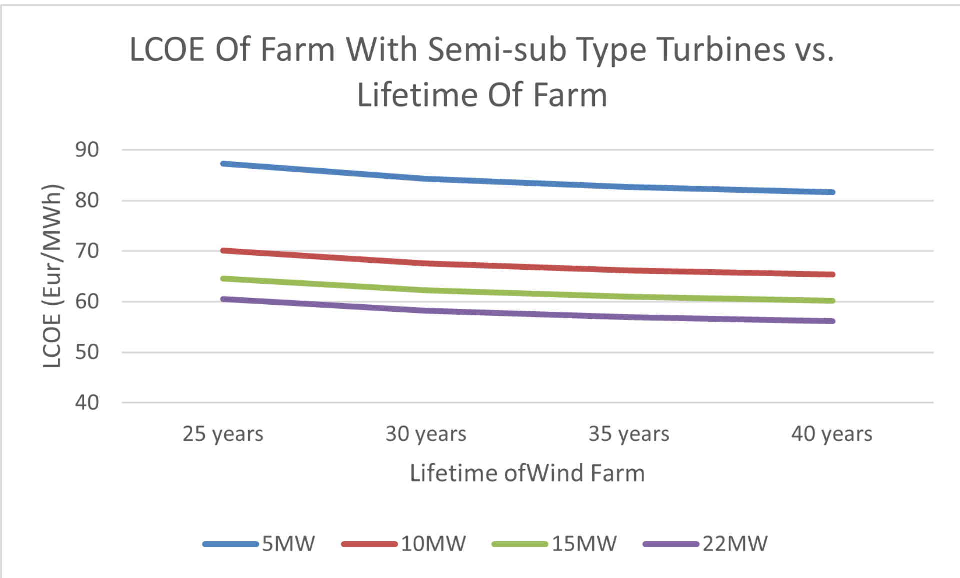


Figure 4.22: Farm LCOE (Euros/MWh) as a function of turbine (semi-submersible type) rating and operational lifetime of the farm.

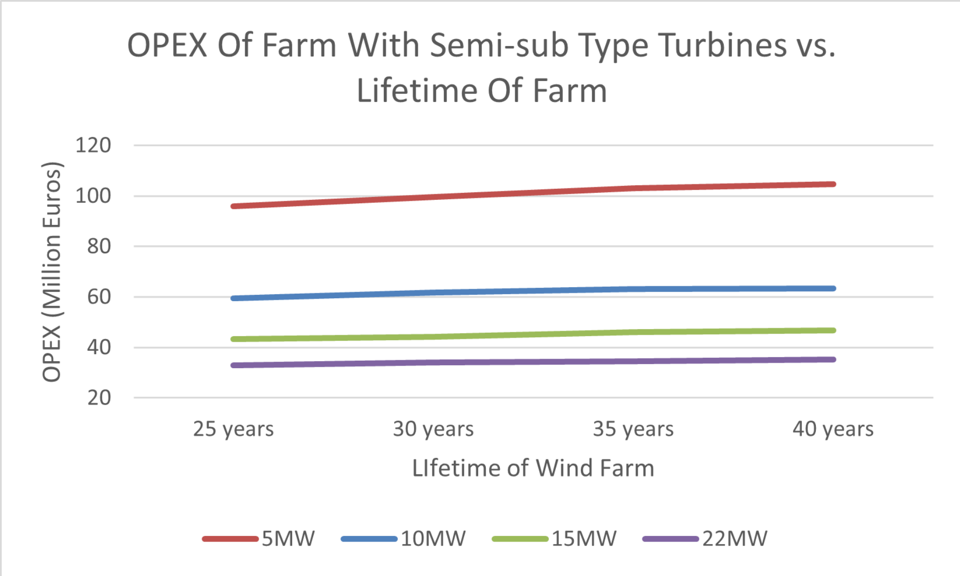


Figure 4.23: Farm OPEX (Million Euros) as a function of turbine (semi-submersible type) rating and operational lifetime of the farm.

The sensitivity of the GWP of semi-submersible type wind farms and spar buoy type wind farms is shown in Figures 4.24 and 4.25, respectively. It gives an idea of which factors affect GWP and to what degree. In the figure, the water depth is increased by 100 m, the farm size is increased by 100 MW, and the lifetime of the farm is increased by 5 years. The corresponding values of GWP are shown in the radar plot. The method of reading the coordinates is shown in the figure.

4.3. Comparison Of Semi-Sub Type And Spar Type Wind Turbines

Choosing between semi-submersible type and spar type floater depends on several factors including water depth, availability of a port close to the wind farm, etc. However, it is also interesting to see how the impacts differ compared to each other. Compared to semi-submersible floaters, spar floaters are suitable for deeper waters because of very large drafts in spar floaters. For example, a 5 MW, 10 MW, 15 MW and 22 MW spar turbine has an average draft of around 87 m, 111 m, 110 m and 120 m, respectively. This means that theoretically only 5 MW spar floaters can be used in waters that are 100 m deep. However, this is also not done practically and a semi-submersible type floater is used. In the results, a hypothetical scenario is considered to have 10 MW, 15 MW, and 22 MW turbines at 100 m water depths to compare the results with a semi-submersible floater. In reality, the spar buoy would penetrate into the sea bed and different forces will start acting on the floater, which in turn will change the metacentric height and stability.

Spar type floaters have lower emissions compared to semi-submersible type floaters, as shown in Figure 4.6. For 5 MW, 10 MW, 15 MW and 22 MW turbines, the spar type turbine has 2.85%, 4.94%, 8.86% and 11.45% lower emissions, respectively, than a semi-submersible type turbine. This is because of the lower mass of steel used in a spar type floater. Since the structure is simpler, the amount of steel used is lesser. However, a spar type floater uses a higher quantity of ballast which stabilizes the floater [40], as shown in Figure 4.26. For the submersible floater, the concrete mass is taken as zero as some designs consider only water as ballast, as in the OC4-DeepCwind submersible platform [41]. On average (considering all turbine sizes), the mass of steel in a spar type floater is 28.09% lower than in a semi-submersible type floater. Similarly, the mass of ballast is 69.59% higher than the ballast mass in semi-submersible type floater. The differences in masses for a 5 MW and 10 MW turbines are shown in Figure 4.27. If the ballast is considered concrete, then the GWP becomes abnormally high. Hence, only steel mass is considered.

Since the emissions from a single turbine is lower in case of a spar type turbine, the emissions from the wind farm and hence, the GWP are also expected to be less. This is shown in Figures 4.7 and 4.9. For a 400 MW wind farm at 100 m water depth, a 5 MW spar type turbine has 2.36% lower GWP than a 5 MW semi-submersible type turbine. Similarly, 10 MW, 15 MW and 22 MW spar type turbines have 3.16%, 8.01% and 9.78% lower GWP, respectively, compared to the semi-submersible type counterparts.

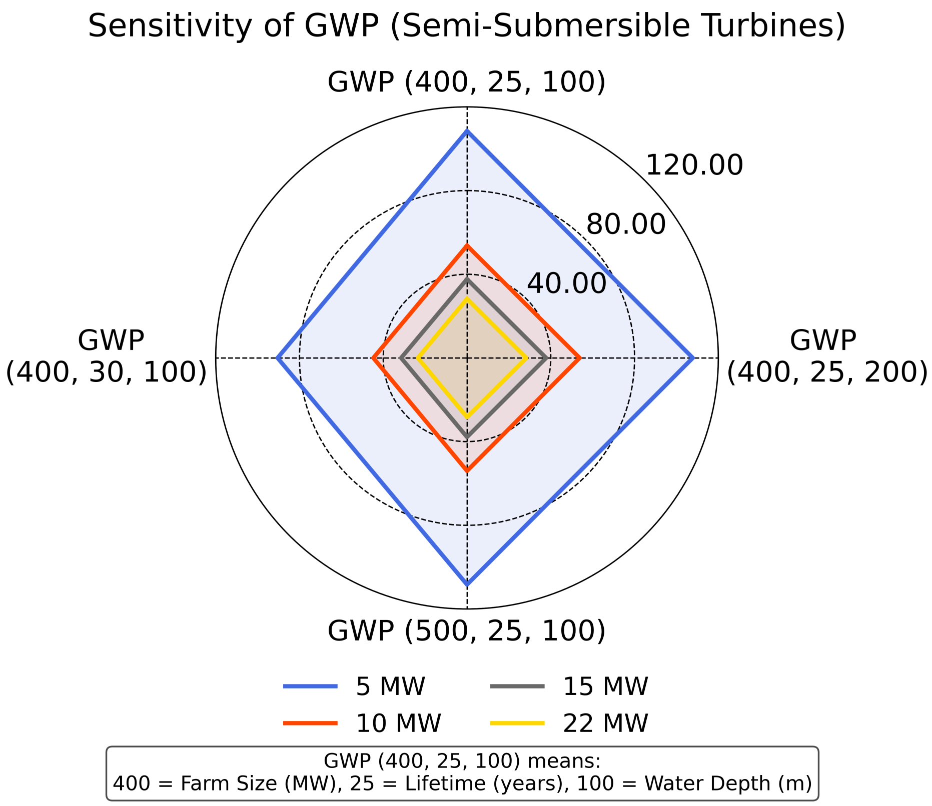


Figure 4.24: Sensitivity of GWP (g CO_2-eq./kWh) of a semi-submersible type wind farm to different factors.

For larger turbine ratings, the difference increases, which shows that the requirement of steel in semi-submersible type wind turbine increases at a higher rate than that of a spar type wind turbine when the turbine rating is increased. Furthermore, since the amount of steel used is lower in spar type turbines, the material cost is also lower than a semi-submersible type turbine. This can be seen from Table 4.5 and Figure 4.11, that the CAPEX of a spar type turbine is lower than the CAPEX of a semi-submersible type turbine. In addition to material cost, the cost of fabricating the floater also increases with increasing complexity of the design. Since the semi-submersible floater has several parts such as an offset column, cross-braces, etc. whereas a spar buoy has a central column only, the design of a semi-submersible floater is more complex. A cost parameter has been used in the framework to take the complexity into consideration, and hence, the fabrication cost of spar buoy is lesser. Therefore, the LCOE of a wind farm made of spar type wind turbines is also less compared to the semi-sub type. For a 400 MW wind farm at 100 m water depth, the LCOE of a 5 MW , 10 MW, 15 MW and 22 MW spar type turbine configuration is 6.68%, 9.11%, 13.42% and 12.95% lower, respectively, than the semi-submersible type counterparts. This is shown in Figure 4.10. What can make the spar buoy floater expensive is the availability of a shelter where the spar buoy is erected and assembled. This can be observed from the installation costs of the spar type turbines in Table 4.5. The installation cost increases due to the extra cost of a shelter. If there is a shelter available near the port and farm, then the spar buoys are cheaper.

It can be concluded that spar type turbines are cheaper and more environmentally friendly compared to the semi-submersible type counterparts. Considering the manufacturing and depth constraints, in ideal cases, spar type wind turbines are a better option.

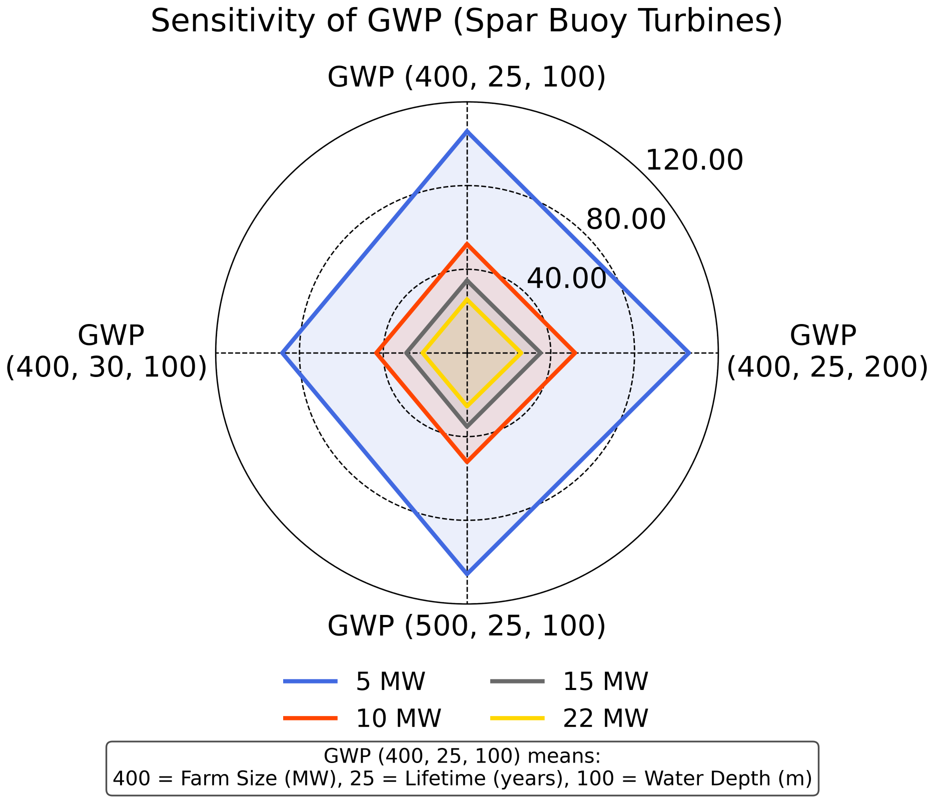


Figure 4.25: Sensitivity of GWP (g CO_2-eq./kWh) of a spar-buoy type wind farm to different factors.

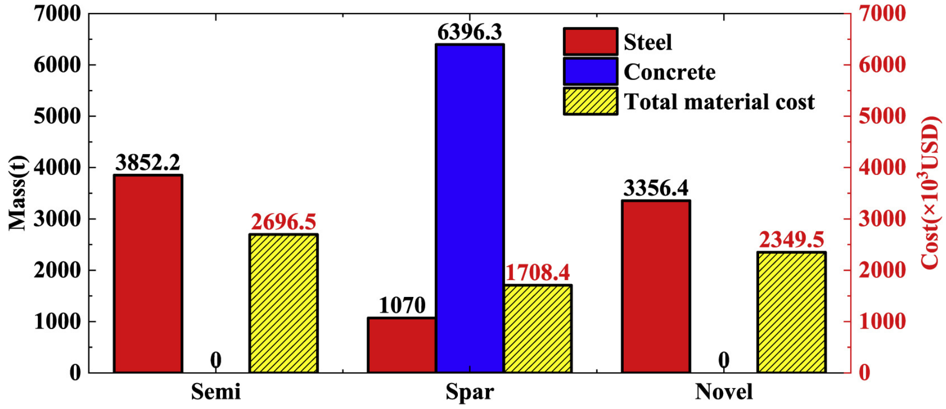


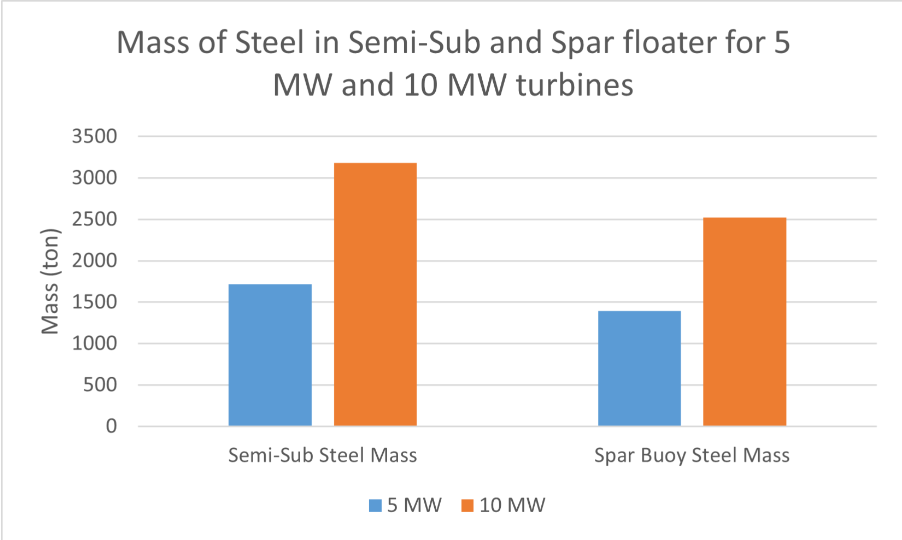
Figure 4.26: Variation of steel mass and ballast mass between semi-submersible floater and spar buoy floater [40].

4.4. Fixed-Bottom Wind Turbines

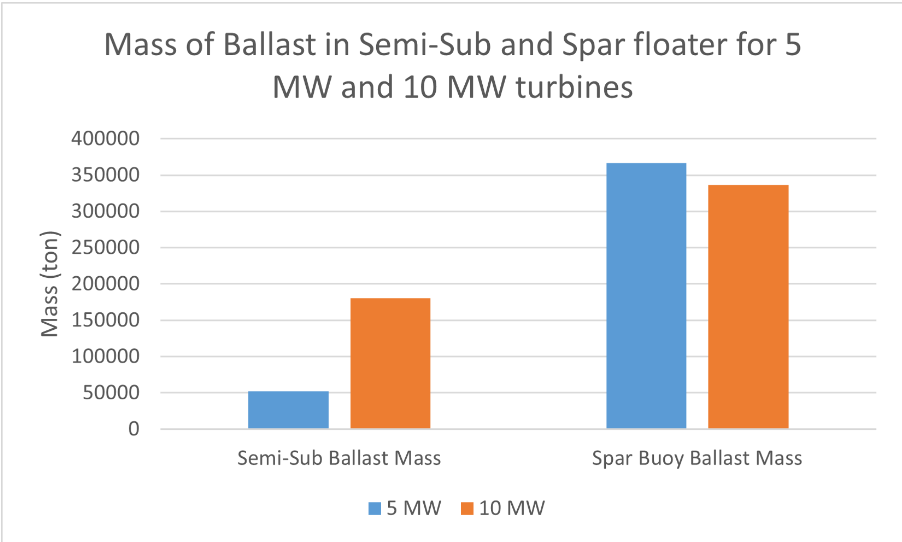
In this section, estimations of the environmental impact of fixed bottom wind turbines are compared and analyzed. As mentioned above, a different framework is used to optimize the wind turbine and the wind farm. Different parameters are varied and studied to observe changes in impacts.

