A Methodology to Calculate the Greenhouse Gas Emissions of the Offshore Wind Turbine Installation Process in an Early Design Phase

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A Methodology to Calculate the Greenhouse Gas Emissions of the Offshore Wind Turbine Installation Process in an Early Design Phase

by

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Abstract

With the European Union targeting a 55% reduction in greenhouse gas (GHG) emissions by 2030, the shift to renewable energy sources like offshore wind is crucial. Another consequence of the 55% reduction goal is the new upcoming registration and levy on carbon emissions. Since there is a noticeable lack of research on the emissions from the installation offshore wind farms, and marine contractors will have to pay for those emissions in the near future, there is a need for a framework to predict those emissions prior to the installation process. This thesis aims to develop such a framework to predict GHG emissions during the installation process using Wind Turbine Installation Vessels (WTIVs).

The study starts with a review of current methods for calculating maritime GHG emissions, following the EU Emissions Trading System (ETS) guidelines. It then looks at the steps and technology involved in offshore wind farm installations, pinpointing the main energy consumers. Using a physics-based approach, the model estimates fuel consumption and the the GHG emissions for the installation of wind turbines for an offshore wind farm.

For the complete installation of 50 wind turbines, the model predicts a total effective energy requirement of approximately 408,000 kWh, leading to GHG emissions of around 312,533 kg CO2. The results highlight the significant impact of activities like vessel transit and auxiliaries on total emissions. The sensitivity analysis performed identifies critical parameters influencing the model's accuracy, such as vessel speed, jack-up height, and crane efficiency. The model's validation through a real-world case study for the crane part of the developed model shows its accuracy in predicting emissions.

The thesis ends with suggestions for improving the model and finding ways to reduce emissions in offshore wind installations. This involves the validation of the other aspects of the model, technology upgrades, and checking if feedering might me an interesting solution to reduce the impact on the environment even more.

Overall the developed model for the prediction of greenhouse gas emissions proves to be a stable framework that could be used in the future by marine contractors when negotiating contracts and installation costs, including the predicted costs of the carbon levy.

Acknowledgements

This Master's thesis marks the end of my academic journey, and thus the end of my time as a student Mechanical Engineering at Delft University of technology. I immensely enjoyed my time as a student, and I am grateful I had the opportunity to pursue this education.

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This research project was also guided by Huisman Equipment BV, a company specialising in the production of offshore equipment. I am grateful for the opportunity to complete my thesis at this company and would like to thank my supervisor, Fred Bos, and my manager, Lester Verhoef, for their assistance.

To my colleagues at Huisman, I would like to extend a special thank you for the coffee and cake breaks that provided not just a much-needed respite but also extra motivation. Your support was invaluable to me.

During my time as student, many of my fellow students became my friends. I would like to thank all my friends for their support and companionship. You have all been incredible at lifting my motivation, and the fun activities we have shared have been a delightful distraction. And to my family, thank you for your unwavering support and encouragement throughout my studies. Your belief in me has made all the difference.

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Acronyms

GHG	Greenhouse Gas	1
ETS	Emissions Trading System	2
EU	European Union	2
MDO	Marine Diesel Oil	27
BDN	Bunker Fuel Delivery Note	7
EWEA	European Wind Energy Association	3
LEC	Leg Encircling Crane	9
WTIV	Wind Turbine Installation Vessel	3

1

Introduction

In the last century, human activities, primarily from burning fossil fuels that have led to the release of carbon dioxide and other Greenhouse Gases (GHGs) into the atmosphere, have disrupted Earth's energy balance. This has led to an increase of GHG emissions in the atmosphere and ocean. The level of carbon dioxide in Earth's atmosphere has been rising consistently for decades and traps extra heat near Earth's surface, causing temperatures to rise [1]. GHGs consist of carbon dioxide, methane, ozone, nitrous oxide, chlorofluorocarbons, and water vapor. There is an urge for the GHGs to reduce.

Figure 1.1 offers a comprehensive view of global GHG emissions. It describes the sources and activities across the global economy that produce greenhouse gas emissions, as well as the type and volume of gases associated with each activity [2].

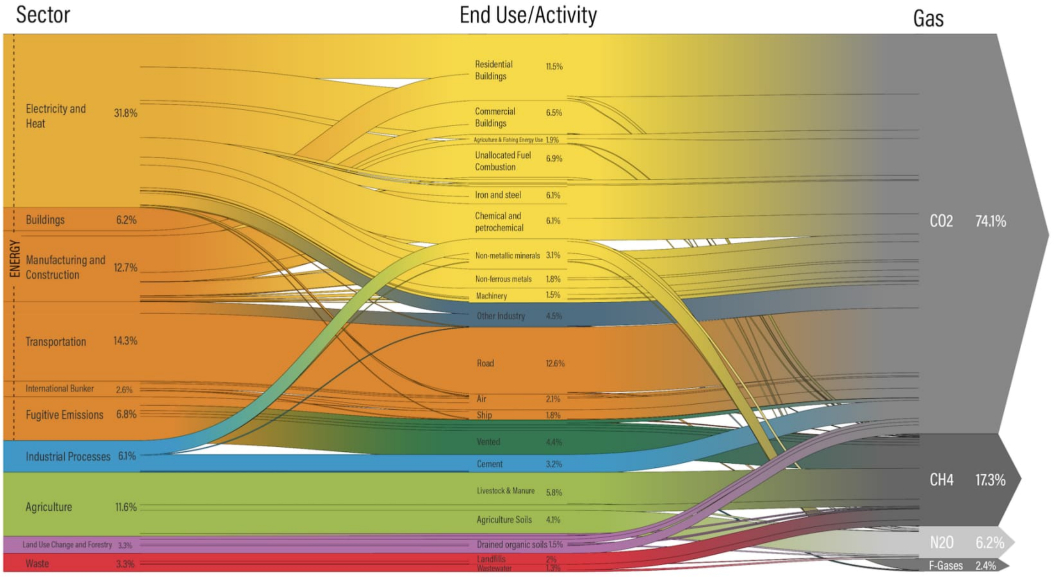

Figure 1.1.: World Greenhouse Gas Emissions in 2019 by Sector, End Use and Gases [2]

As can be seen from this figure, one of the most emitting sectors is manufacturing and construction.

1.1. Background

On 14 July 2021, the European Commission adopted a series of legislative proposals setting out how it intends to achieve climate neutrality in the European Union (EU) by 2050, including the intermediate target of an at least 55% net reduction in GHG emissions by 2030 [3].
There are two main repercussions that motivate the gap and need of this research:

1.1.1. Green Wind Energy

The first consequence that arises for the goal of a 55% reduction in emissions by 2030 is the need for a energy transition [4]. The global energy sector should shift from fossil-based systems of energy production and consumption to renewable energy sources, which cause less emissions. Wind energy is a fast growing renewable energy source. First, it started to establish on land with classic wind turbines, but due to the limited availability of land and the 'Not In My Backyard' discussion, non-floating wind turbines also established in shallow seas. There are more advantages to offshore wind turbines such as higher wind speeds. Wind turbines are growing larger and larger because the power they produce increases quadratic with blade length and more power from renewable energy sources is needed to decrease the amount of non-renewable energy sources.