4.4.1. Greenhouse Gas Emissions

Like floating wind turbines, the mass of material used in a fixed-bottom wind turbine also increases with increasing turbine capacity. Larger capacity turbines larger rotor/blades and a heavier tower and foundation is required. Fixed-bottom turbines used in this thesis have a monopile foundation and not a



(a) Comparison of steel mass of floaters



(b) Comparison of ballast mass of floaters

Figure 4.27: Comparison of mass of steel and ballast used in different types of floaters and different sizes of turbines. In this case, a 5 MW turbine and a 10 MW turbine are compared.

concrete foundation. Hence, the mass of concrete is zero. The tower is attached to a transition piece which in turn is attached to a monopile. With bigger turbines, the mass of transition piece and monopile also increases to bear the loads. The change in the mass of the components with increasing turbine capacity is shown in Table 4.9 and Figure 4.28.

Table 4.9: Variation of component masses of different turbine (fixed bottom) sizes in a 400 MW wind farm at 30 m water depth.

Turbine Rating	Tower Mass (ton)	RNA Mass (ton)	Monopile Mass (ton)	Transition Piece Mass (ton)
5 MW	156.19	211.03	369.13	86.97
10 MW	424.85	574.14	714.30	168.29
15 MW	963.17	1287.62	1205.02	282.51
22 MW	1681.12	2255.04	1820.66	411.89

As a result, GHG emissions increase with increasing turbine size. A single fixed-bottom turbine of size 5 MW, 10 MW, 15 MW and 22 MW emits around 52012.58 ton, 52680.26 ton, 53329.19 ton and 54417.67 ton of CO_2 eq. of GHG gases. Compared to a 5 MW turbine, a 10 MW, 15 MW, and 22 MW turbine

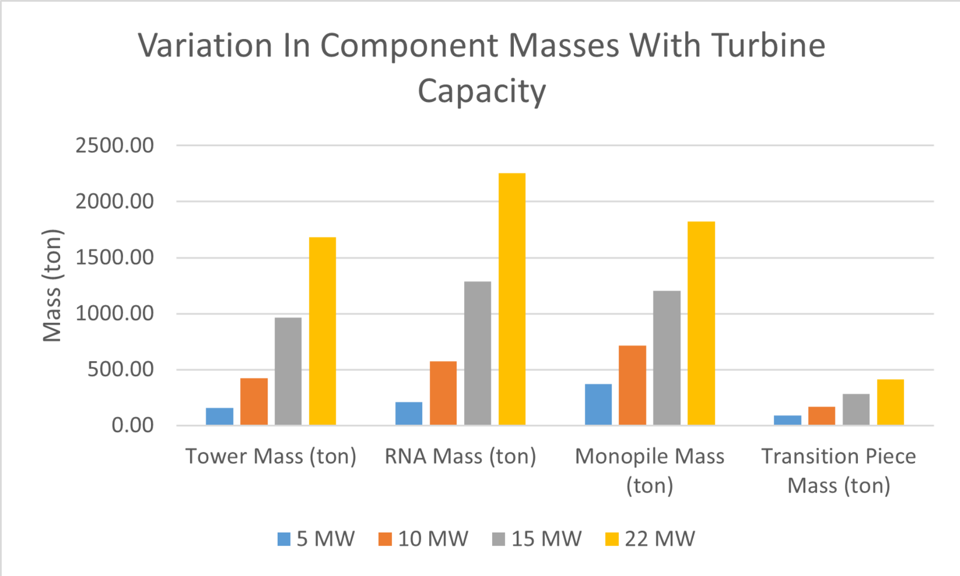


Figure 4.28: Variation in component masses of a fixed-bottom wind turbine with increasing turbine capacity.

emits 1.28%, 2.53% and 4.62% more GHG, respectively. The difference is not as great as that of floating wind turbines. For the farm, the emissions decrease with increasing capacity of the turbines as the number of turbines decreases. A farm made of 5 MW, 10 MW, 15 MW and 22 MW turbines emits around 4161006.52 tons, 2107210.30 tons, 1439888.26 tons, and 979518.15 tons of CO_2 eq. of GHG gases over the lifetime. Compared to a farm made up of 5 MW turbines, farms made up of 10 MW, 15 MW and 22 MW turbines emit 49.36%, 65.40% and 76.46% less greenhouse gases, respectively. The variation in parameters is shown in Table 4.10 and Figures 4.29 and 4.30. The conclusion is similar to that of floating wind turbines. It is better to use fewer higher capacity turbines in a farm than more smaller turbines.

Table 4.10: Environmental and economic metrics of different fixed-bottom turbine ratings in a 400 MW wind farm at 30 m water depth.

Turbine Rating	Turbine Emissions (ton CO_2 eq.)	Farm Emissions (ton CO_2 eq.)	Farm GWP (g CO_2 eq./kWh)	Farm LCOE (€/MWh)
5 MW	52012.58	4161006.52	102.39	70.71
10 MW	52680.26	2107210.30	47.43	60.35
15 MW	53329.19	1439888.26	28.06	56.44
22 MW	54417.67	979518.15	19.68	58.49

4.4.2. Global Warming Potential

Since the GHG emissions of the farm decrease with increasing turbine capacity, the GWP of the farm is also expected to decrease. This is also similar to floating wind turbines. The farm AEP increases with increasing turbine size, but decreases slightly when the size is increased from 15 MW to 22 MW, like floating wind turbines. The variation in farm AEP is shown in Figure 4.31. The trend is similar to floating turbines because the same turbine model is used by both frameworks. However, GWP decreases with increasing turbine size. Compared to a farm (400 MW at 30 m depth) consisting of 5 MW turbines, a farm with 10 MW, 15 MW and 22 MW turbines has 53.67%, 72.60% and 80.78% less GWP, respectively. The variation in GWP is shown in Table 4.10 and Figure 4.32.

4.4.3. Levelized Cost Of Electricity

As mentioned earlier, the calculation of the LCOE depends on the framework and cost models used in it. Since the framework for fixed-bottom turbines is different, the variation of LCOE is also different compared to floating wind turbines. As shown in Table 4.5 and Figure 4.33, the LCOE decreases with the turbine capacity until it reaches a minimum at 15 MW. Thereafter, it increases slightly when the size is changed to 22 MW. Compared to a 400 MW farm at 30 m depth consisting of 5 MW turbines, a similar farm consisting of 10 MW, 15 MW and 22 MW turbines has 14.65%, 20.19% and 17.28% lower LCOE,

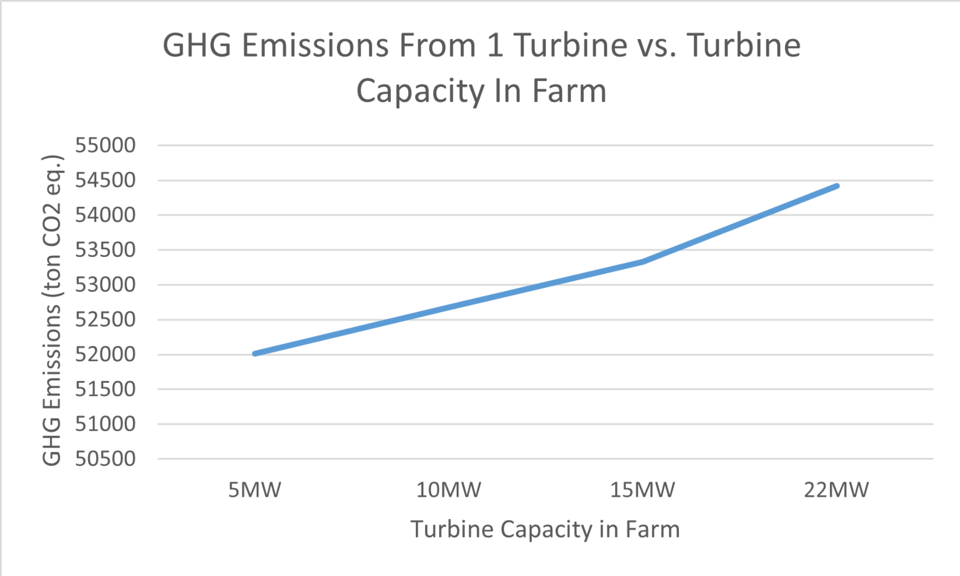


Figure 4.29: Variation in GHG emissions from a single turbine (fixed bottom type) with varying turbine capacities in a 400 MW wind farm at 30 m water depth.

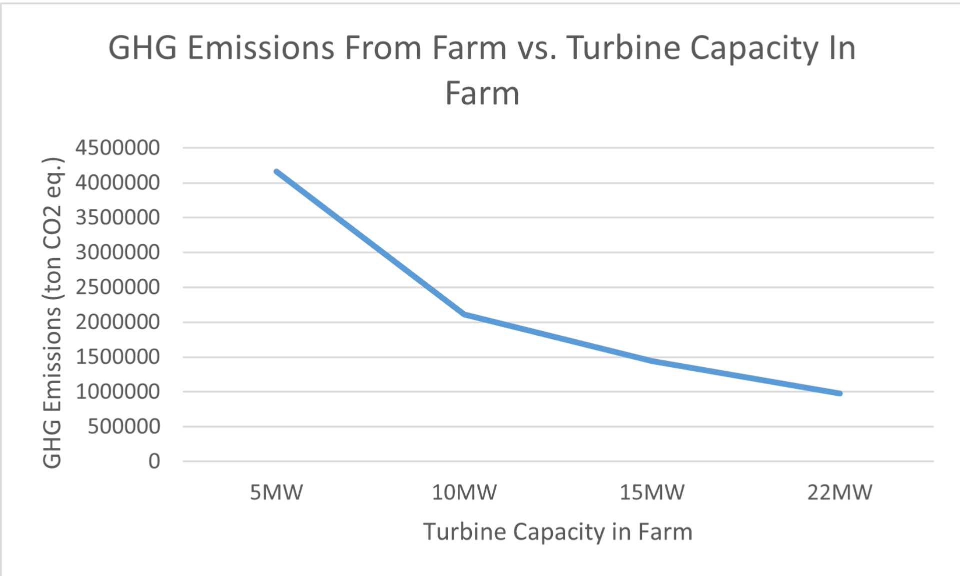


Figure 4.30: Variation in GHG emissions from the farm with varying turbine (fixed bottom type) capacities in a 400 MW wind farm at 30 m water depth.

respectively.

In this framework, the CAPEX of the farm increases because certain cost components scale with the size of the turbine. Furthermore, there is an additional cost of insurance and a contingency cost which increases significantly with the turbine size. All of these, collectively, raise the CAPEX. On the other hand, the installation cost and the OPEX of the farm decrease since the number of turbines decrease. At some point after the 15 MW turbine, the OPEX becomes less than the installation cost, as shown in Figure 4.34, and is close to the lowest LCOE point, as mentioned in [34].

4.4.4. Size Of Wind Farm

When the farm size is increased in the framework for fixed-bottom wind turbines, the number of turbines is increased and given as input to the main script. The construction time and the number of turbines installed per year are not changed by the user. Therefore, the assumption of dividing the number of turbines over the years, as in the case of floating turbines, does not hold here. The farm size is changed from 400 MW to 1000 MW, and the changes are various parameters are explained below.

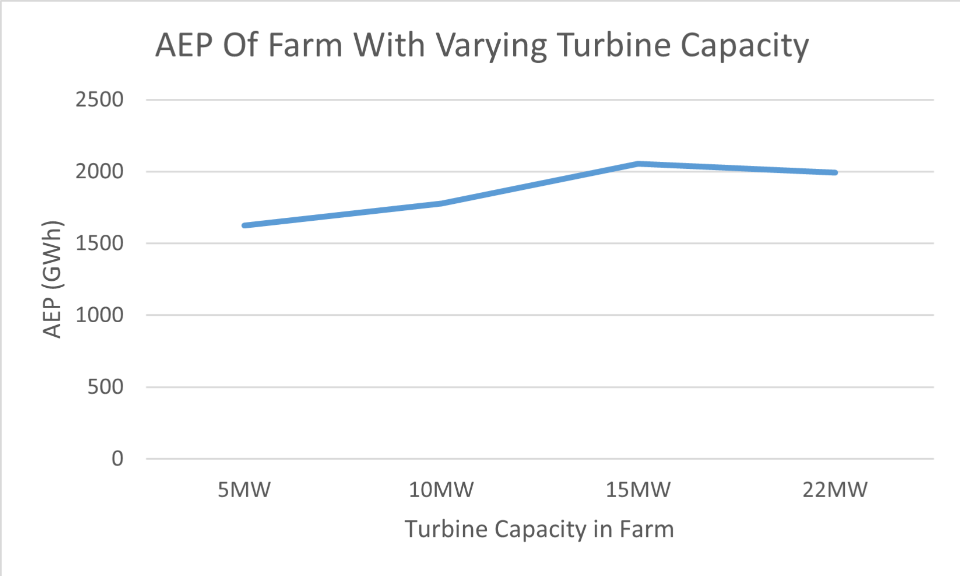


Figure 4.31: Variation in farm AEP with turbine size in wind farm (fixed-bottom turbines only).

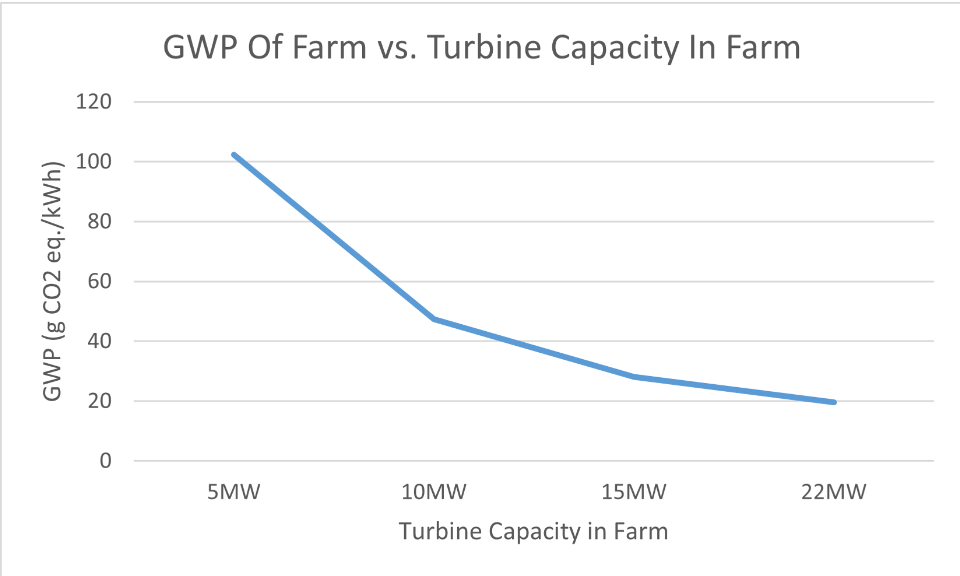


Figure 4.32: Variation in farm GWP with turbine size in wind farm (fixed-bottom turbines only).

The GHG emissions for a single turbine remain constant because there are no changes in the turbine when the farm size increases. However, the emissions of the entire farm are expected to increase as the number of turbines increases. The GHG emissions for a farm with 5 MW turbines increase at a rate of 10402.52 ton CO_2 eq./MW increase in wind farm capacity. Similarly, for farms with 10 MW, 15 MW, and 22 MW turbines, the rates are 5268.03 ton CO_2 eq./MW, 3555.28 ton CO_2 eq./MW, and 2448.80 ton CO_2 eq./MW increase in wind farm capacity, respectively. The variation in the GHG emission from the farm against the wind farm size is shown in Figure 4.35.

The GWP of the farm increases slowly with increasing wind farm capacity. This means that the increase in GHG emissions is nearly compensated for by the increase in AEP of the farm. The variation of GWP with increasing farm capacity is shown in Figure 4.36. It can be observed that there is a spike in GWP from 800 MW onward, in the case of farms with 5 MW turbines. This is because the layout of the turbines in the farm is not an optimum layout. For fixed-bottom wind turbines, the framework accepts a set of coordinates as the turbine's location. The turbine's location is not changed by the framework. Consequently, the spacing between the turbines functions as an input by the user. Using the layout for different turbines can lead to sub-optimal spacing. Since the number of 5 MW turbines is large, the turbine spacing of

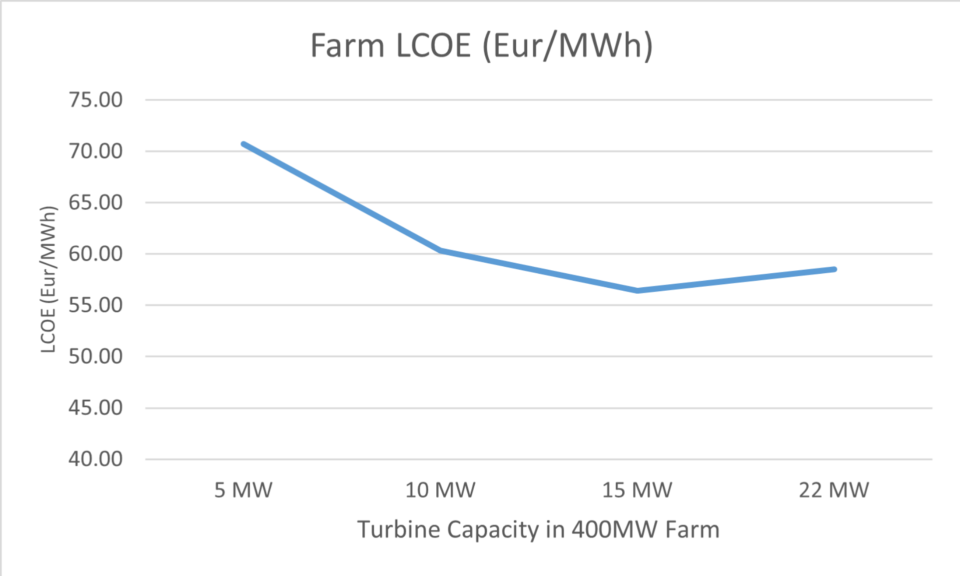


Figure 4.33: Variation in farm LCOE with turbine size in wind farm (fixed-bottom turbines only).