"In 2022 wind electricity generation increased by a record 265 TWh (up 14%), reaching more than 2100 TWh" [5]. This was the second highest growth among all renewable power technologies, only solar power exceeded this growth. However, to get on track with the Net Zero Emissions by 2050 Scenario, which envisions approximately 7400 TWh of wind electricity generation in 2030, the average annual generation growth rate needs to increase to about 17% [5]. Achieving this will require increasing annual capacity additions from about 75 GW in 2022 to 350 GW in 2030 [5]. Thus, the offshore wind energy sector is set for a large increase.

For this set increase, offshore wind farms need to be installed. The installation of an offshore wind farm is complex and requires different types of vessels and barges equipped with different types of machinery such as cranes and grippers.

1.1.2. Maritime Emissions Reporting

Another consequence of the 55% reduction goal is the new upcoming registration and levy on carbon emissions. For this the EU Emissions Trading System (ETS) is designed. The EU ETS is a cornerstone of the EU's policy to combat climate change and its key tool for reducing GHG emissions cost-effectively. It is the world's first major carbon market and remains the biggest one [3]. This carbon market is based on a system of cap-and-trade of emission allowances for energy-intensive industries and the power generation sector [4].

Currently the EU ETS is not obliged for all companies that cause emissions of greenhouse gases, some sectors still have a certain amount of free emission rights. The maritime sector is currently still one of those sectors, but as of 1 January 2025 the EU ETS regulation shall also apply for offshore ships of 400 gross tonnage or above in respect of the greenhouse gas emissions released during their voyages from their last port of call to a port of call under the jurisdiction of a Member State and from a port of call under the jurisdiction of a Member State to their next port of call, as well as within ports of call under the jurisdiction of a Member State [6]. This means that the amount of GHG emissions of offshore operations need to be reported, and a tax will be paid over those emissions. Therefore, companies will want to gain insights into these emissions, predict them, and reduce them wherever possible.

1.1.3. Research Gap

New wind farms will have to be installed in order to make the transition towards green energy. Unlike more mature sectors such as the automotive industry and onshore wind, the offshore wind supply chain is currently flexible in terms of both participants and contracting structures [7]. Different companies are employed to together realise an offshore wind farm, such as wind turbine manufacturers, marine contractors, cable installers, and more. The European Wind Energy Association (EWEA) created Figure 1.2, which offers a schematic overview of scope allocation possibilities. Marine contractors are involved in the installation of the substations, the substructures (e.g. foundations), and the wind turbines.

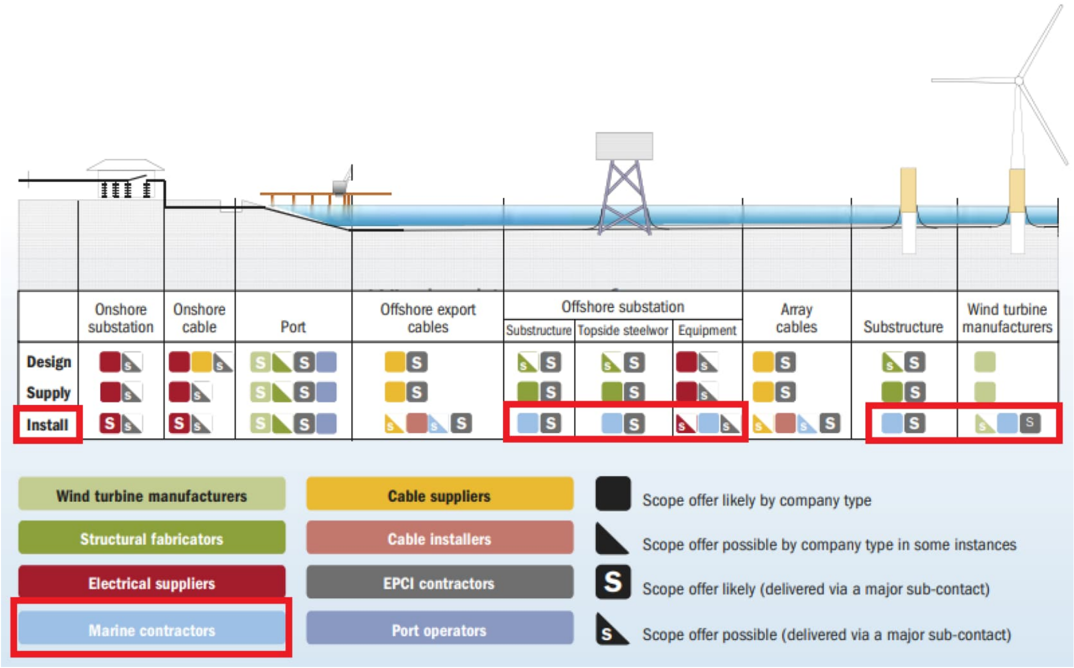

Figure 1.2.: Installation procedure offshore wind farm, marine contractors' involvements in light blue [7]

Marine contractors often have to compete in the early design phase of a potential wind farm for the contract. Thus, it is important a prediction of the total installation costs can be made. With the new regulations on a levy on the emissions of the marine industry, the costs of those emissions play a part in the early design phase of a potential wind farm. Since the offshore wind industry is relatively new, no research can be found on the emissions of wind farm installations.

This research is initiated by the company Huisman Equipment BV. Huisman is a designer and fabricator of all sorts of lifting and handling equipment for heavy and large loads. This includes the cranes needed on Wind Turbine Installation Vessels (WTIVs). While Huisman has a good view on the emissions that are the result of designing and fabricating the equipment, the company does not have a proper view of the emissions related to the operational use of the equipment after contractual delivery.

1.1.4. Research Objective

Maritime emissions need to be monitored and reported, and offshore wind farms need to be installed. The combination of those measurements, coming from the previous mentioned 'Fit for 55'-package, form the scope of this research: the GHG emissions caused by the installation of wind farms. This project focuses on developing a methodology to predict the greenhouse gas emissions of the wind farm installation process carried out by WTIVs equipped with cranes made by Huisman Equipment.

The main research question of this thesis is:

"How can the greenhouse gas emissions of the installation of an offshore wind farm by wind turbine installation equipment be predicted?"

To answer the main research question, the following subquestions are formed:

Subquestions:

- How can the GHG emissions of marine operations be computed?
- What are the installation procedures of an offshore monopile wind turbine?
- What are the energy consumers during the installation procedures?
- Which variables influence the amount of energy needed for an offshore wind turbine installation?
- How can a model be generated for the emissions of the installation procedure?
- What case study can be used to validate the model?
- What are the opportunities to reduce emissions?

1.2. Scope

This research is about the emissions of WTIVs, which are employed by marine contractors. Thus, the only parts of the Wind Farm installation processes taken into consideration are the installation of the offshore substation, the foundation, and the turbine itself. The cables are left out of scope.

Monopiles are expected to continue to dominate the marketplace up to the technical limits of their feasibility in terms of turbine size, water depth and ground conditions [7]. This is why, for this research, specifically the installation of offshore wind farms with monopile foundations are analysed. This is illustrated in Figure 1.3. However, the aim is to develop an easily adaptable model, so that other types of foundations can be implemented in the future.