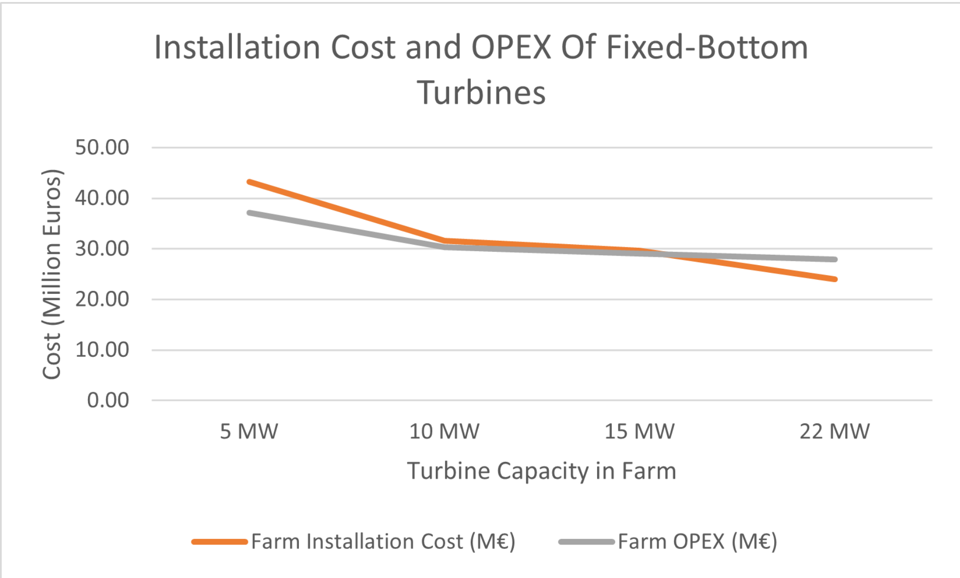


Figure 4.34: Variation in installation cost and OPEX of a 400 MW wind farm at 30 m water depth consisting of fixed-bottom wind turbines (different capacities).

smaller farms was used as a reference for the larger farms. Due to this, wake losses are higher in these farms, and hence the AEP of the farm decreases. Consequently, the GWP increases. From the other trends, it can be assumed that the GWP of the farm with 5 MW turbines will also increase slowly with increasing farm size. It should be noted that the change in AEP with farm size is highly dependent on wind conditions and farm layout, and having larger farms can also decrease GWP.

The LCOE of the farm decreases with increasing farm size. The drop in LCOE shows a decreasing trend as the farm capacity approaches 1 GW. This is in accordance with the wind energy industry as energy producers are moving towards larger wind farms. As mentioned earlier, in the case of floating wind turbines, the LCOE increased with increasing size of the wind farm because of the underlying assumptions on construction time and the number of turbines installed per year. However, this is not the case for fixed-bottom wind turbines, and construction and installation are handled by the framework. The variation is shown in Figure 4.37. The spike in LCOE of the farm from 800 MW onward is due to the layout, as explained previously. Since LCOE also depends on the AEP of the farm, the LCOE increases when the AEP decreases. However, it can be assumed that for farms consisting of 5 MW turbines, will follow a trend similar to the other configurations.

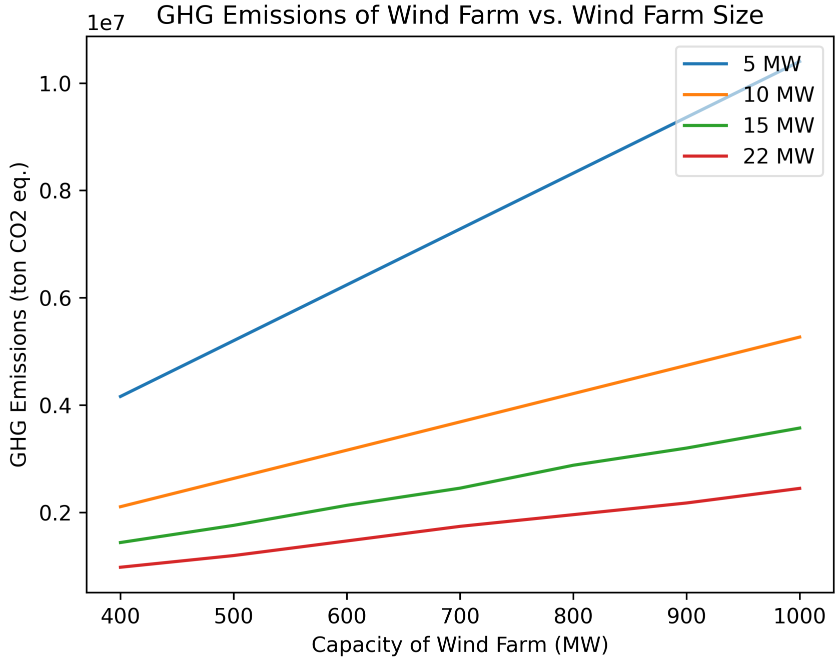


Figure 4.35: Variation of GHG emissions of the farm against the wind farm capacity for fixed-bottom wind turbines.

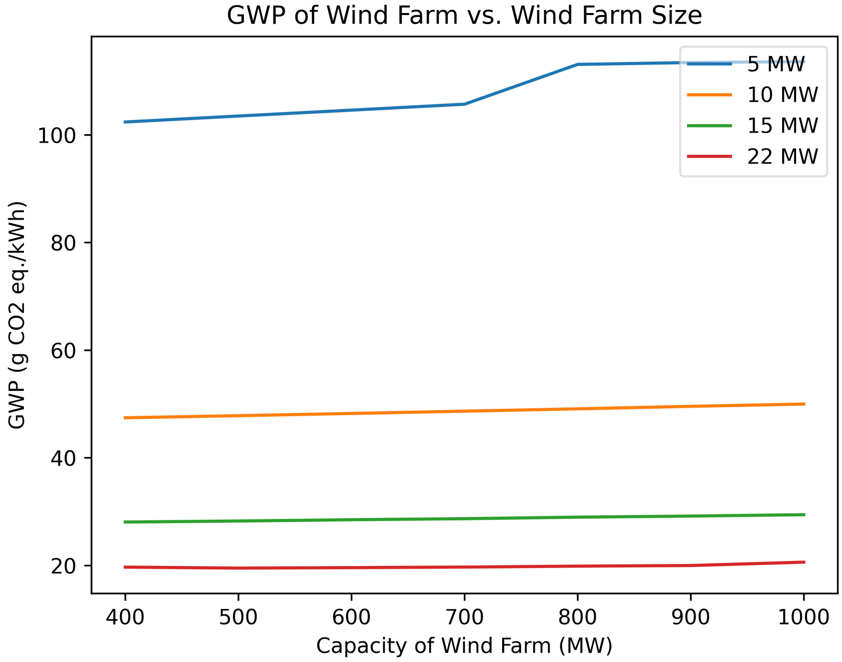


Figure 4.36: Variation of GWP of the farm against the wind farm capacity for fixed-bottom wind turbines.

It can be concluded that larger farms are better than smaller farms economically. When environmental impacts are considered, the larger farms are similar to the smaller farms. So, constructing and operating larger farms has an overall benefit since they are cheaper, though they are similar in terms of impacts.

4.4.5. Water Depth

With increasing water depth, the length of transition piece and monopile increases, consuming more steel. It can be expected that the mass of transition piece and monopile would increase, increasing

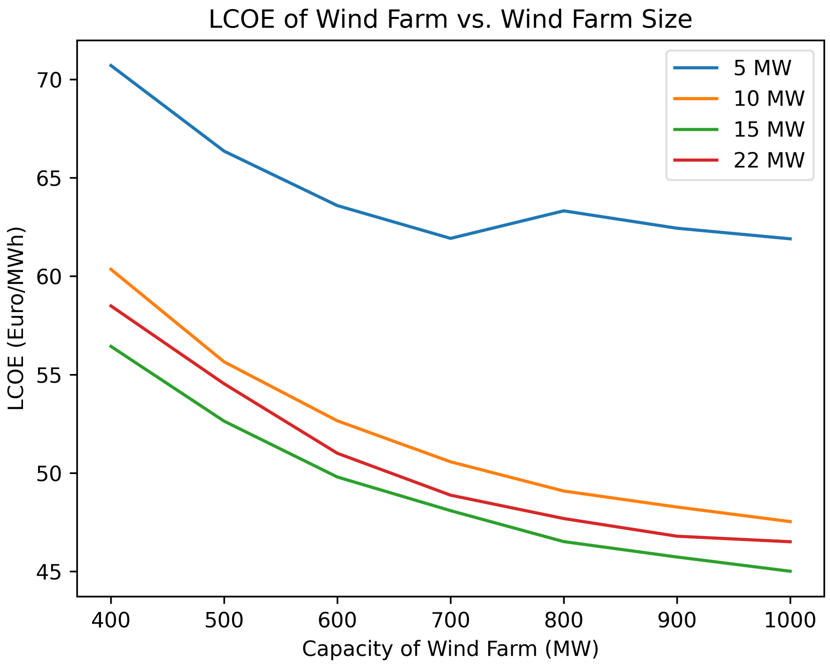


Figure 4.37: Variation of GWP of the farm against the wind farm capacity for fixed-bottom wind turbines.

the GHG emissions, GWP, and LCOE. The variation in LCOE and GWP is shown in Figures 4.38 and 4.39, respectively, and the variation in the monopile mass and the transition piece mass is shown in Figures A.27 and A.28, respectively. In case of fixed-bottom wind turbines the GWP keeps on increasing, contrary to the trend observed in case of floating wind farms, because the AEP of the farm does not increase with increasing water depth. This happens because the wind conditions are assumed to be the same in this framework. Furthermore, in this framework, water depth cannot be increased more than 60 mdue to the risk of buckling. However, it can be theoretically designed, but it will require changing the underlying equations and conditions and is out of scope for this thesis.

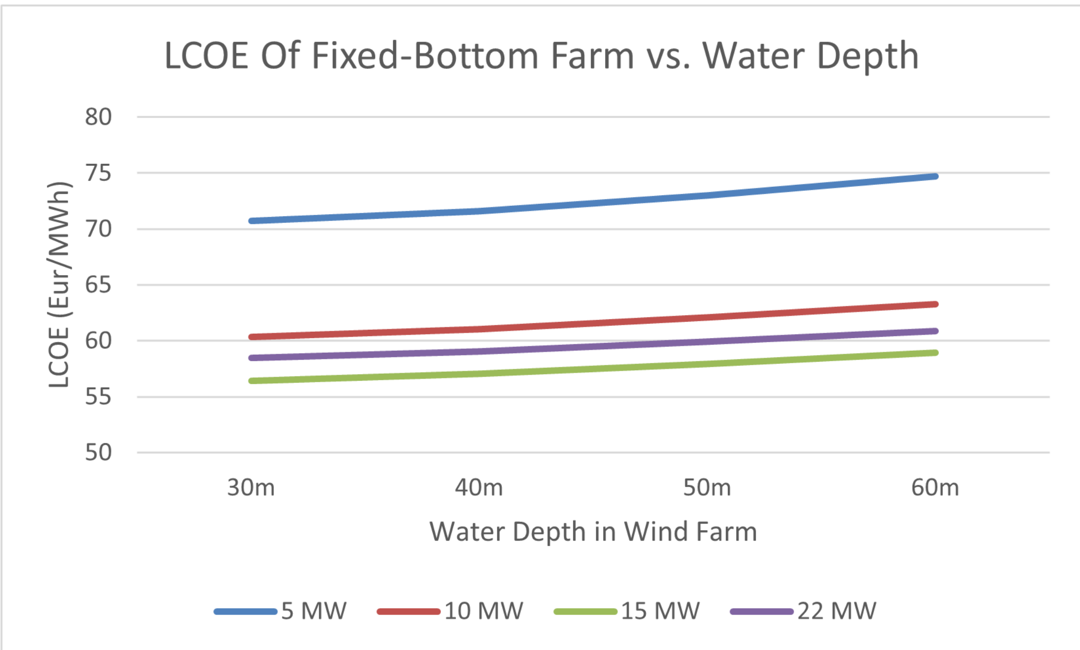


Figure 4.38: Variation in LCOE of a 400 MW fixed-bottom wind farm with water depth.

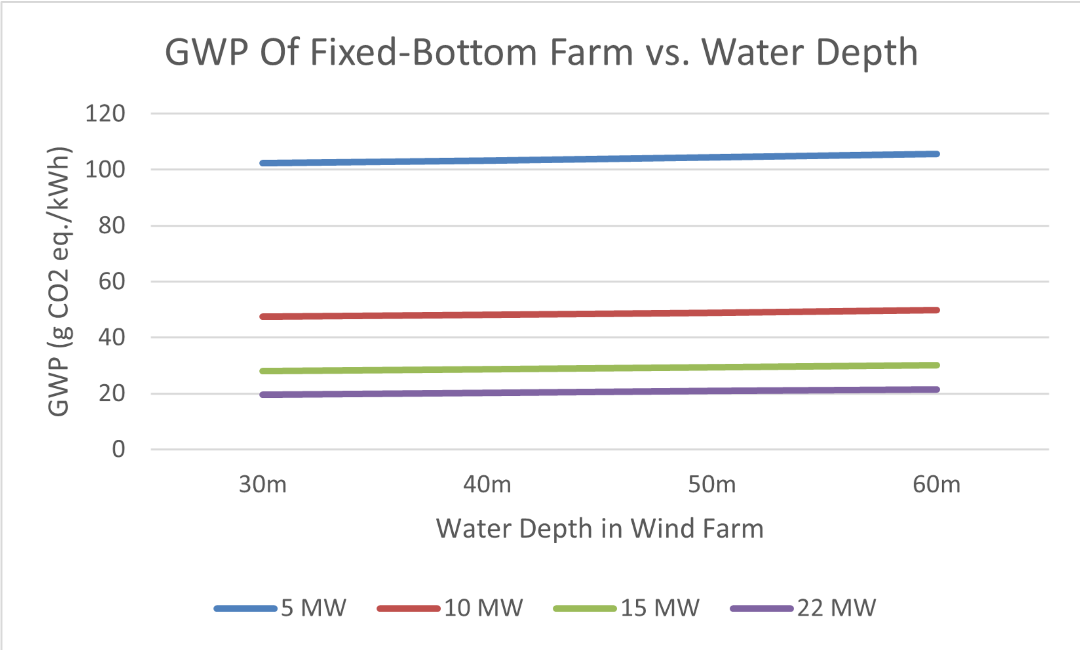


Figure 4.39: Variation in GWP of a 400 MW fixed-bottom wind farm with water depth.

4.4.6. Lifetime Of Wind Farm

In this chapter, it has been previously concluded that increasing the lifetime of the wind farm decreases the impact of turbines on the environment and also lowers the LCOE. Thus, a similar result is expected for the case of fixed-bottom wind turbines. As shown in Table 4.11 and Figures 4.40 to 4.41, both LCOE and GWP decrease when the lifetime of the farm increases. Compared to a 400 MW farm with 5 MW fixed bottom turbines, a similar farm with 10 MW, 15 MW and 22 MW turbines has 6.58%, 11.02% and 14.04% lower LCOE, respectively. Similarly, they have 16.67%, 28.57%, and 37.5% lower GWP.

The sensitivity of the GWP of the fixed-bottom type wind farm is shown in Figures 4.42. It gives an idea of which factors affect GWP and to what degree. In the figure, the water depth is increased by 10 m, the farm size is increased by 100 MW, and the lifetime of the farm is increased by 5 years. The corresponding values of GWP are shown in the radar plot. The method of reading the coordinates is shown in the figure.

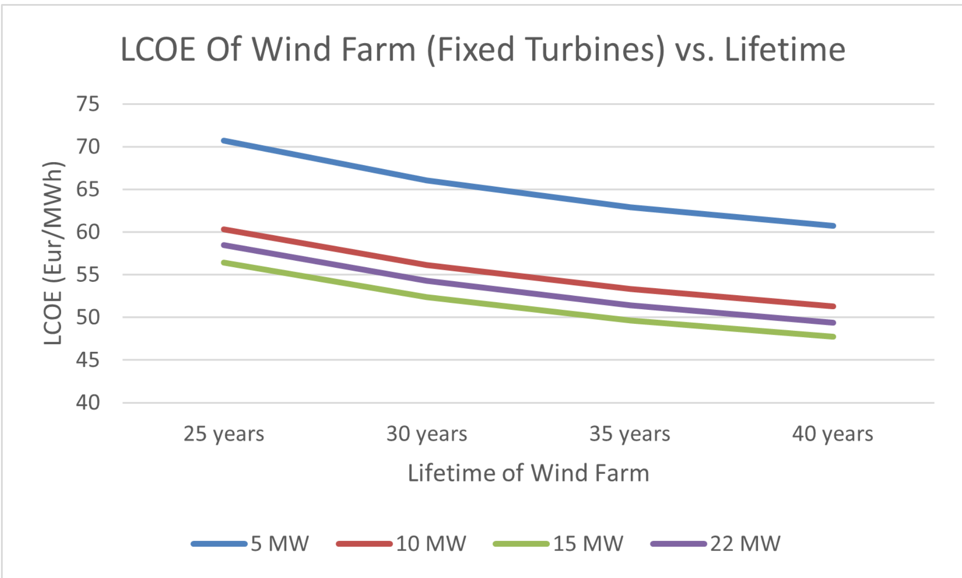


Figure 4.40: Variation in LCOE of 400 MW wind farm at 30 m depth with different operational lifetimes of the farm.

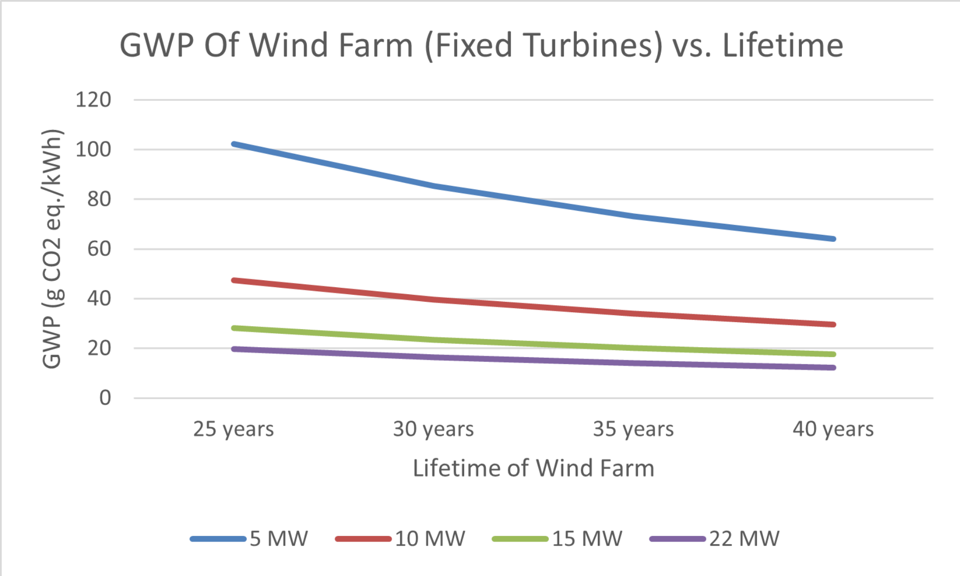


Figure 4.41: Variation in LCOE of 400 MW wind farm at 30 m depth with different operational lifetimes of the farm.

Table 4.11: Variation of LCOE and GWP with turbine rating and farm lifetime for a 400 MW fixed-bottom wind farm.

(a) LCOE (EUR/MWh)

Lifetime	5 MW	10 MW	15 MW	22 MW
25 years	70.71	60.35	56.44	58.49
30 years	66.06	56.15	52.40	54.27
35 years	62.92	53.32	49.68	51.42
40 years	60.71	51.33	47.77	49.42

(b) GWP (g CO_2-eq./kWh)

Lifetime	5 MW	10 MW	15 MW	22 MW
25 years	102.39	47.43	28.06	19.68
30 years	85.33	39.53	23.38	16.40
35 years	73.14	33.88	20.04	14.05
40 years	63.99	29.65	17.53	12.30

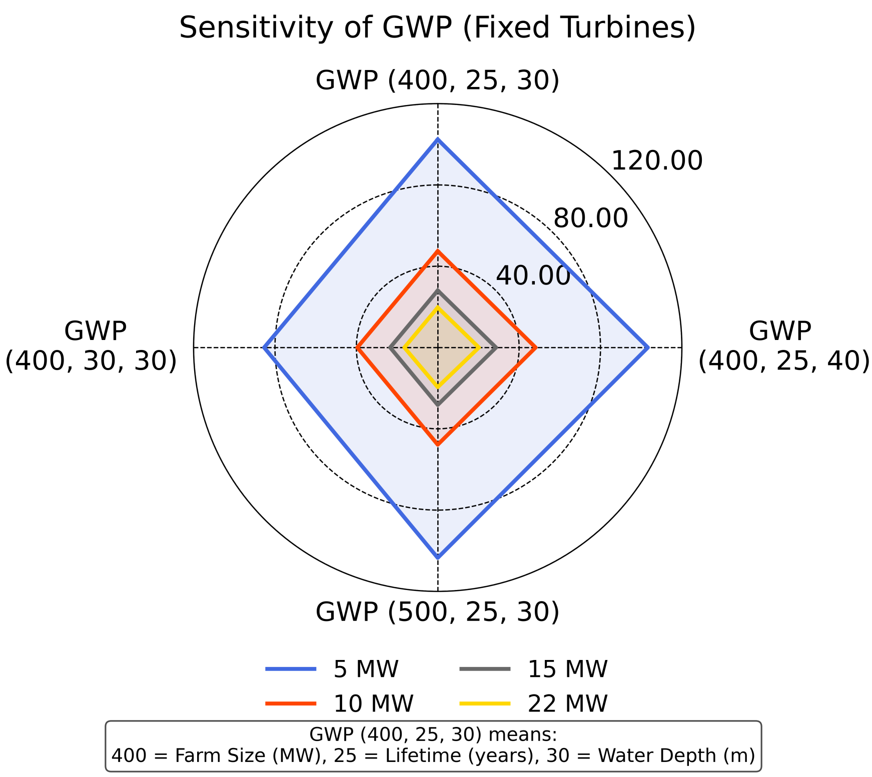


Figure 4.42: Sensitivity of GWP (g CO_2-eq./kWh) of a fixed-bottom type wind farm to different factors.

4.5. Comparison Of Floating And Fixed-Bottom Wind Turbines

Floating and fixed-bottom wind turbines are used in very specific site conditions, for example, spar buoy type turbines are generally used for water depths more than 120 m and fixed bottom wind turbines are used in shallow waters. However, semi-submersible type wind turbines have a lower draft compared to spar type turbines. In transitional waters, where water depths vary from 50 m to 60 m, it is interesting to compare turbine choices with respect to cost and environmental impacts. For this, semi-submersible and fixed-bottom turbines are compared at water depths between 40 m and 70 m. It should be noted that the 5 MW fixed bottom turbines could not be designed for 70 m water depth because the tower design equations did not support such depths. The stresses in the tower exceeded the allowable stress limits, which means that the tower would buckle. Spar turbines have not been considered in the comparison because the draft of the spar buoy is very large compared to the depth of water.

From the comparison, it is observed that the LCOE and GWP of floating turbines is higher than that of fixed-bottom turbines. The main reason for this difference is the extra mass of steel used in the semi-submersible floater. Since the same turbines are used in both fixed bottom and floating wind turbines, the mass of the turbines is the same for both cases. The structures below the tower make the difference. It is obvious that transition piece and monopiles are simpler than semi-submersible floaters in terms of design and fabrication. In addition, floating turbines also have mooring lines and anchors that cost more and use more steel. The comparison of LCOE and GWP of semi-submersible and fixed bottom turbines are shown in Figures 4.43 and 4.44, respectively. Compared to a farm of 10 MW floating turbines, a farm of 10 MW fixed-bottom turbines has approximately 9.03% lower LCOE and 7.08% lower GWP at a given depth of 60 m. For farms with bigger turbines, the difference becomes smaller, and for 22 MW turbines, the LCOE of the floating farm is lower than a fixed-bottom farm (made of 22 MW turbines) at just 50 m deep water. The GWP of the floating farm is still higher than that of fixed-bottom farm. As mentioned previously, the assumption made on the construction time and number of turbines installed per year affected the LCOE of floating wind farms. It is possible that the LCOE of floating wind farms can be lower than current values depending on the construction time and the number of turbines installed per year. This gives a scope of having cheaper floating wind farms than fixed-bottom farms at lower transitional depths. It also gives the opportunity to have floating wind farms made of lower capacity turbines (example 15 MW or 18 MW) be cheaper than the corresponding fixed-bottom farms at lower depths. So floating farms can be cheaper than fixed farms at capacities like 18 MW, for example, instead of 22 MW.

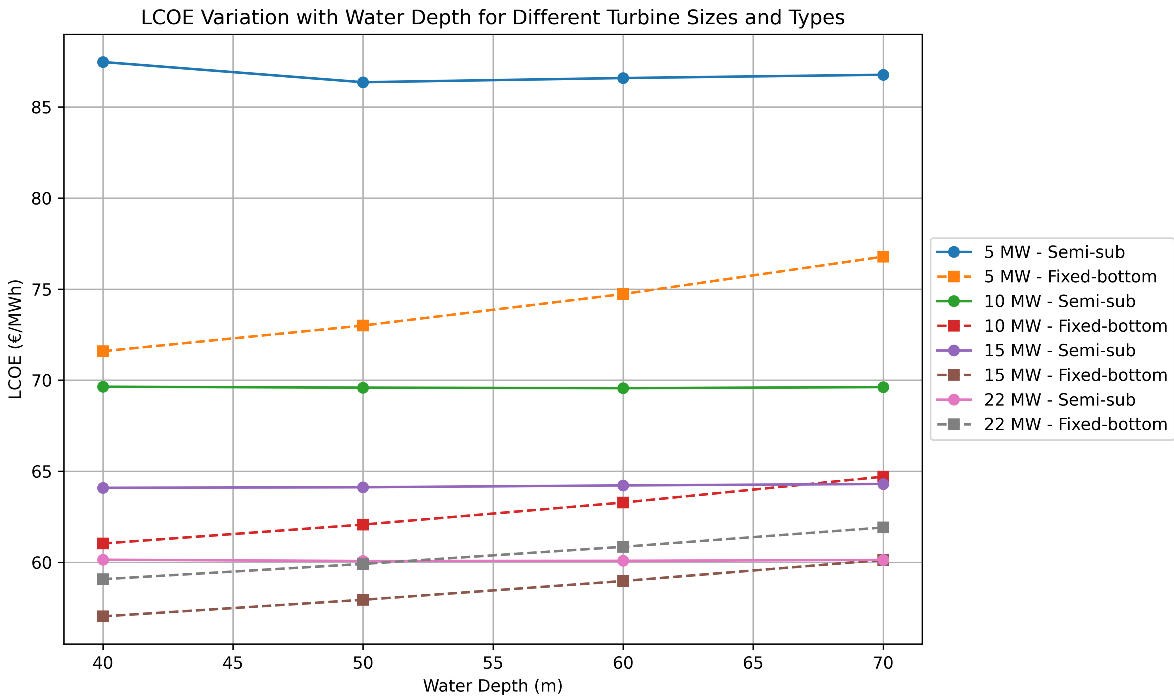


Figure 4.43: Comparison of LCOE of semi-submersible and fixed-bottom turbines of different sizes.

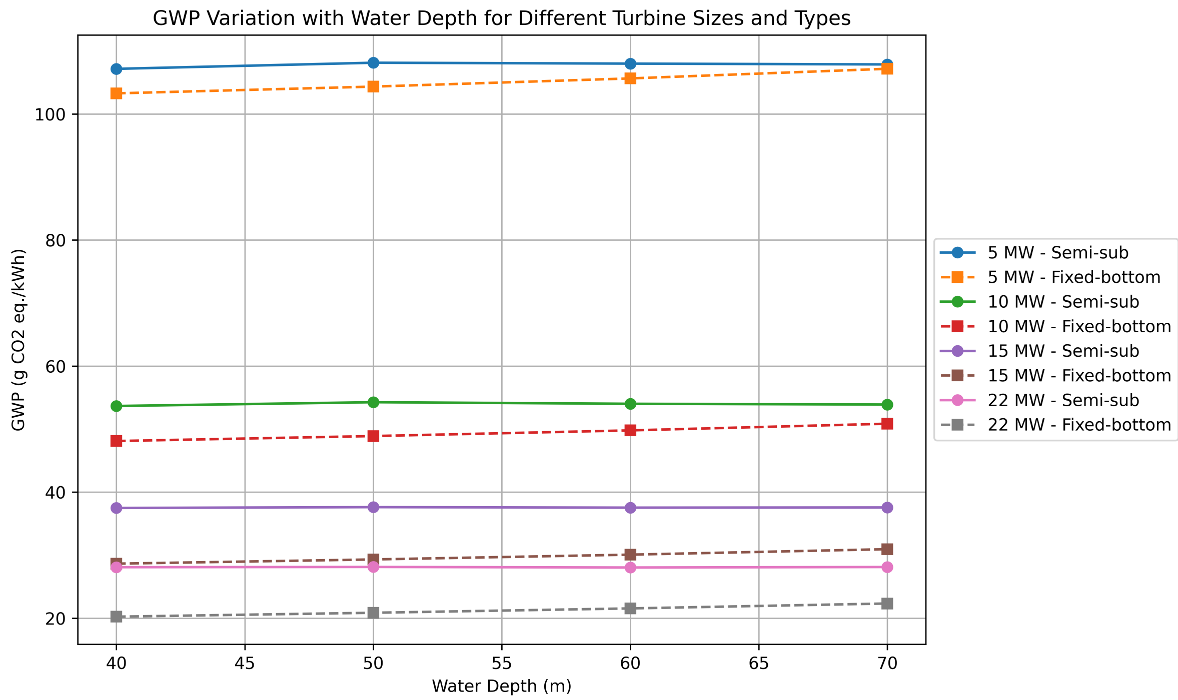


Figure 4.44: Comparison of LCOE of semi-submersible and fixed-bottom turbines of different sizes.

If LCOE is considered as the objective of the wind farm design, then the farm design with the least LCOE will be chosen. From Figure 4.43, at 70 m water depth, the cheapest design would consist of 22 MW semi-submersible floating type wind turbines. But at 60 m, the cheapest design would be 15 MW fixed-bottom turbines. Similarly, it can also be noted that after 50 m water depth, 22 MW floating wind turbines become cheaper than the 22 MW fixed-bottom turbines. Figure 4.43 can be used to select the best turbine comparison based on the availability of the turbines and the depth of water (transitional water) at the site.

If GWP is considered as the objective of the wind farm design, then the farm design with the least GWP will be chosen. In this regard, the 22 MW fixed-bottom turbines have the lowest GWP at all depths (transitional waters). It can be observed that the GWPs of fixed-bottom and floating wind turbines of 5 MW capacity at 70 m depth are very close to each other. The difference between GWPs of floating and fixed-bottom wind turbines decreases with increasing depths for other turbine sizes as well. However, the difference does not decrease as much as in the case of 5 MW turbines at 70 m depth. Furthermore, it can be observed that the GPWs of 15 MW fixed-bottom turbines and 22 MW semi-submersible turbines are also very close to each other at 40 m depth. In this case, choosing the 15 MW fixed-bottom turbine can be considered a better option as the LCOE of the farm is much lower in the case of the 15 MW configuration, although it is slightly higher in GWP. Thus, Figures 4.44 and 4.43 can be used to select the best option, based on the requirement.

4.6. Discussion Of Results

The results obtained from the MDAO frameworks depend on how the physics, economics and the optimization problem has been modeled. This leads to the scope of improving the model, increasing accuracy of scaling laws, increasing fidelity of the model, making the framework consistent with other models or some standards, etc. The scope of these improvements also show up in the results. The framework of floating wind turbines and fixed bottom wind turbines is different, and the scaling of the costs of construction, operation, and decommissioning of a wind farm is also different. Consequently, the LCOE of the farm with increasing farm size and turbine size change differently. Similarly, the construction time of the farm and the number of turbines installed per year are also modeled differently in both frameworks, leading to different trends in LCOE. The scaling of costs with turbine size is different in both frameworks. In the framework for floating wind turbines, the cost of vessels used for the construction of the farm is modeled in a deterministic way [33]. The number of vessels used for the construction of the farm is not changed when the farm size is increased, and hence it is not known what the effect of changing it would be on the LCOE. Although the cost of vessels is quite small compared to the overall cost of the wind farm, it can increase the accuracy of the results.

The layout of the wind farm is very important for the wind farm AEP and hence the LCOE and the GWP. For the framework for floating wind turbines, the layout has restrictions on entering the number of turbines in the form of a matrix, leaving the scope for numbers with more than two factors. However, the distance between the turbines is adjusted to have the highest AEP. For fixed-bottom turbines, the layout is input as a set of coordinates and an odd number of turbines can also be used with one or more turbines laying just outside the regular matrix of turbines. This gives more flexibility to the number of turbines in the farm, but it comes with the disadvantage of manually spacing the turbines. It leads to lower AEP in cases where the spacing is not appropriate and hence to a higher wake effect.

In addition, the design of floater for semi-submersible wind turbines can be done in different ways, with floaters having larger offset radius and smaller outer column radius or vice versa. Depending on the design choice, the amount of steel used and the cost of manufacturing can change, leading to a topic that can be investigated. For spar buoy type floater, the MDAO framework designs it for drafts greater than the water depth, which is not feasible. A check of this design can be implemented to prevent physically infeasible designs. However, there are checks for many other conditions, and the framework explores the design space to avoid such infeasible combinations. For example, in the case of fixed-bottom turbines, the tower design failed for 5 MW turbines at a depth of 70 m.

In summary, larger turbines in a wind farm are beneficial for the environment. Among floating wind turbines, semi-submersible wind turbines emit more GHGs and also cost more than the spar buoy type counterparts. The benefit of semi-submersible turbine is the lower draft, which makes it easy to install in transitional waters. In addition to that, the semi-submersible also compete against the fixed-bottom wind turbines in transitional waters, where fixed-bottom turbines increase in cost rapidly and also have more emissions with small changes in depth. Conclusion of all the research work is described in the next chapter. A future scope of work is also mentioned, which highlights the direction in which this work can be progressed.

5 Conclusion and Future Scope of Work

This chapter synthesizes and concludes the research conducted in this study, with a focus on addressing the research questions and summarizing the key observations and results. It also outlines the potential directions for future work, presenting possible next steps to extend the study. Finally, opportunities for improving the models are identified to enhance their consistency, robustness, and accuracy.

5.1. Conclusion

With an increasing mean temperature of the Earth's surface, the threat to living organisms is increasing, and energy is an important factor in it. With an increasing population and development of people and countries, the demand for energy is increasing. To meet the demand and prevent global warming at the same time, switching to renewable sources of energy is an important alternative. In this regard, wind energy has immense potential in providing clean energy to meet the demand. However, even though wind energy is much cleaner than conventional sources of energy, there are some impacts on the environment. These impacts range from emissions of greenhouse gases and toxic chemicals to behavioral changes and habitat alteration in animals, birds, fishes and water mammals. Among all the impacts, the direct impact on living organisms is still under study, with uncertainty in its effect (positive or negative) and intensity, and lack of generalization for all species or individuals of a species. Thus, quantifying direct impacts on living beings is difficult. In addition, currently, the greatest impact on the environment seems to be the GHG emissions from wind turbines.

Greenhouse gases are emitted during the manufacturing, transportation, installation, maintenance, and decommissioning of wind turbines. The end-of-life use of turbine components also significantly changes the emissions. It has been observed that the emissions are heavily dependent on the amount of material used in a wind farm. Consequently, it is important to compare wind farm designs consisting of fewer number of larger turbines or more number of smaller turbines to have the least emissions over the lifetime. Quantifying the emissions from turbines is done using life cycle assessments, in which the entire life of the turbine is studied and all emissions from different processes are calculated. This concept is used as an inspiration to quantify the environmental impacts of the wind farm and use it in MDAO frameworks to assess wind farm designs. This leads to the answer to the first research question: How can environmental impacts be quantified? Several LCAs from Vestas have been compiled and their GWP have been analyzed. From the GWP, the total GHG emission from the farm has been calculated and a relation has been developed between the GHG emissions and the amount of materials used in the wind farm. This relation is further used to estimate the GHG emissions of other farm designs, and from this the GWP of the new farm is calculated. The GWP is used as the metric to compare the designs. The estimated GWP is validated from other studies to ensure that the method is correct.