The subquestions will be answered for all assets marine contractors install, but for the application the wind turbine is used as an example and the only asset that will be used for the development and results.

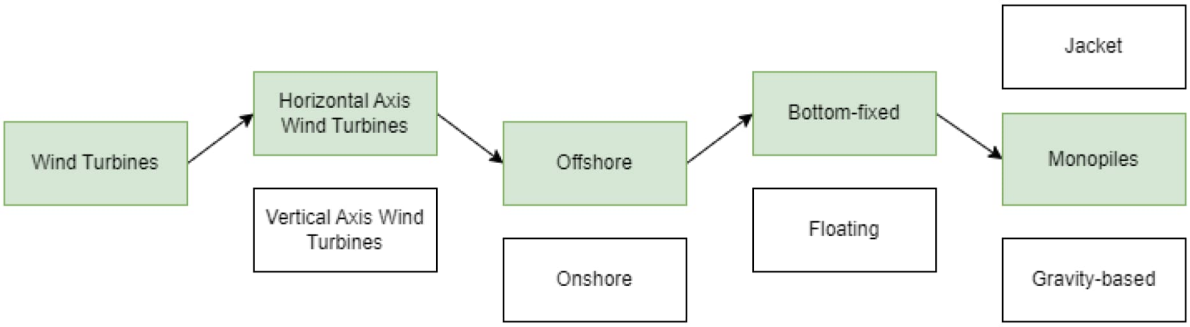

Figure 1.3.: Wind Turbine Scope

1.3. Methodology

In order to answer the main research question and the accompanying sub questions of this thesis the following methodology, which is also pictured in Figure 1.4, will be approached:

Literature

First, in the ”Literature” section a literature search will be performed and the subquestions *”How can the GHG emissions of marine operations be computed?”*, *”What are the installation procedures of an offshore monopile wind turbine?”*, and *”What are the energy consumers during the installation procedures?”* will be answered.

Model development

In the next section, ”Model development”, the methodology towards making the choises for the model development and thus the subquestion *”How can a model be generated for the emissions of the installation procedure?”* will be answered. The main energy consumers discussed in the ”Literature” section will be addressed and implemented in this model.

Results

Next, the ballpark values for general results will be presented in the section ”Results”, and insights will be given in the results of the model. Also, a sensitivity analysis will be performed to gain even more insights. This sensitivity analysis will also answer the subquestion *”Which variables influence the amount of energy needed for an offshore wind turbine installation?”*

Validation

The subquestion *”What case study can be used to validate the model?”* will be answered in the section ”Validation”, and the model will be partially verified. Since there is a limited amount of data available of only the crane operations, the validation is done for the energy consumer ’crane’ only.

Conclusions & Recommendations

In the conclusion, an answer will be given to the main research question of this thesis *”How can the greenhouse gas emissions of the installation of an offshore wind farm by wind turbine installation equipment be predicted?”*. Also the last subquestion will be answered in this last section: *”What are the opportunities to reduce emissions?”*.

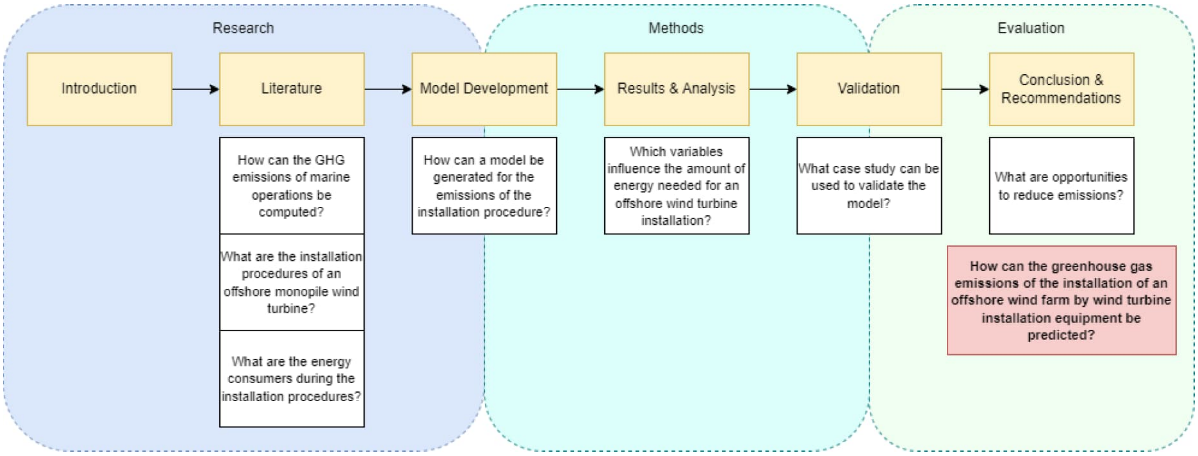

Figure 1.4.: Report Structure

2

Literature

In this chapter, literature will be reviewed and an answer to the first three subquestions will be given. The first section will cover subquestion 1: *"How can the GHG emissions of marine operations be computed?"*. This will be done by diving into the European regulations. The most relevant aspects will be found in section 2.1, but a more thorough research had also been done, and this can be found in Appendix B. The second section will cover the wind farm installation procedures and thus answers the subquestion *"What are the installation procedures of an bottom fixed offshore monopile wind turbine?"*. Multiple flowcharts will be visualised and explained, which together form a clear picture of the installation procedures. The different types of equipment and vessels that perform the procedures will also be discussed. Finally, in the third section, the energy consumers of the installation procedure will be further gone into. This will answer the subquestion *"What are the energy consumers during the installation procedures?"*.

2.1. Emissions calculations of marine operations

The EU ETS introduced in the previous Chapter obliges the offshore sector to report their emissions. For the reporting of emissions several standards and regulations have been created and legalised. The primary legislation governing the EU ETS is the Directive 2003/87/EC. Annex IV of the directive addresses the principles for monitoring and reporting the greenhouse gas emissions. However, this reporting section only covers the aviation sector and stationary installations. For the monitoring and reporting of emissions from maritime transport directive 2003/87/EC refers to regulation 2015/757.

Fuel consumption in regulation 2015/757

Regulation 2015/757 states: 'For the purposes of calculating CO2 emissions companies shall apply the following formula: *"Fuel consumption × Emission factor"* ' [8]. Part B of Annex I of this regulation is about various methods for determining the fuel consumption. The actual fuel consumption for each voyage shall be calculated using one of the following four methods:

- **BDN and periodic stocktakes of fuel tanks**
  This method is based on the quantity and type of fuel as defined on the Bunker Fuel Delivery Note (BDN) combined with periodic stocktakes of fuel tanks based on tank readings. The fuel at the beginning of the period, plus deliveries, minus fuel available at the end of the period and de-bunkered fuel between the beginning of the period and the end of the period together constitute the fuel consumed over the period. Where the amount of fuel uplift or the amount of fuel remaining in the tanks is determined in units of volume, expressed in litres, the company shall convert that amount from volume to mass by using actual density values [kg/l]. The company shall determine the actual density by using one of the following: a.) on-board measurement systems; b.) the density measured by the fuel supplier at fuel uplift and recorded on the fuel invoice or BDN; c.) the density measured in a test analysis conducted in an accredited fuel test laboratory, where available [8].