The second research question investigates whether there is only one metric that can capture all the environmental impacts of wind farm designs. Like GWP, there are other parameters that quantify other impacts such as eutrophication, acid rain, water eco-toxicity, etc. These metrics can also be estimated and used in a similar way to that of GWP. It has not been used in the current study but has been explored on how to calculate and use it in the framework. In the current thesis, the most important impact has been captured, but using other metrics can capture other impacts on the environment.

The third research question investigates the method by which the metric can be included in the MDAO framework. The metric is calculated using the results of the framework, extracting design values, and using it in the relation developed from the LCAs. The estimated GWP of a wind farm design is compared to the GWP of another wind farm design. The wind farm design is manually changed because the framework is required to be given a set of input. By varying the turbine sizes in the wind farm, several insights are obtained, many of which suggest that using fewer number of larger turbines in a farm is better than using more number of smaller turbines, given the farm capacity remains the same. The method has been used in two frameworks, for floating wind turbines and for fixed-bottom wind turbines. The framework designs the wind farm by minimizing the LCOE and not the GWP, since the LCOE is still an important metric. The new metric, GWP, is used to compare wind farm designs and evaluate design choices.

The fourth question is to investigate how the wind farm design compares when the metric is used in the framework. To answer this question, the metric is used as an indicator to compare designs, though the basic design consisting of the number of turbines and the size of turbines is manually changed. The type of turbine is also changed and three types are compared. The resulting designs are also compared on the basis of LCOE to consider one of the most important drivers. This gives a set of options to consider the design choices, the availability of the turbine models, and the site conditions. Choosing the type of turbine and wind farm design in transitional waters can become complicated and the results obtained from the MDAO can act as a guide to select the design based on what the priority is. Overall, as mentioned before, it can be concluded from the study that larger turbines are better than smaller ones in terms of greenhouse gas emissions.

In summary, this thesis demonstrates that using insights from LCAs offers a viable method to quantify the environmental impacts of wind farms and integrate them into MDAO frameworks. Keeping LCOE as the objective ensures economic feasibility, while incorporating metrics such as GWP allows for more sustainable design choices. There is always room to improve and advance the work that has already been done. In this regard, the following topics can be worked upon:

1. other metrics can also be incorporated and used to compare turbines based on different priorities. For example, eutrophication potential, water eco-toxicity, acidification potential, etc.
2. the frameworks can be made more consistent with each other, resulting in fewer abnormalities in the results. Having similar installation parameters and processes, scaling of costs, layouts, etc. will give results that can be compared even better
3. the framework can also be modified to change the objective function of the optimization problem to obtain the lowest GWP or to have multiple objective functions (both LCOE and GWP or some other metric)

5.2. Future Scope Of Work

The current thesis investigates how the environmental impact can be captured in the form of a metric and how it can be used in the MDAO framework. The framework still uses LCOE as the objective of the optimization problem, which means the impact of the cheapest wind farm design is estimated and compared to other designs. In continuation of the work, the objective of the optimization problem can be changed from LCOE to GWP, leading to the greenest design instead of the cheapest design. This can be compared to the designs in which the lowest LCOE was the objective. Furthermore, the optimizer used in the framework is COBYALA which supports only one objective function, and if a different optimizer can be used which supports multiple objectives, then a design can be optimized for both the lowest LCOE and the lowest GWP. However, since LCOE is also dependent on the cost of the material and hence the amount of material, the design should not vary drastically when the objective function is changed to minimize the GWP. Furthermore, the estimation of GWP can be improved by adding the mass of cables, polymers used in cables, ballast mass, etc. There are other parameters such as water eco-toxicity, acidification potential, eutrophication potential, etc. that can be added to the MDAO framework as well. Since all of these parameters depend on the mass of specific materials used, they can be estimated using the same methodology as that of GWP. This will give a more complete list of impacts, rather than just the emissions. Certain impacts that are still under study can also be added to the framework, the easiest and most popular being the collision of birds. Since there is already a model [23] to calculate the probability of collision of birds, it can be added to the framework, with an assumed spatial distribution of birds. The frameworks can also be made more uniform in terms of options and flexibility, such as the optimization of layout, scaling of costs, etc. The frameworks can also be made more uniform in terms of options and flexibility, such as the optimization of layout, scaling of costs, etc.

The framework is now in the form of a script, and there is work going on to add a user-interface to it. Estimated environmental impact can be added to the interface to give the user an idea of the emissions from the wind farm. The user interface is also being developed only for fixed-bottom wind turbines but an interface for floating wind turbines can also be built, leading to the comparison of impacts from either type of turbines.

The insights and methods presented in this thesis hope to contribute to making the development of wind turbines and wind farms cleaner, greener, and more aligned with global Net Zero Emissions targets.

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A

Appendix A

Table A.1: Design equations for Vryhof drag anchors [42].

Anchor Type	Soil Type	Metric Units		US Customary Units	
		a	b	a	b
Stevin MK3	Very Soft Clay	161.23	0.92	17.51	0.92
	Medium Clay	229.19	0.92	24.90	0.92
	Sand and Hard Clay	324.42	0.90	35.80	0.90
Stevpris MK5	Very Soft Clay	392.28	0.92	42.61	0.92
	Medium Clay	552.53	0.92	60.02	0.92
	Sand and Hard Clay	686.49	0.93	73.98	0.93
Stevpris MK6	Very Soft Clay	509.96	0.93	54.96	0.93
	Medium Clay	701.49	0.93	75.60	0.93
	Sand and Hard Clay	904.21	0.92	98.22	0.92

Notes:

- UHC (Ultimate Holding Capacity): kN (metric), kips (US)
- W (Anchor Weight): MT (1–50 MT), kips (1–110 kips)
- Design equation: UHC = $a \cdot W^b$

Continued Below

Table A.2: Life cycle assessment parameters for different wind turbine models in different wind farms [16].

Model Name	Year	Power (MW)	Rotor Dia. (m)	Plant Cap. (MW)	Energy (GWh)	Steel (t)	Concrete (t)	Polymer (t)	ADP Elem.	ADP Foss.	AP (SO2)	EP (PO4)	FAETP (DCB)	GWP (CO2)	Total GHG (t)
V100-1.8	2011	1.8	100	50	3756	6872	21230	1251	0.53	0.13	42	4.2	110	9.3	34930.8
V80-2.0	2011	2	80	50	4135	7404	27633	1218	0.44	0.1	37	3.7	100	7.7	31839.5
V90-2.0	2011	2	90	50	3129	6139	18772	1279	0.58	0.13	45	4.5	130	9.7	30351.3
V100-2.0	2015	2	100	50	4200	5360	20067	552	0.06	0.08	28	3.3	55	6.2	26040
V110-2.0	2015	2	110	50	3783	5860	22836	681	0.06	0.1	32	3.7	62	7.2	27237.6
V116-2.0	2018	2	116	50	4877	6147	18328	546	0.08	0.07	18	2.2	48	5.1	24872.7
V120-2.0	2018	2	120	50	4394	8371	22807	564	0.08	0.09	24	2.9	58	6.7	29439.8
V100-2.6	2013	2.6	100	90	6121	9799	34520	410	0.4	0.1	36	3.9	54	7.9	48355.9
V90-3.0	2013	3	90	90	6514	8419	29600	428	0.31	0.08	29	3.1	43	6.2	40386.8
V105-3.3	2014	3.3	105	100	8146	11093	29289	896	0.17	0.08	24	2.6	40	5.2	42359.2
V126-3.45	2018	3.45	126	90	9078	14125	40049	993	0.23	0.11	30	3.5	46	6.6	54880.2
V136-4.0	2018	4	136	120	12997	18856	47436	1050	0.17	0.07	18	2.1	28	3.8	56299.2
V150-4.2	2019	4.2	150	252	23420	22772	52974	1124	0.1	0.06	12	1.5	18	2.5	63613.4
V150-5.6	2020	5.6	150	392	37944	36288	72895	1238	0.1	0.06	11	1.3	15	2.1	91883.2
V162-5.6	2021	5.6	162	336	38800	37110	71589	1162	0.1	0.05	9	1.1	13	1.8	89463.2
V172-7.2	2022	7.2	172	936	78600	62567	112709	3997	0.16	0.05	9	1.2	15	2	182204
V162-7.2	2023	7.2	162	792	74500	66590	105689	3504	0.12	0.04	8	1.1	13	1.7	173126
V164-8.0	2014	8	164	480	59904	67552	108974	2863	0.12	0.04	7	1	11	1.6	179377.9
V164-9.5	2017	9.5	164	570	77472	64594	120295	3089	0.09	0.04	6	0.8	9	1.2	187091.6
V174-9.5	2019	9.5	174	570	78900	65169	123086	3092	0.09	0.04	6	0.8	9	1.2	190506
V236-15 (30 yr)	2024	15	236	990	125600	216290	12000	13723	1.21	0.11	28	4.5	37	7	879200

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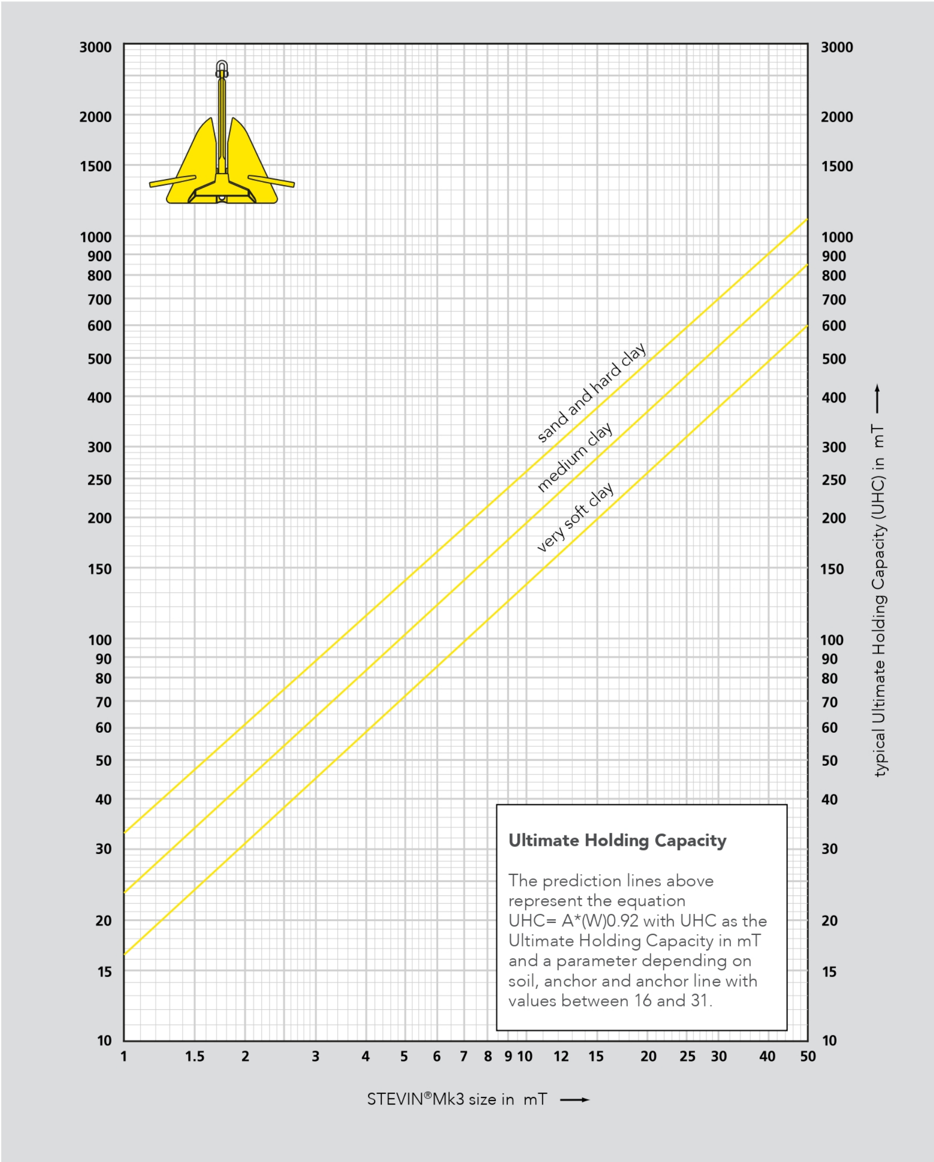
STEVIN®Mk3
UHC CHART



The STEVIN®Mk3 design line very soft clay represents soils such as very soft clays (mud), and loose and weak silts.
The line is applicable in soil that can be described by an undrained shear strength of 4 kPa at the surface increasing by 1.5 kPa per meter depth or in the equation Su = 4+1.5*z. with Su in kPa and z being the depth in meters below seabed. In very soft soils the optimum fluke/shank angle is typically 50°.

The design line 'sand' represents competent soils, such as medium dense sands and stiff to hard clays and is based on a silica sand of medium density. In sand and hard clay the optimal fluke/shank angle is 32°.

The 'medium clay' design line represents soils such as silt and firm to stiff clays. The fluke/shank angle should be set at 32° for optimal performance.

VRYHOF MANUAL

Figure A.1: Stevin MK3 drag anchor UHC and weight chart [38]

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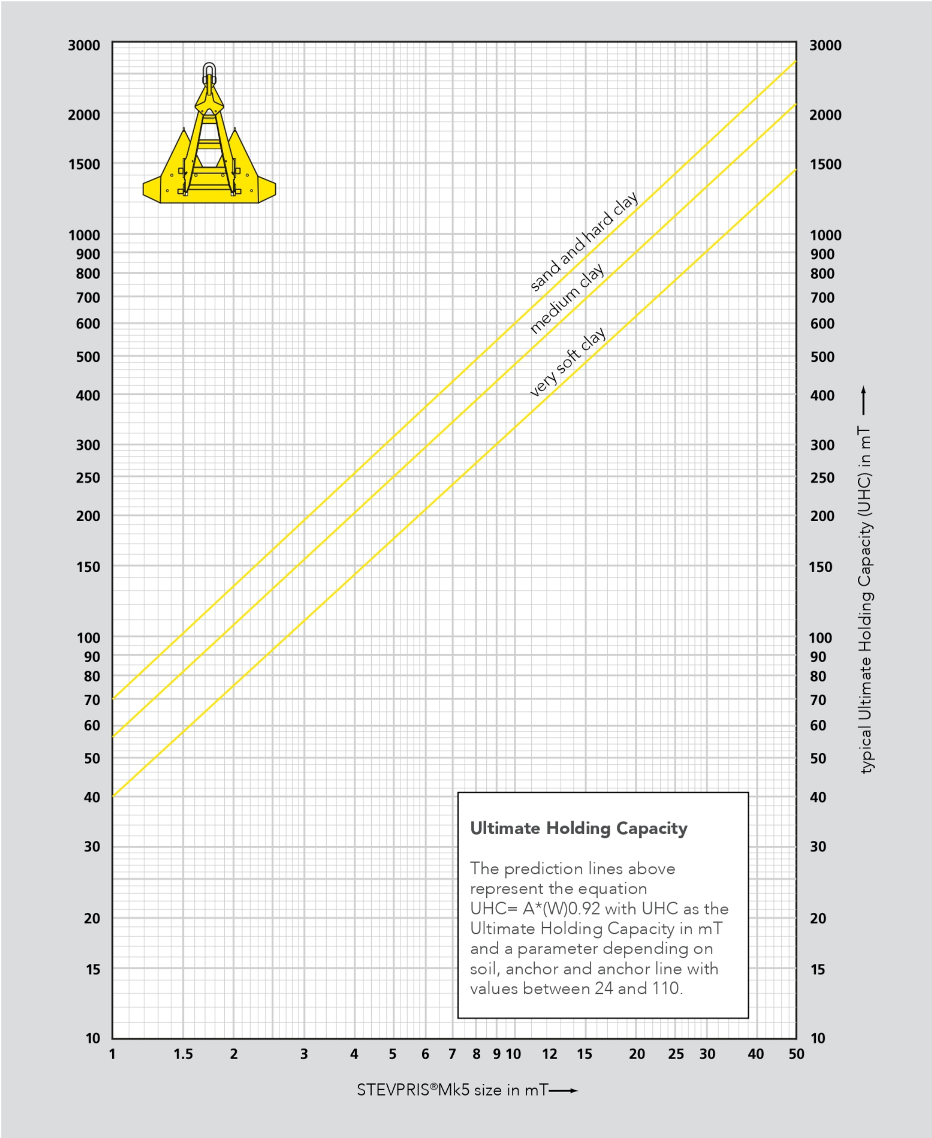
STEVPRIS®Mk5
UHC CHART



The STEVPRIS®Mk5 design line very soft clay represents soils such as very soft clays (mud), and loose and weak silts.
The line is applicable in soil that can be described by an undrained shear strength of 4 kPa at the surface increasing by 1.5 kPa per meter depth or in the equation Su = 4+1.5*z. with Su in kPa and z being the depth in meters below seabed. In very soft soils the optimum fluke/shank angle is typically 50 deg.

The design line sand represents competent soils, such as medium dense sands and stiff to hard clays and is based on a silica sand of medium density. In sand and hard clay the optimal fluke/shank angle is 32°.

The medium clay design line represents soils such as silt and firm to stiff clays. The fluke/shank angle should be set at 32° for optimal performance.