- **Bunker fuel tank monitoring on board**
  This method is based on fuel tank readings for all fuel tanks on-board. The tank readings shall occur daily when the ship is at sea and each time the ship is bunkering or de-bunkering. The cumulative variations of the fuel tank level between two readings constitute the fuel consumed over the period. Fuel tank readings shall be carried out by appropriate methods such as automated systems, soundings and dip tapes. The method for tank sounding and uncertainty associated shall be specified in the monitoring plan. Also for this method the company shall convert the amount of volume to density if applicable, just like with the previous method[8].

- **Flow meters for applicable combustion processes**
  This method is based on measured fuel flows on-board. The data from all flow meters linked to relevant CO2 emission sources shall be combined to determine all fuel consumption for a specific period. Also for this method the company shall convert the amount of volume to density if applicable, just like with the previous methods[8].

- **Direct CO2 emissions measurements**
  The direct CO2 emissions measurements may be used for voyages and for CO2 emissions occurring in ports located in a Member State's jurisdiction. CO2 emitted shall include CO2 emitted by main engines, auxiliary engines, gas turbines, boilers and inert gas generators. For ships for which reporting is based on this method, the fuel consumption shall be calculated using the measured CO2 emissions and the applicable emission factor of the relevant fuels. This method is based on the determination of CO2 emission flows in exhaust gas stacks (funnels) by multiplying the CO2 concentration of the exhaust gas with the exhaust gas flow[8].

These methods are also pictured in Figure 2.1. The company shall define in the monitoring plan which monitoring method is to be used to calculate fuel consumption for each ship under its responsibility and ensure that once the method has been chosen, it is consistently applied. Any combination of these methods, once assessed by the verifier, may be used if it enhances the overall accuracy of the measurement[8]. Expert review and literature research (e.g. [9]) both agreed on the first method (BDN) being the most conventionally used one. This means that in order to predict the amount of greenhouse gas emissions of a marine operation, the amount of fuel needed needs to be calculated or predicted.

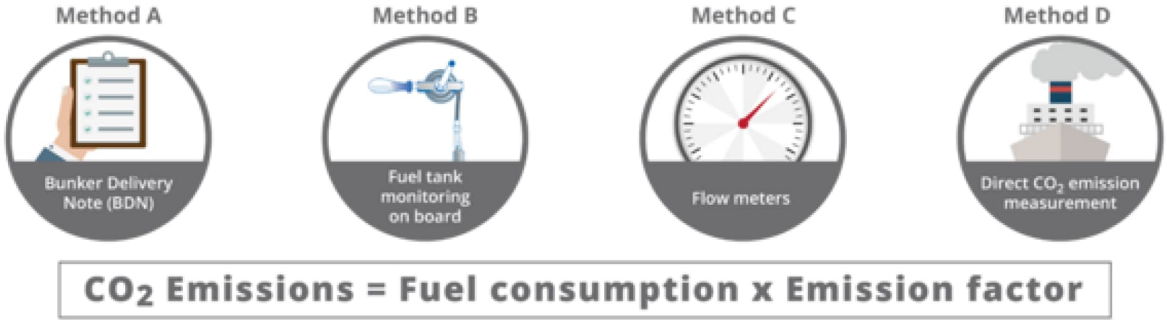

Figure 2.1.: Illustration of the methods for fuel monitoring [10]

2.2. Wind Farm installation

In this section the installation procedure of an offshore wind farm will be discussed. First, the different types of vessels that can perform the installation will be described. Next, the total installation process will be examined, and then the installation procedure per asset will be discussed.

2.2.1. Vessels

Different types of WTIVs can be used to perform the installation of the different assets of the wind farm. The main points of consideration when selecting vessels for these tasks include: ship performance, cost, lift capacity, precision when lifting, vessel dimensions, metocean (meteorological and oceanographic) limitations, technical risk and commercial availability [7]. The main vessel types used for installations of offshore wind farms will be discussed in this section.

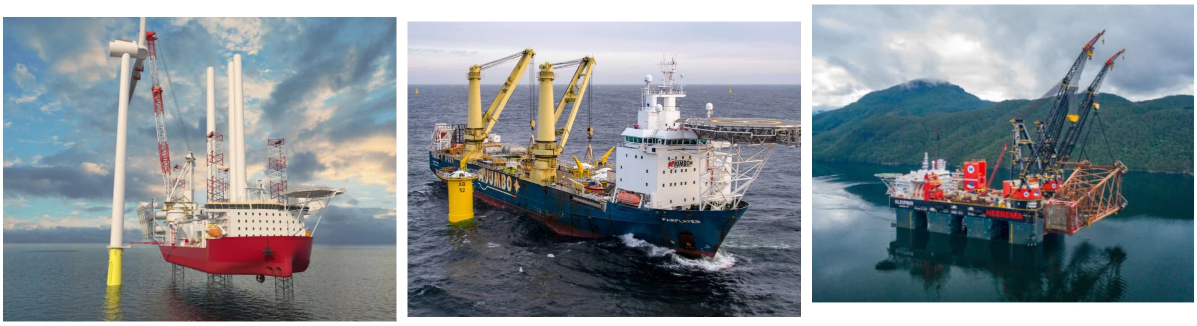

Figure 2.2.: Jack-Up vessel [11]

Figure 2.3.: Heavy lift vessel [12]

Figure 2.4.: Semi-submersible vessel [13]

Figure 2.5.: Three types of WTIV's

Jack-up vessels

A jack-up vessel has four to six legs. When a jack-up vessels arrives at the site, its legs are lowered onto the seabed and the whole vessel is lifted to the desired height. The stability provided by a jack-up vessel results in these types of vessels being the most dominating vessel for the installation of an offshore wind turbine. They are ideal for installing the nacelles and blades of turbines, which are the most precise lifts required on a project. The vessels are also suitable for the installation of the foundation. A jack-up vessel is often equipped with a Leg Encircling Crane (LEC) to perform the installation process. A picture of a jack-up vessel is shown in Figure 2.2

Heavy lift vessels

Although a Jack-up vessel can be used for the installation of offshore foundations, for a monopile type foundation it is more common for the installation to be performed by a heavy lift vessel. Heavy-lift vessels are barge-shaped hulls with high capacity cranes; they lack an elevating system, and may or may not be self-propelled . They may be dynamic positioned or conventionally moored. Heavy-lift vessels include mast cranes, sheerleg cranes, or other floating cranes. They are rarely used to install turbines, but may be used for foundation work, for carrying fully assembled turbines, or for installing substations [14]. A picture of a heavy lift vessel is shown in Figure 2.3

Semi-submersible vessels

The hull of semi-submersible vessels can be flooded, greatly increasing the dead weight of the craft, and it is designed so that this ballasting operation dramatically lowers the period of roll of the craft [7]. This change in vessel dynamics effectively “tunes out” the effect of the waves on the craft, and therefore the problem of inopportune wave-periods leading to resonance can be avoided. The vessel is effectively motionless in the water, unaffected by all but the biggest waves. Clearly the huge structure presents a large surface to the wind, but again, the overall stability is such that even delicate lifting operations can be carried out in deep water during relatively strong wind conditions [7]. A picture of a semi-submersible vessel is shown in Figure 2.4

2.2.2. Installation Procedure

The installation procedure of an offshore wind farm is complex and a lot of different factors determine the steps that need to be taken. The scope of installation work and the necessary equipment are determined by the type of foundation ([15]). For example, monopile foundations require heavy hydraulic hammer works to ram steel pipes with diameters of 4 meters up to 20 meters into the seabed. However, according to Kaiser, the differences in installation procedure are relatively minor [14]. There are also logistical challenges that determine the amount of steps that have to be taken offshore.

The installation process of a vessel installing assets of the offshore wind farm is pictured in Figure 2.6. The ’asset installation’ part of this schematic representation will be discussed for each of the assets in the next sections. As defined in the scope of this research, the assets covered in this research are the offshore substations, the monopile foundations, and the wind turbine itself. In Figure 2.6 it is assumed the WTIV will be load up at the port, before transit. However, this is not always the case. For some Wind Park installations the vessel gets the wind turbine parts through feedering. In this case, the load up vessel part can be completely skipped, or be put after transit, depends on if the parts will be loaded onto the vessel or directly installed. A schematic overview of the total installation procedure for the assets is pictured in Figure 2.7. When installing offshore wind farms, different subcontractors are involves with the different installation stages. For wind farm installations, the installation of the foundation and transition piece are usually incorporated in one contract, and the installation of the wind turbines in another contract.

Wind Turbine Foundation

There are a variety of ways in which monopiles can be installed. If one vessel is employed, the vessel may transport and install all foundations followed by the transport and installation of all the transition pieces, or a vessel may simultaneously transport foundation and transition pieces and installs both in sequence [14]. After arrival on site the pile is upended so that it is sitting vertically on the seabed. This is accomplished by a crane and/or a specialized pile gripping device and is the step which usually defines the required crane capacity [14]. Then, a hydraulic hammer is placed on top of the pile and it is driven into the seabed to a predetermined depth. The time to drive the piles depends on the soil type, diameter and thickness of the piles, and the weight of the hammer. A rocky subsurface may prevent driving operations, in which case a drill will be inserted into the pile to drill through the substrate. Drilling adds to the time to install foundations.

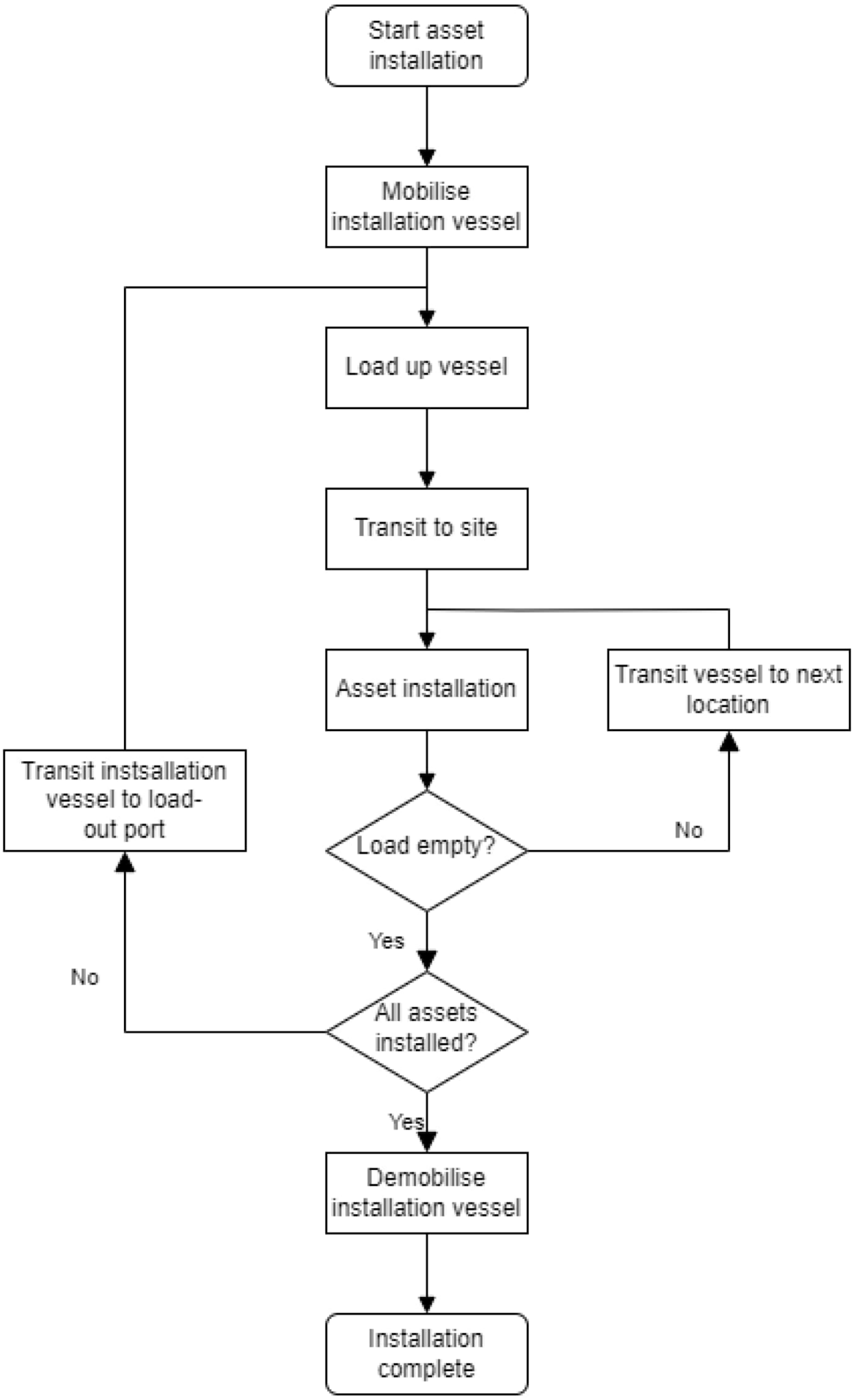

Figure 2.6.: Flowchart for a Offshore Wind Farm asset installation process [16]

Transition Piece

After the foundation is installed, a transition piece is placed on top of the foundation to levelize horizontal inaccuracies [14]. As mentioned, a vessel may simultaneously transport foundation and transition pieces and installs both in sequence. The transition piece is lifted and grouted onto the pile. The length of the transition piece is usually smaller than the water depth at the site, and thus, will not reach the bottom of the seabed. In some cases the transition piece may be bolted [14].