VRYHOF MANUAL

Figure A.2: Stevpris MK5 drag anchor UHC and weight chart [38]

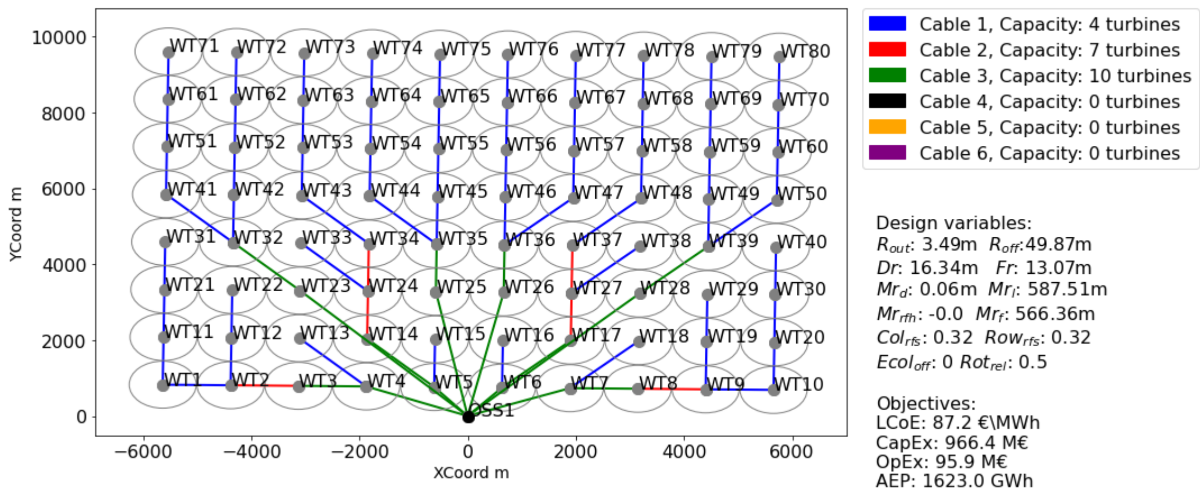


Figure A.3: Floating wind farm design of a 400 MW farm at 100 m water depth consisting of 5 MW semi-submersible type turbines.

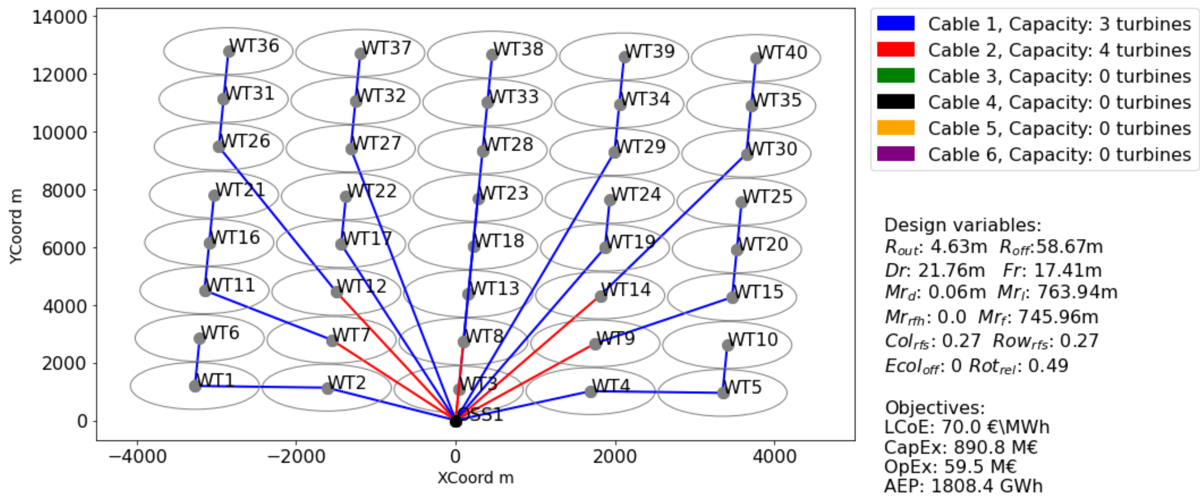


Figure A.4: Floating wind farm design of a 400 MW farm at 100 m water depth consisting of 10 MW semi-submersible type turbines.

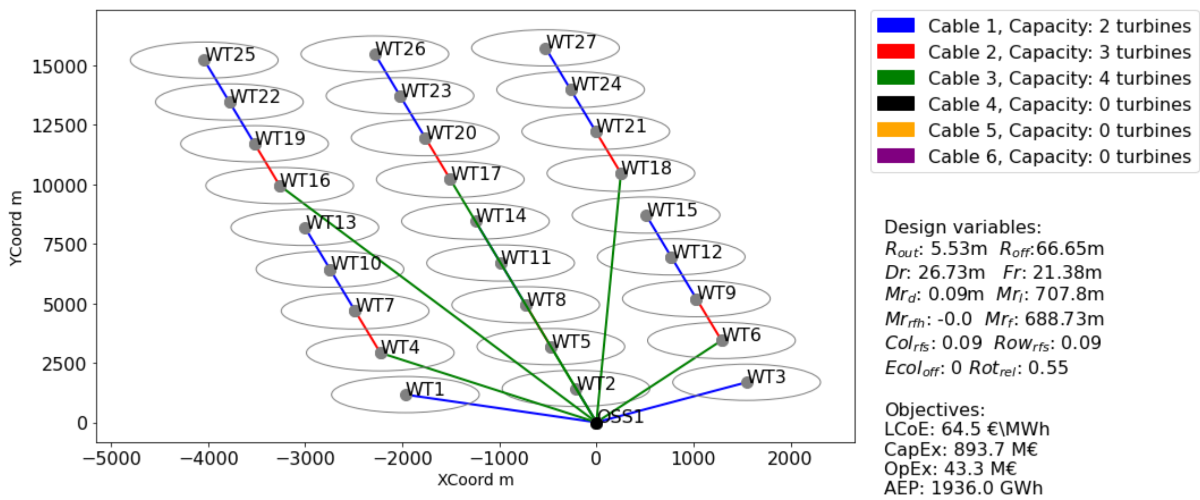


Figure A.5: Floating wind farm design of a 400 MW farm at 100 m water depth consisting of 15 MW semi-submersible type turbines.

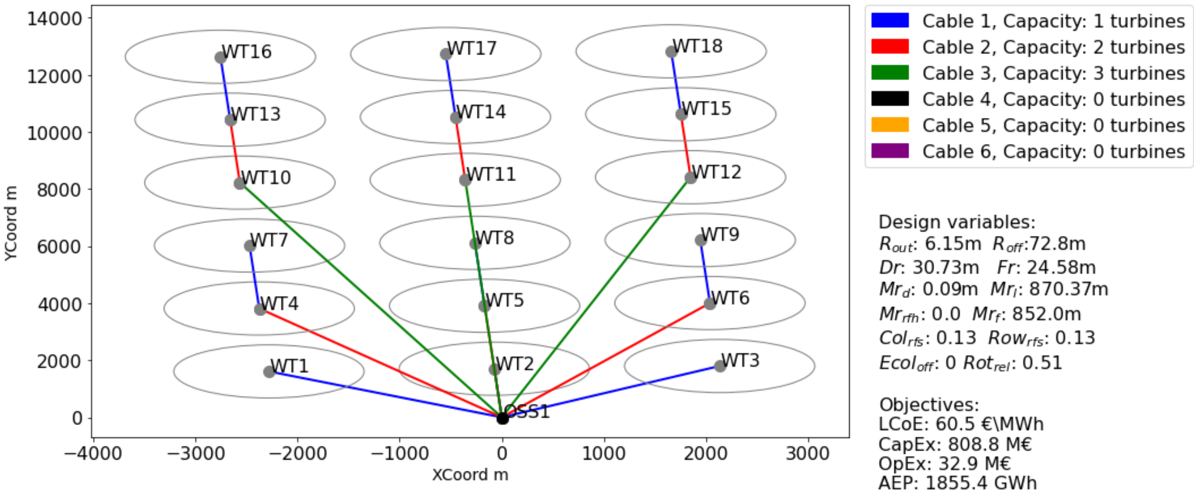


Figure A.6: Floating wind farm design of a 400 MW farm at 100 m water depth consisting of 22 MW semi-submersible type turbines.

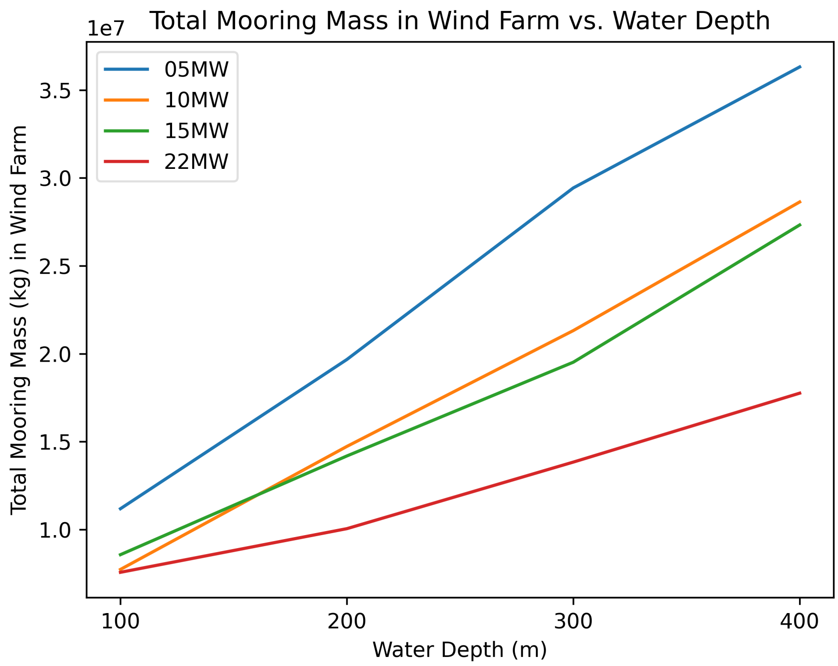


Figure A.7: Variation in total mooring mass in farm with depth of water for farms made of semi-sub type turbines with different ratings.

Table A.4: Farm GWP (g CO_2 eq./kWh) as a function of turbine (spar buoy type) rating and operational lifetime of farm.

Lifetime (years)	5 MW	10 MW	15 MW	22 MW
25	105.91	51.99	34.64	25.49
30	88.21	43.33	28.98	21.22
35	75.59	37.10	24.86	18.14
40	66.24	32.48	21.65	15.85

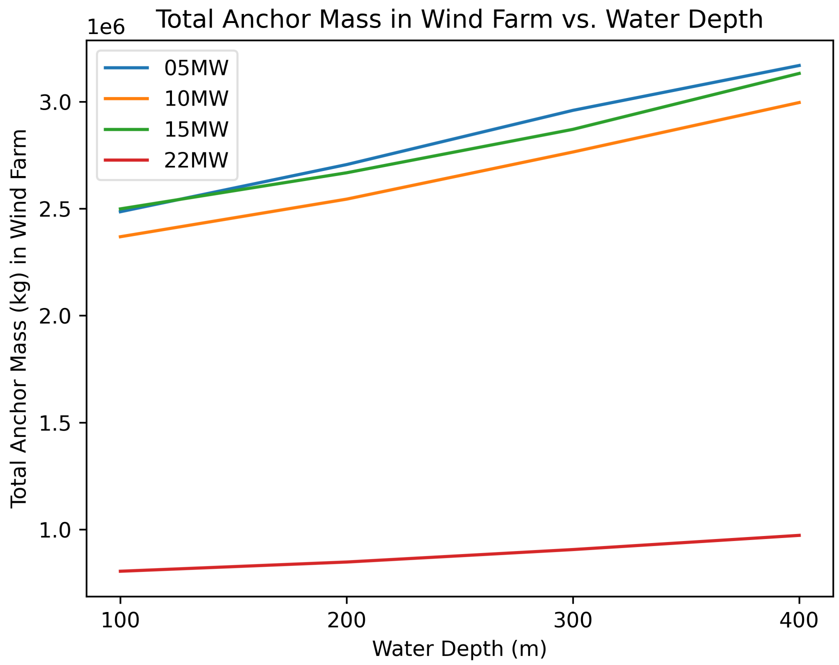


Figure A.8: Variation in total anchor mass in farm with depth of water for farms made of semi-sub type turbines with different ratings.

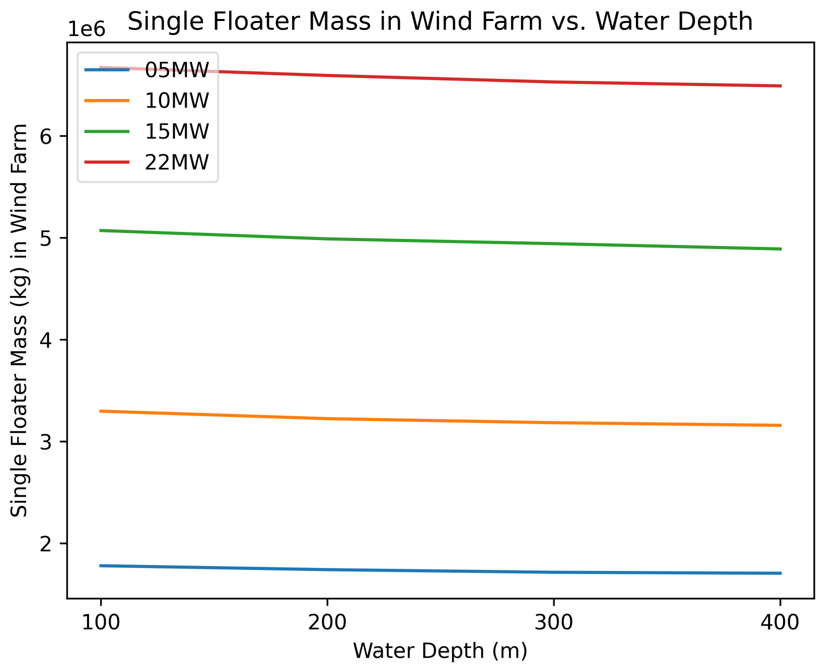


Figure A.9: Variation in floater mass of turbine with depth of water for farms made of semi-sub type turbines with different ratings.

Table A.5: Farm LCOE (€/MWh) as a function of turbine (spar buoy type) rating and operational lifetime of farm.

Lifetime (years)	5 MW	10 MW	15 MW	22 MW
25	81.43	63.66	55.86	52.64
30	78.27	61.56	53.90	50.84
35	76.78	60.29	52.82	49.84
40	75.87	59.58	52.19	49.18

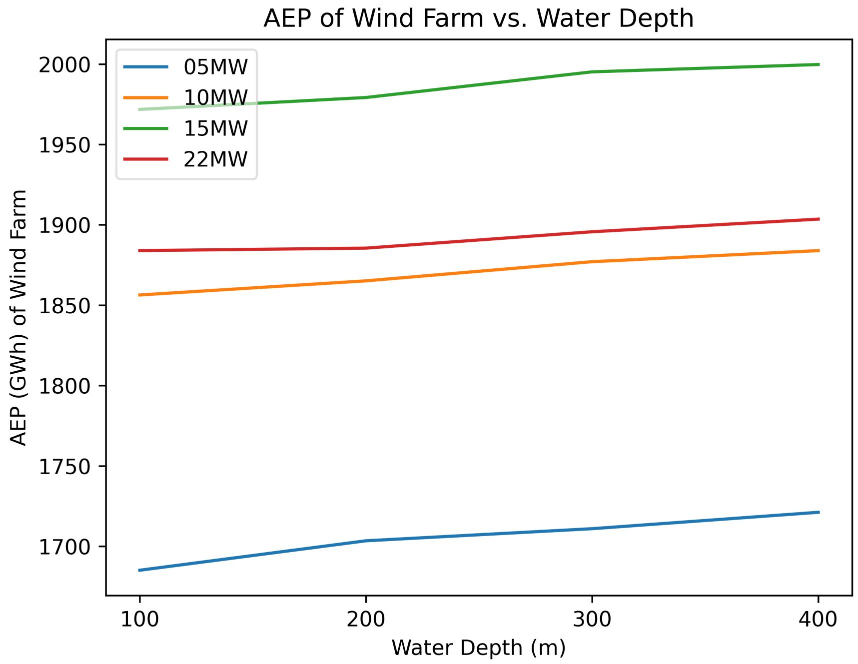


Figure A.10: Variation in AEP of farm with depth of water for farms made of semi-sub type turbines with different ratings.

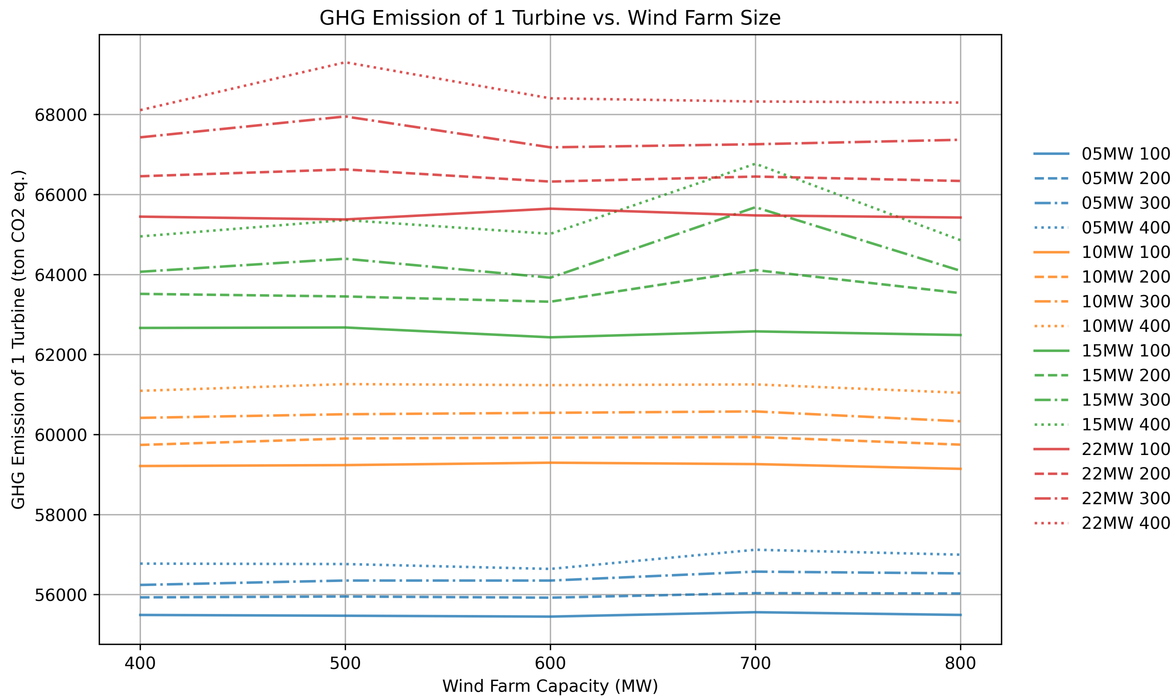


Figure A.11: Variation in GHG emissions from a single spar type turbine when the capacity of wind farm is changed.

Table A.6: Farm OPEX (Million Euros) as a function of turbine (spar buoy type) rating and operational lifetime of farm.

Lifetime (years)	5 MW	10 MW	15 MW	22 MW
25	137.67	90.15	71.70	59.89
30	140.76	93.63	73.73	62.70
35	143.68	96.25	75.02	63.89
40	145.64	97.28	77.10	65.24

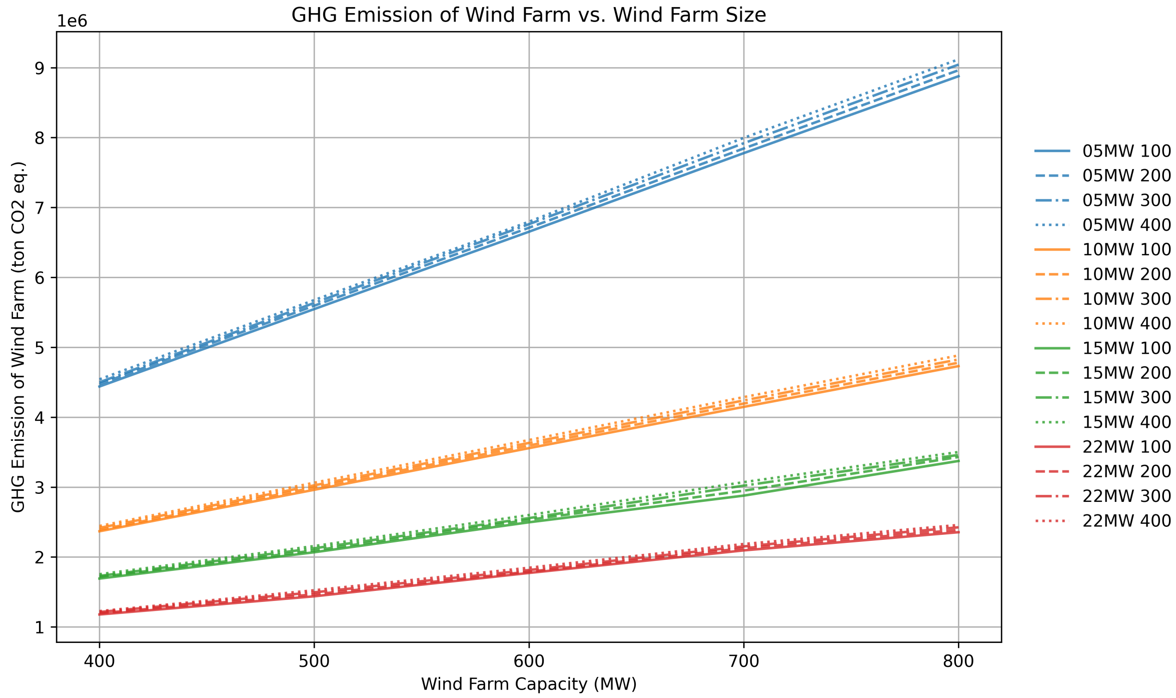


Figure A.12: Variation in GHG emissions from the wind farm with different turbine (spar buoy type) ratings when the capacity of wind farm is changed.

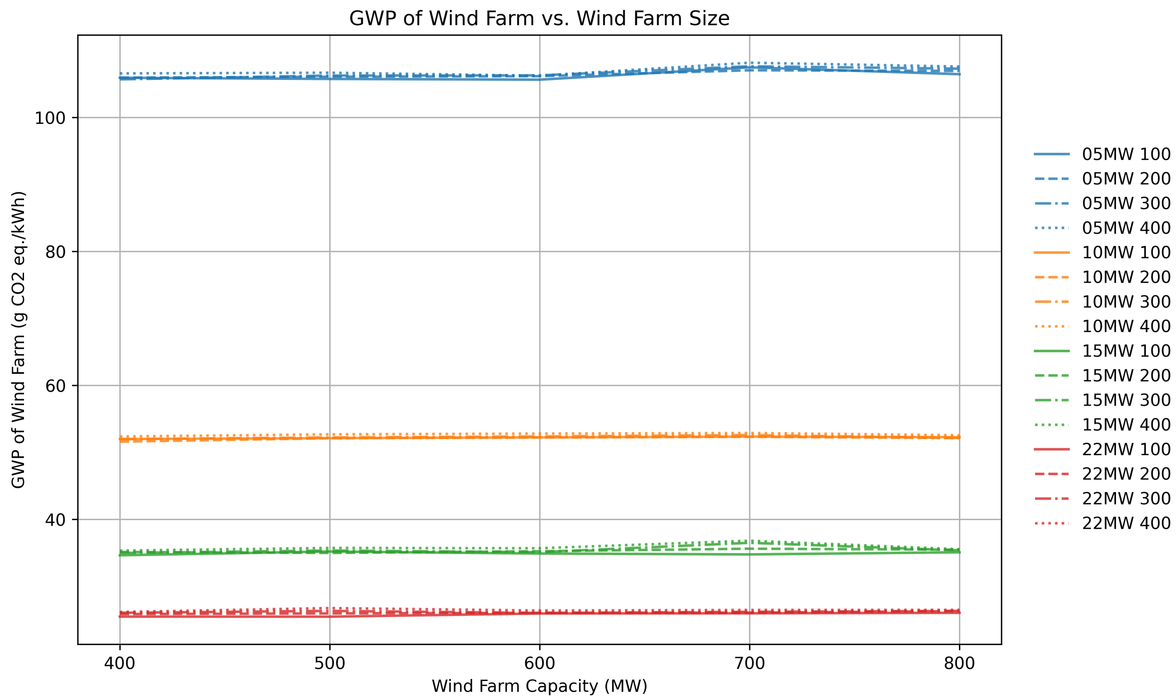


Figure A.13: Variation in GWP of the wind farm with different turbine (spar buoy type) ratings when the capacity of wind farm is changed.

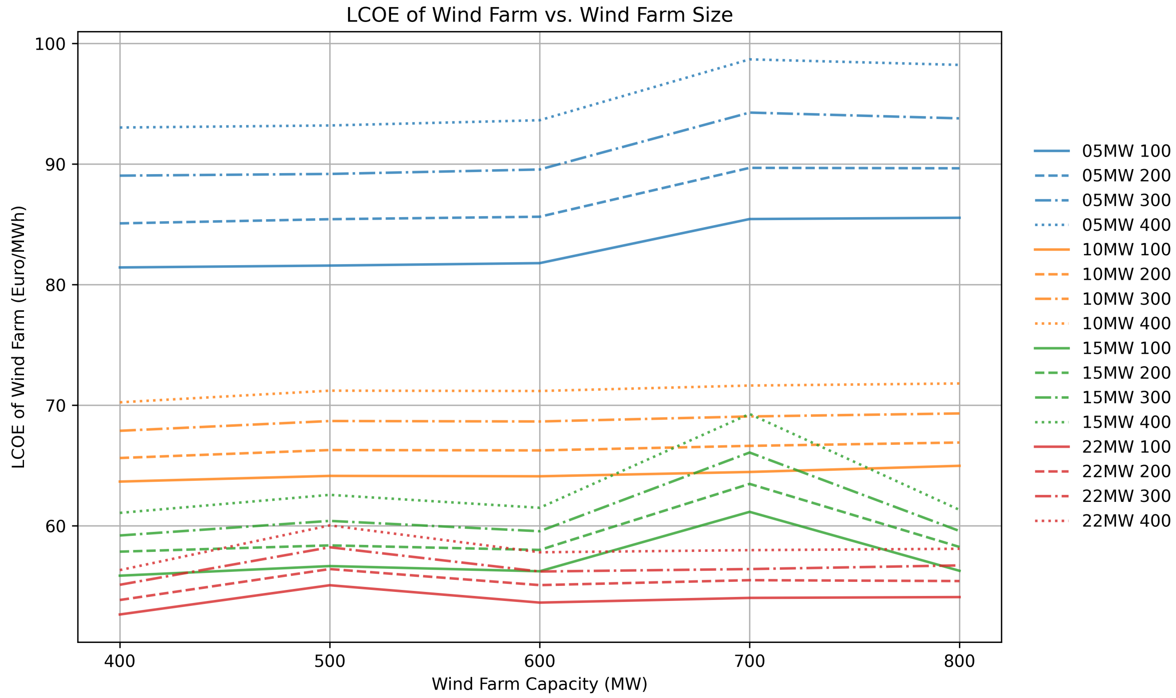


Figure A.14: Variation in LCOE of the wind farm with different turbine (spar buoy type) ratings when the capacity of wind farm is changed.

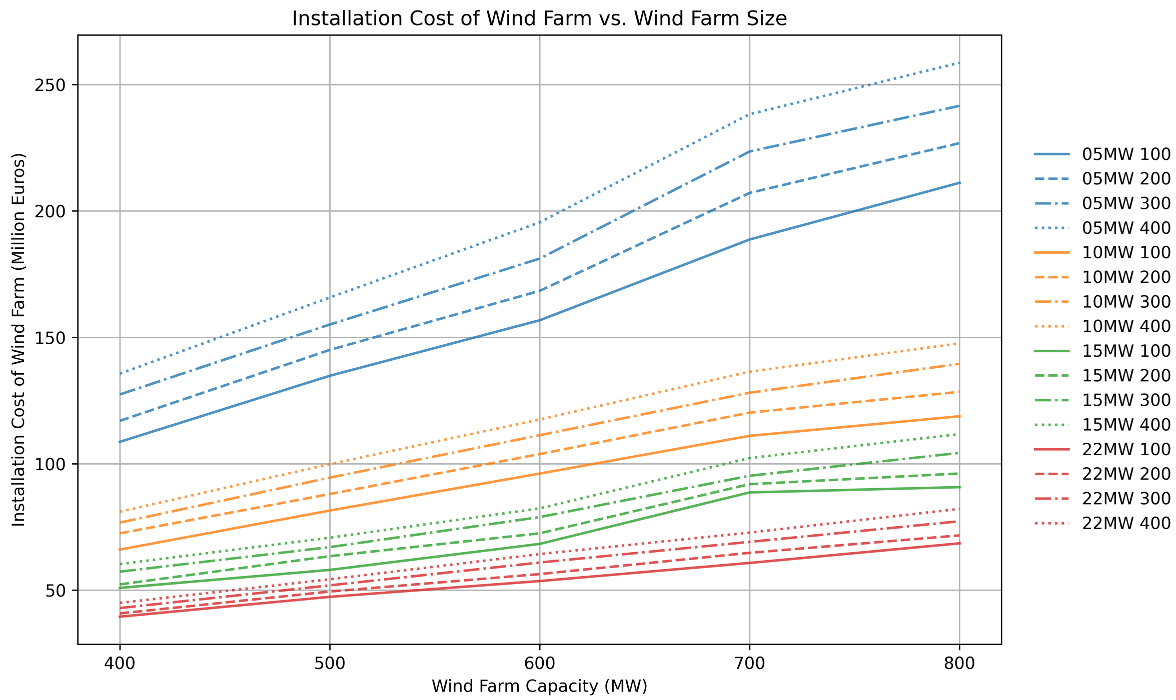


Figure A.15: Variation in installation cost of the wind farm with different turbine (spar buoy type) ratings when the capacity of wind farm is changed.

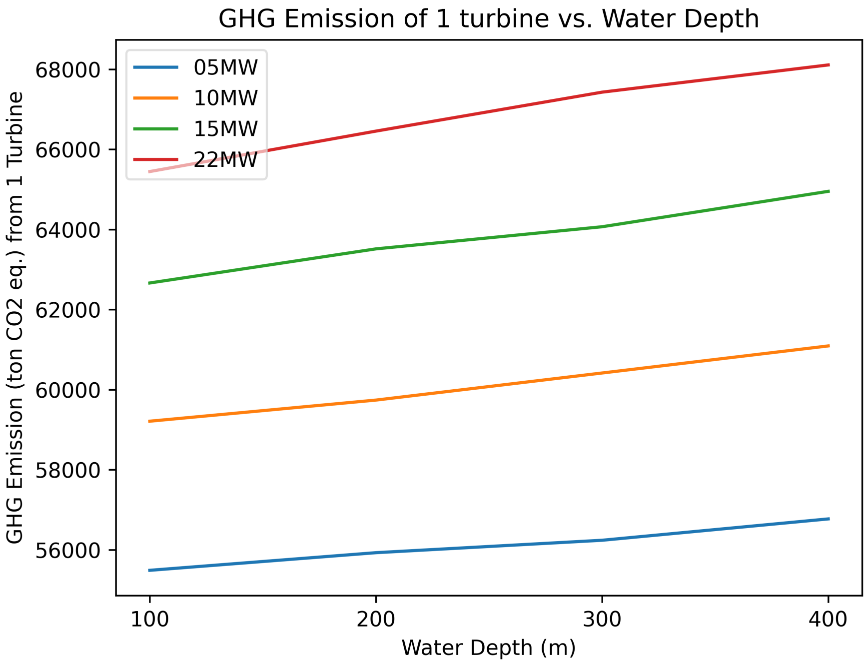


Figure A.16: Variation in GHG emissions with depth of water for spar type turbines with different ratings.

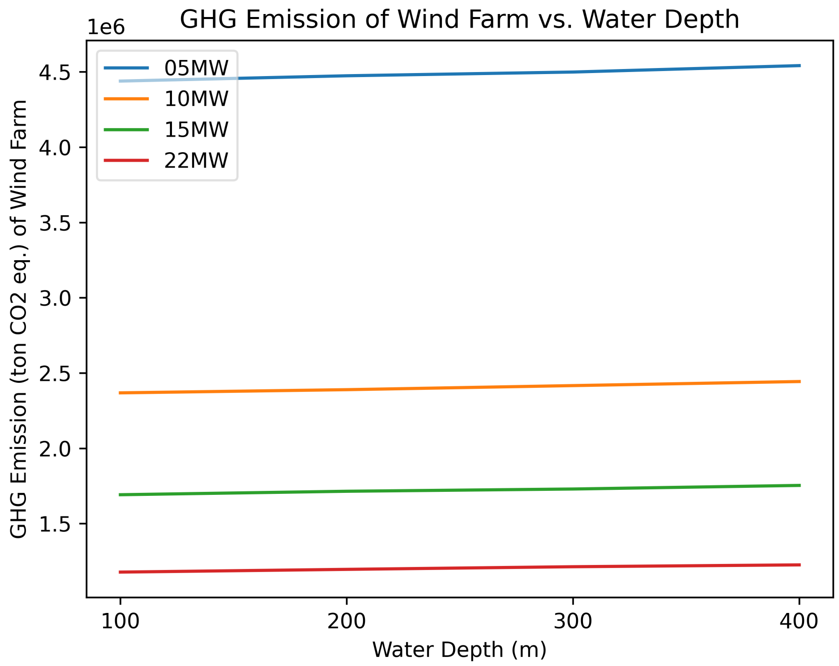


Figure A.17: Variation in GHG emissions with depth of water for wind farms made of spar type turbines with different ratings.

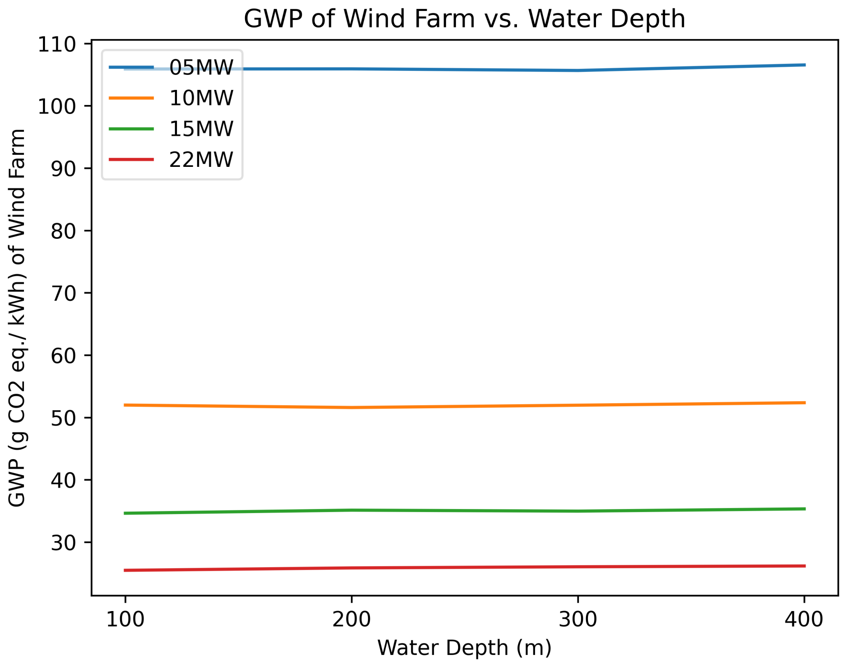


Figure A.18: Variation in GWP with depth of water for farms made of turbines with different ratings.