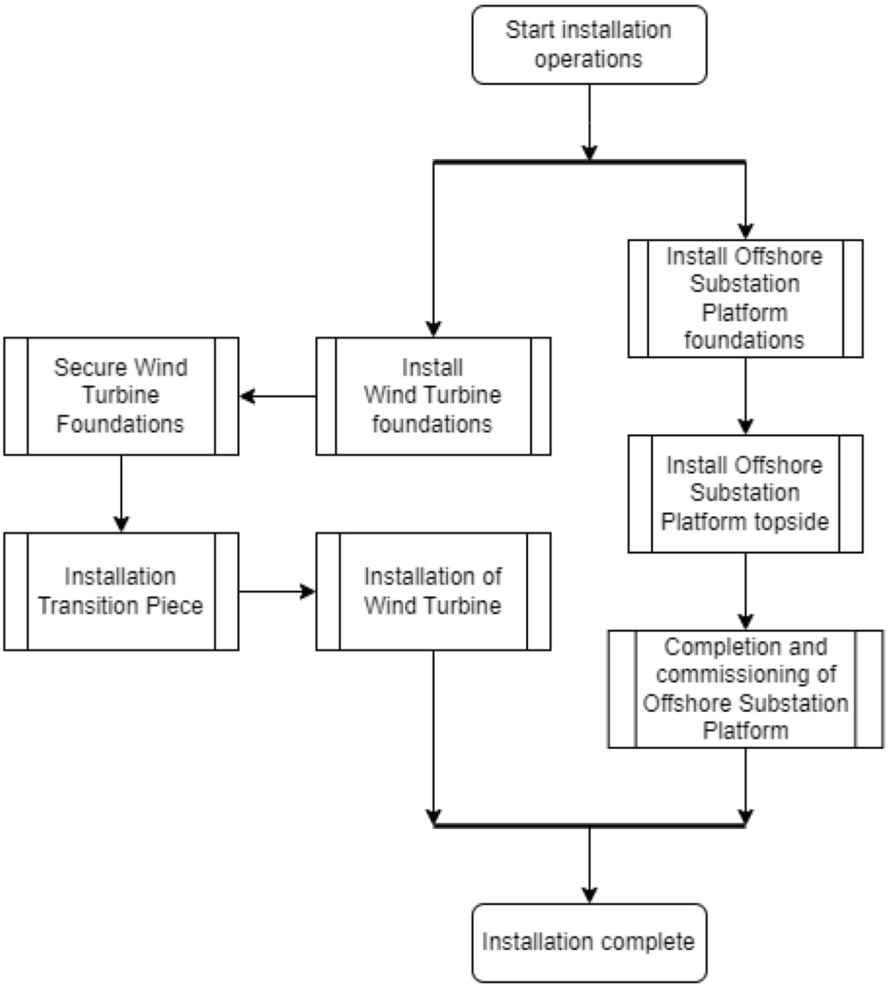

Figure 2.7.: Schematic overview of Wind Farm installation

Offshore substation

Offshore substations are placed on monopile, jacket or gravity foundations. The same foundation used for the turbines may be used or a different foundation applied. Similar installation techniques for foundations are used for the substation foundation and in some cases, the substation foundation is installed at the same time as the rest of the foundations [14]. A 'topsides' structure is built onshore, complete with all electrical equipment, and commissioned as far as possible, before being transported to the site and installed on the foundation structure[7]. The installation of the foundation and substation offshore is in done by marine subcontractors.

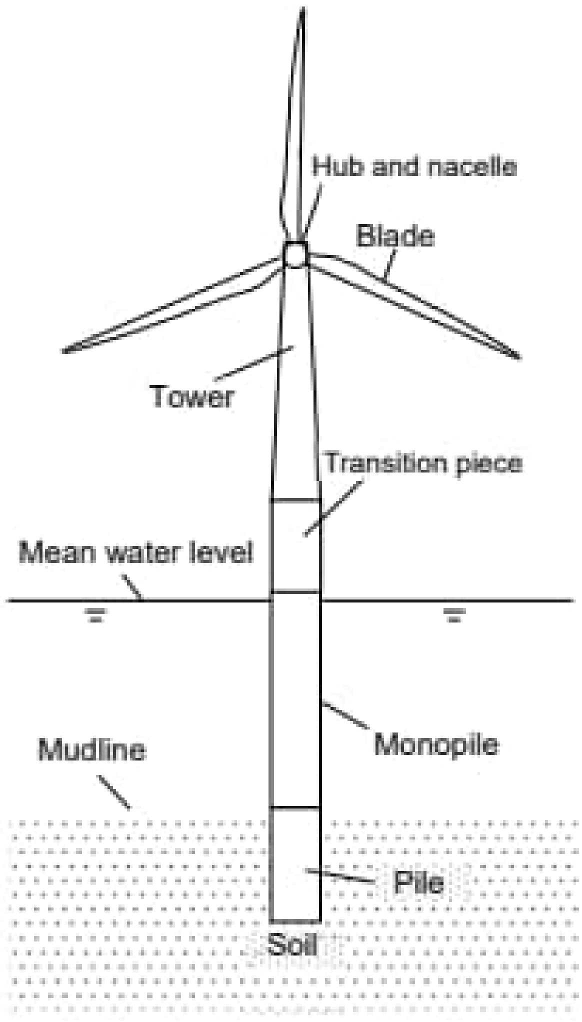

Figure 2.8.: Parts of a wind turbine

Wind Turbine

There are a large number of options for turbine installation. When delivered, turbines typically consist of seven individual components, including three blades, at least two tower sections, the nacelle and the hub. [14] Some degree of onshore assembly is performed to reduce the number of offshore lifts and the degree of pre-assembly will impact vessel selection and installation time. Offshore lifts are risky and are susceptible to delay due to wind speeds, so preference is usually to minimize offshore assembly [14]. A representation of the different methods to install the wind turbine offshore is pictured in Figure 2.9. Nowadays, because the wind turbines are getting bigger and bigger, and pre assembly onshore is no longer feasable for most turbines, installation method #2 is the most common one. This method requires 5 offshore lifts.

Regarding offshore contracts, it is conventional that one contractor is used for the installation of the foundation, the transition pieces, and the offshore substation(s), and another contractor is used for the installation of the wind turbines on top of the transition pieces.

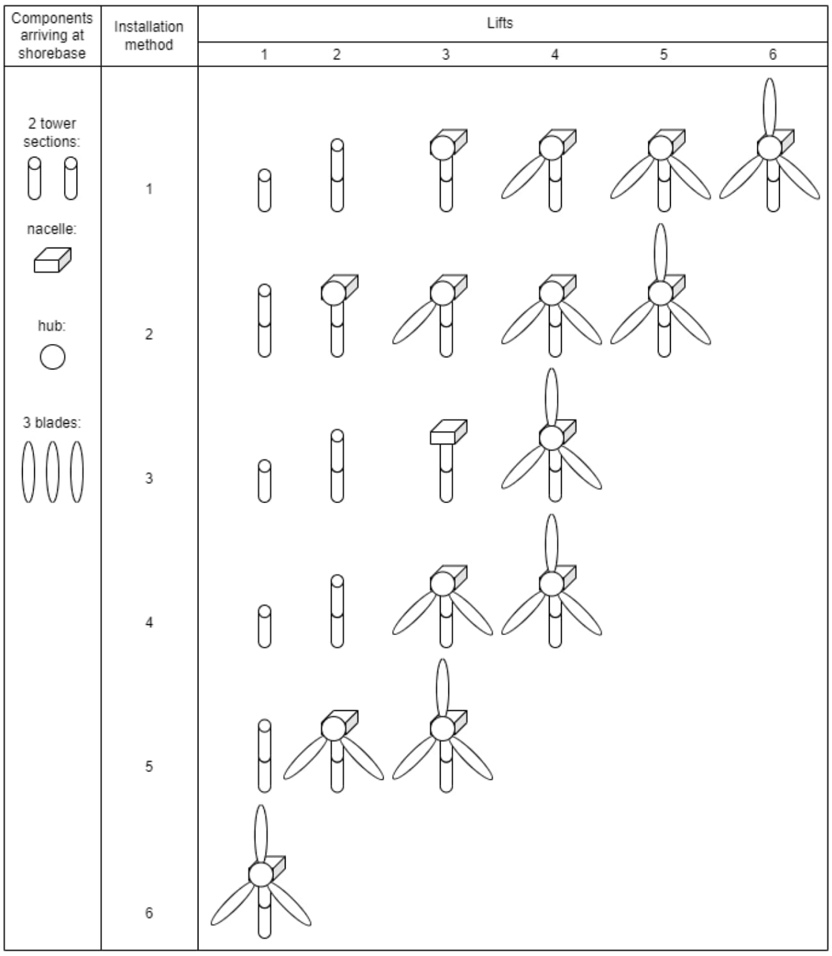

Figure 2.9.: Diagrammatic Representation of Installation Methods [14]

2.3. Energy Consumers

For the installation process of a Wind Farm, different equipment of the wind turbine installation vessel is used. The main energy consumers will now be analysed. Figure 2.10 represents the one-line diagram of a heavy lift vessel. In this diagram you can see the power supply and the main energy consumers: the thrusters and the crane and auxiliaries. These consumers will now be discussed. Also the jack-up system, that is not included in a heavy lift vessel but is in other WTIVs, will be part of this section.

2.3.1. Thrusters

To perform the actual installation of wind turbines, first a WTIV needs to get to the site. The vessel's thrusters require energy to perform this transit by moving the vessel. A WTIV can be equipped with different types and amounts of thrusters: main thrusters/propellers, the azimuth thrusters, stern thrusters, and bow thrusters. The main thrusters, called the propellers, produce the forward impel. The bow thrusters help maneuver a vessel sideways. These thrusters are mostly used for the docking or mooring of the vessel.

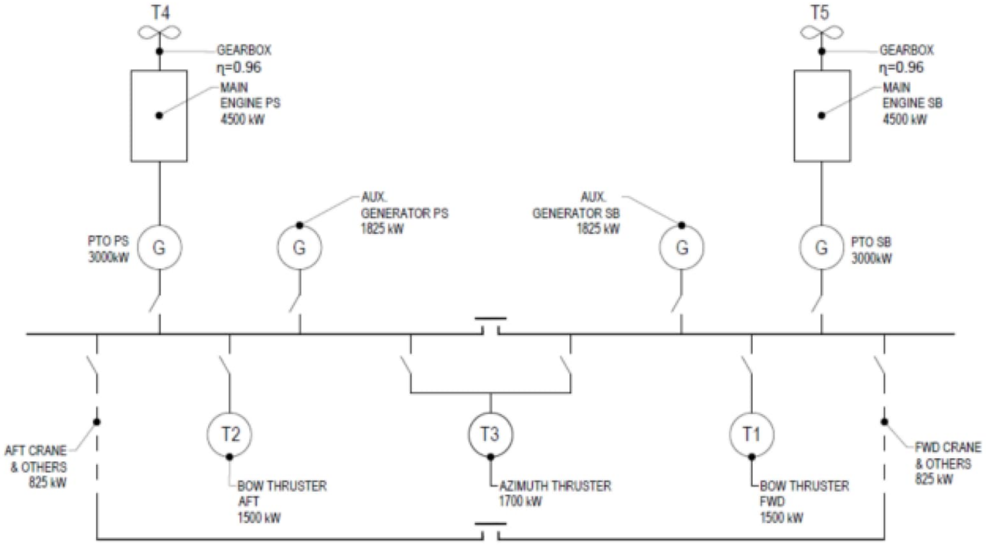

Figure 2.10.: One line diagram of a heavy lift vessel

2.3.2. Crane

For the loading and the installation part of the whole installing process, the crane is essential. Different types of cranes exist, and all have slightly different attributes, but the main properties are the same. A crane structure has 2 degrees of freedom: slewing and luffing, as is pictured in Figure 2.11. Also it has multiple hoisting mechanisms, the ones always included in a crane being the main hoist and the whip hoist. The whip hoist is the hoist in the extension of the boom, and its maximum hoisting load is significantly smaller then the maximum main hoisting load. When installing a wind turbine, usually the steps performed by the crane are in the following order:

1. The crane's boom gets out of the 'boom rest' in which it is positioned during the transit and all other downtime of the crane.
2. The crane performs the luffing movement to the desired boom angle, in which the crane is able to perform load hoists.
3. The crane slews so that it can pick up the desired item off the deck.
4. The main block or the whip hoist block gets down to pick up the item.
5. The item gets hoisted to the desired height.
6. The crane slews to get the item to the desired spot.
7. The item gets installed.
8. Repetition of steps 3 to 7 until all items are installed
9. Crane slews back to its initial state en the boom lowers to get back in it's boomrest

These steps take into account the effective needed angles of the slewing and luffing of the crane. In reality, some more movements are made during installation time, to perform the precise movements. This will be further analysed in Chapter 5.

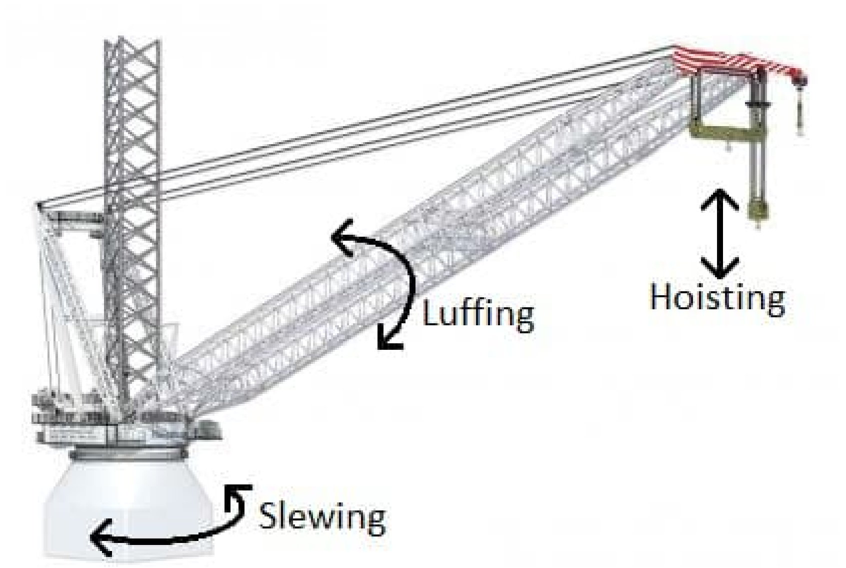

Figure 2.11.: Leg Encircling Crane main motions

2.3.3. Jack-up pillars

As mentioned, there are different types of WTIVs, one of them being jack-up vessels. The four or six jack-up pillars on this vessel lift the vessel when it is arrived at the site. Jack-up pillars typically consist of hydraulic systems that enable controlled elevation adjustments, allowing the vessel to adapt to varying water depths. The hydraulic mechanisms extend the pillars downward until they make contact with the ocean floor. Once the pillars reach the seabed, they exert downward pressure, securing the vessel in place and providing a solid foundation for operations.