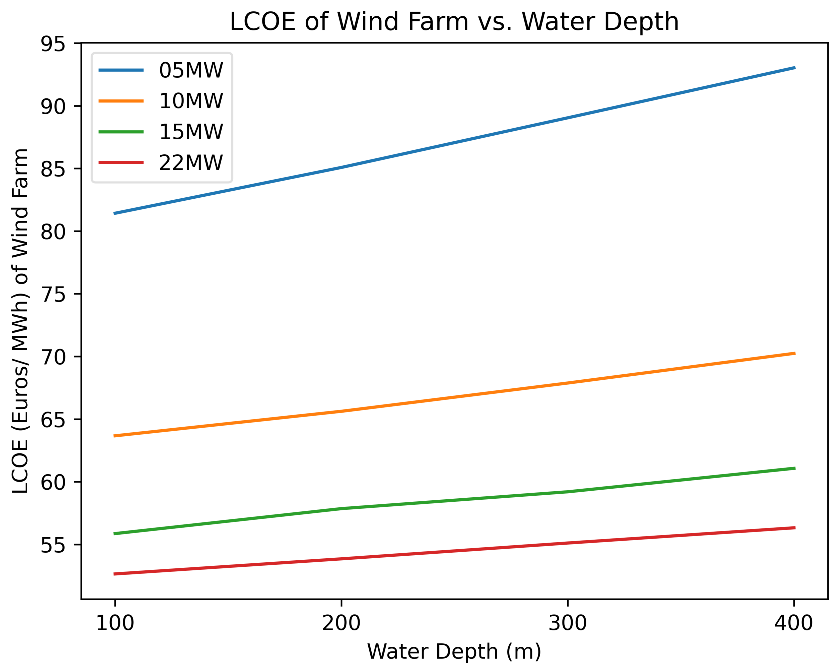


Figure A.19: Variation in LCOE with depth of water for farms made of spar type turbines with different ratings

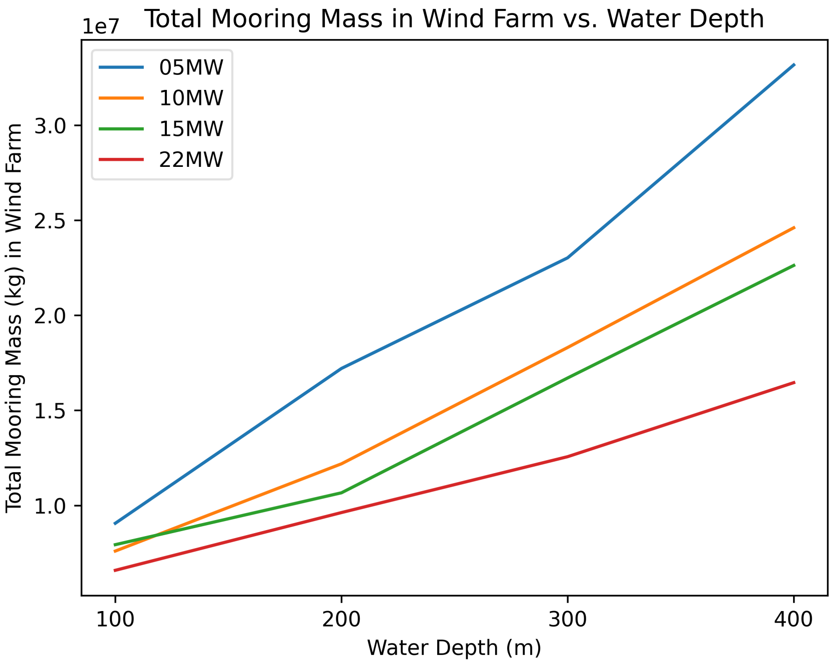


Figure A.20: Variation in total mooring mass in farm with depth of water for farms made of turbines with different ratings.

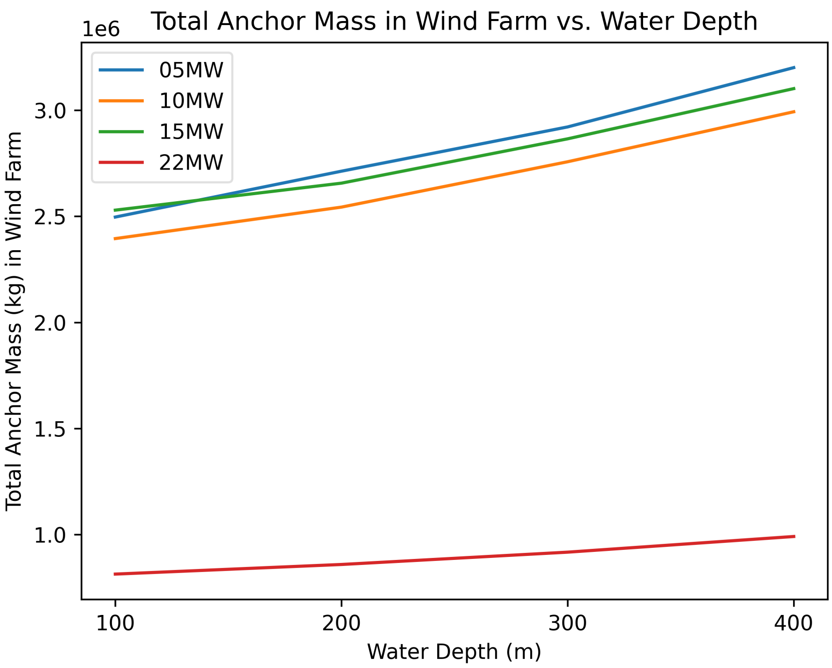


Figure A.21: Variation in total anchor mass in farm with depth of water for farms made of turbines with different ratings.

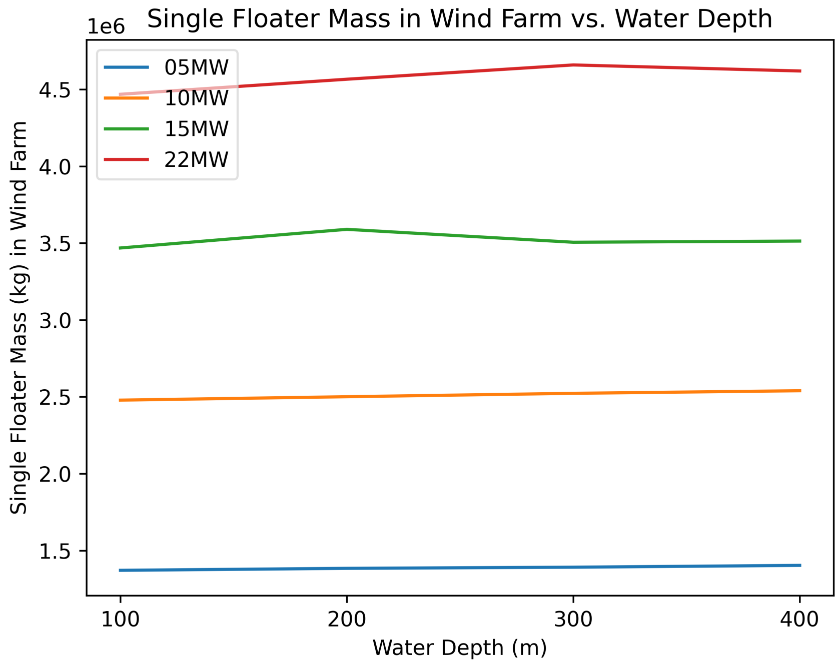


Figure A.22: Variation in floater mass of turbine with depth of water for farms made of turbines with different ratings.

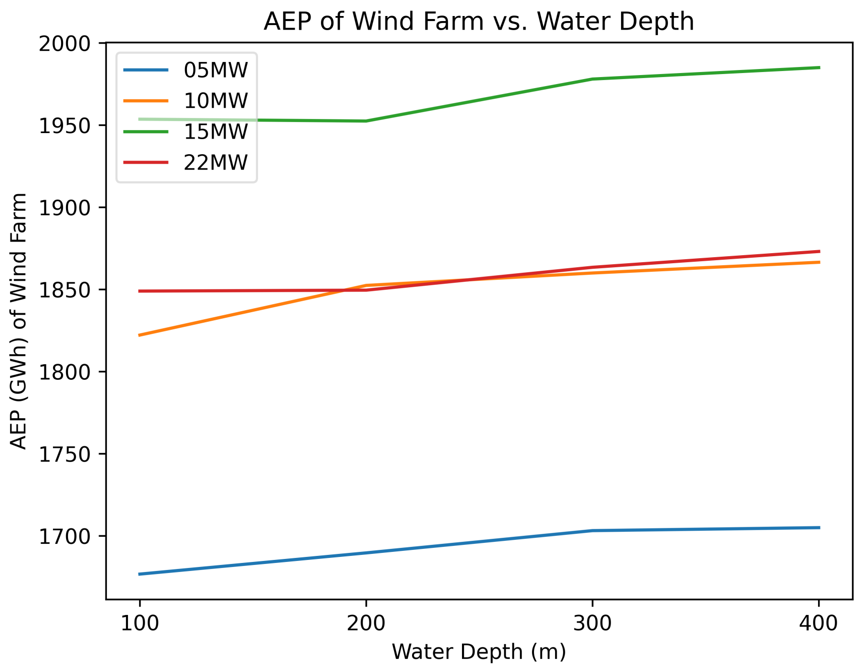


Figure A.23: Variation in AEP of farm with depth of water for farms made of turbines with different ratings.

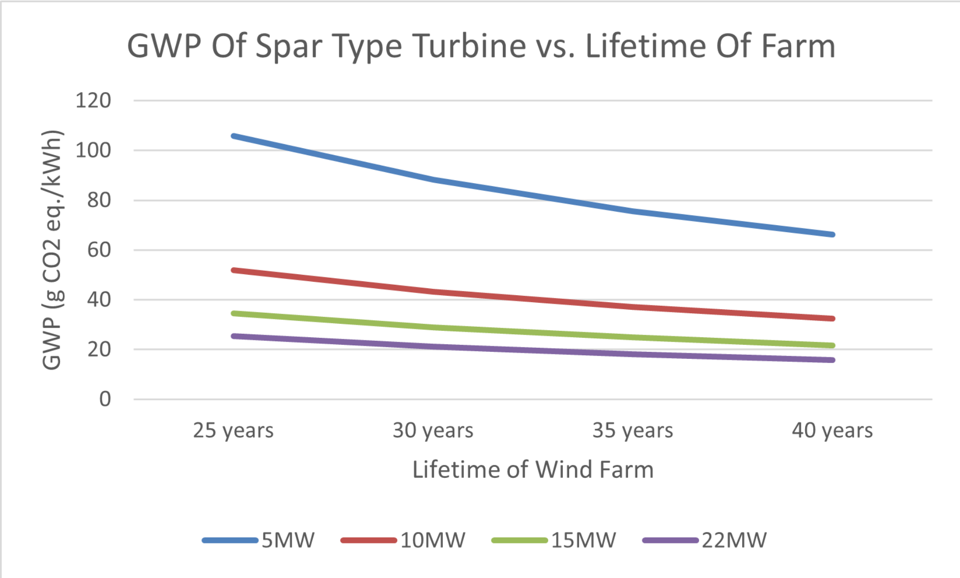


Figure A.24: Farm GWP (g CO_2 eq./kWh) as a function of turbine (spar buoy type) rating and operational lifetime of the farm.

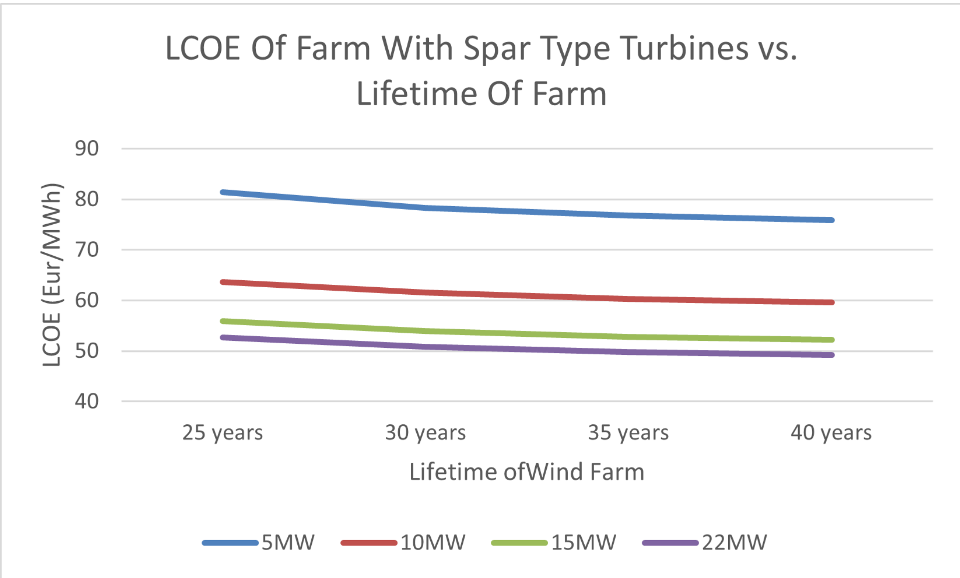


Figure A.25: Farm LCOE (Eur/MWh) as a function of turbine (spar-buoy type) rating and operational lifetime of the farm.

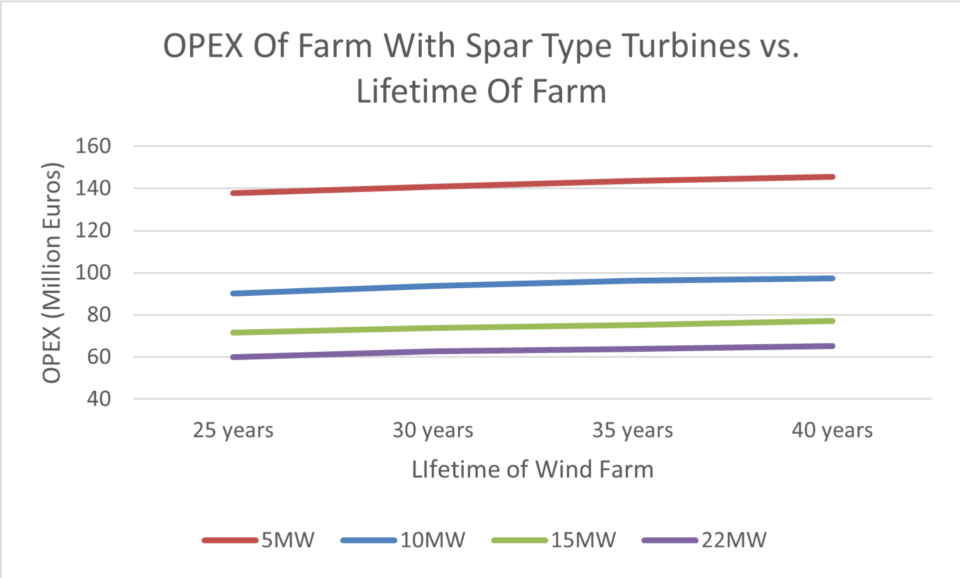


Figure A.26: Farm OPEX (Million Euros) as a function of turbine (spar buoy type) rating and operational lifetime of the farm.

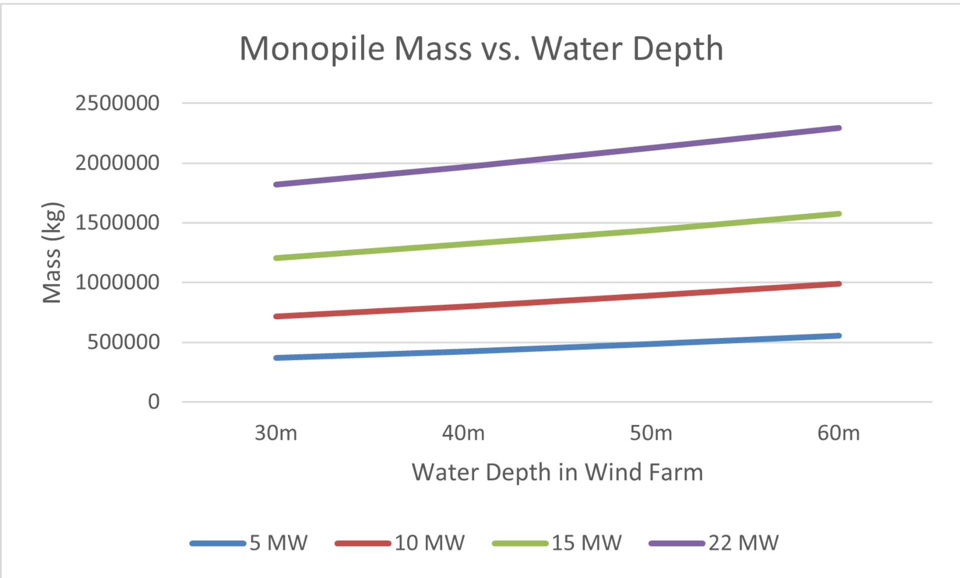


Figure A.27: Variation in monopile mass of fixed turbines with increasing water depth.

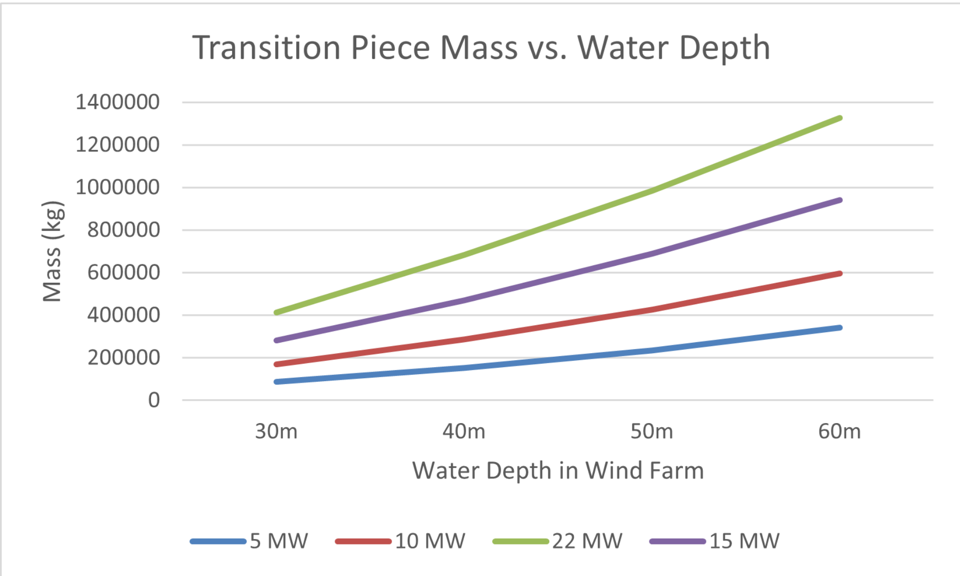


Figure A.28: Variation in transition piece mass of fixed turbines with increasing water depth.