2.3.4. Hotelling/Auxiliaries

WTIVs are equipped with various auxiliary systems, often referred to as the ”hotelling” function, that support their operations and ensure functionality throughout missions. These auxiliary systems encompass a wide range of components, including power generation, HVAC (Heating, Ventilation, and Air Conditioning), fire suppression, and wastewater treatment. This system is continuously consuming energy.

2.3.5. Engines and generators

The fuel consumption of a vessel can be translated into the amount of GHG emissions that it effuses. The amount of fuel the vessel needs depends on the amount of energy it costs to perform its tasks. Many characteristics determine the energy consumption of a wind turbine installation vessel. The energy sources of a vessel are the engines. Different type of engines can usually be found on a vessel. Engines on board ships are amongst the largest types of engines in the world, and their size and characteristics directly influence fuel consumption and CO2 emissions [9]. The main engine turns the ship’s propeller and move the ship through the water, whilst auxiliary engines aim at powering the ship’s electrical systems, and a number of other machinery items providing additional essential services such as gas insertion, heat and steam production, and incineration [9].

In conclusion, the main processes for the installation of an asset are loading, transit, and installing. When performed with a jack up vessel, before the loading and installing the jacking up has to occur, which then also can be called a main energy consumer. The energy consumers per process are pictured in Figure 2.12.

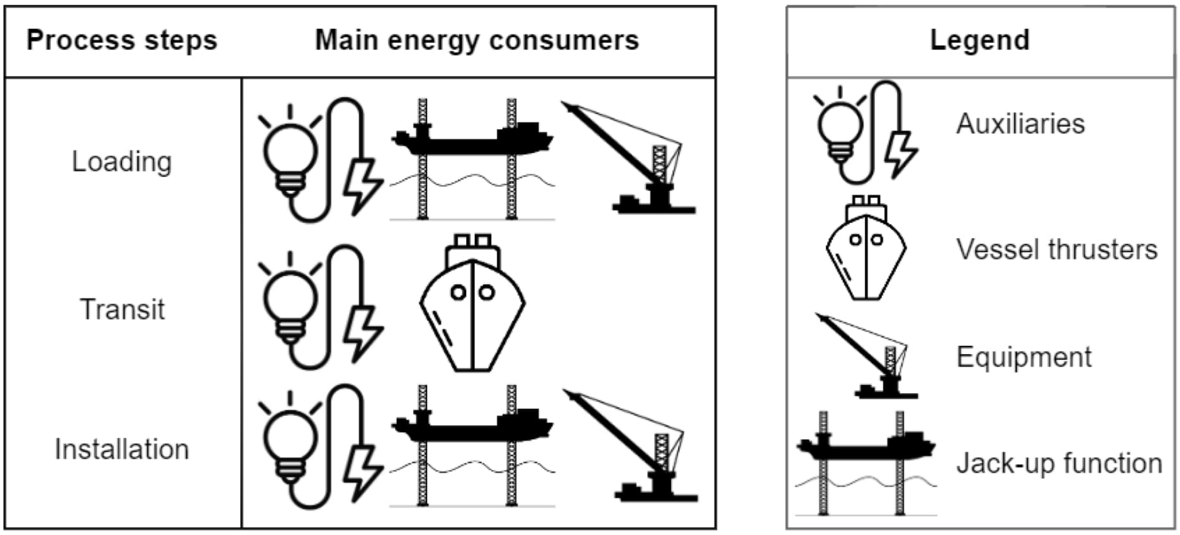

Figure 2.12.: Installation processes and their main energy consumers

2.4. Concluding remarks

This literature review has addressed the first three subquestions of this thesis, insights into the computation of GHG emissions for marine operations, the installation procedures for bottom-fixed offshore monopile wind turbines, and the primary energy consumers during these procedures.

Bunker Fuel Delivery Note combined with periodic stocktakes of fuel tanks based on tank readings was the most commonly used method for reporting the fuel consumption. The emissions can then be calculated by multiplying the fuel consumption with the fuels emission factors.

Marine contractors perform the installation of foundations, transition pieces, wind turbines, and substations. The vessels primary steps for installing those assets are loading, transit, when applicable jack up, and the installation. These are also the main energy consumers, along with the auxiliary/hotelling function of a vessel.

3

Model development

The goal of this thesis is to be able to make a good prediction of the GHG emissions that are formed when installing a wind farm. To do so a model needs to be created. This chapter describes the model and the reasoning behind some steps that have been taken. This answers the subquestion *"How can a model be generated for the emissions of the installation procedure?"*. The aim is to make an adaptable model that can be used for all assets to be installed by marine contractors, but the focus will be on the wind turbine installation, as this is used for the results and the validation of the model.

3.1. Possible modelling approaches and choice

First, possible solutions towards predicting the amount of emissions are thought of. Multiple ways to make this prediction of the amount of GHGs emitted when installing a wind farm are the following:

- **Artificial Intelligence**
  Machine learning model with a lot of data from previous wind park installations. Use all data about the vessel, crane, wind park, and the solutions for multiple previous installations and make a machine learning model that can predict for future installations
- **Data based engine/generator prediction**
  From previous wind park installation looking at the durations of when the motors and generators where running and analyse it more to make a prediction for future wind park installations. Per vessel activity, the amount of time it will run and the relevant engines/generators that will be on. From there, it is possible to predict the amount of fuel needed and translate it into GHG emissions.
- **Data based fuel prediction**
  Check the fuel consumption from past installations, translate it into GHG emissions and compare them and analyse the differences to make a prediction for future installations.
- **Physics based energy prediction**
  A bottum-up approach tha calculates the amount of energy needed per vessel activity by using energy and work calculations and translate this to the amount of fuel needed to get this amount of energy, and then calculate the amount of GHGs emitted with this amount of fuel.

Some of the different possible approaches for the GHG predictions use the different vessel activity modes, and predict the required fuel, energy, or emissions per mode. The distinction between different modes is necessary because each mode has an other setup in terms of which engines and/or generators are running, or what equipment on the vessel is used. The different vessel activity modes are 'Loading', 'Transit', 'Hotelling', 'Installing', and, when applicable 'Jacking'.

3.1.1. Model choice

For the first three methods the amount of data needed to make a reliable prediction is high. Because the availability of data for this thesis project is very limited, the physics based energy prediction is the most feasible approach, and for that reason the model will be build with this method being the core. The model is made in Python using object oriented programming as the base. This is because object-oriented programming provides flexibility and is a programming paradigm that allows packaging data states and functionality to modify those data states together, while keeping the details hidden away. Especially when working with sensitive data this is very convenient.
For the model a bottom-up approach is used with process based modelling: The main processes of installing wind turbines will be modelled separately and the required energy of those processes will be predicted. The total predicted amount of energy that is required for the process can then be translated into the amount of fuel that is needed by using the engine specifications. The amount of fuel can then be translated to the predicted amount of GHG emissions that will me emitted. This approach is pictured in Figure 3.1.

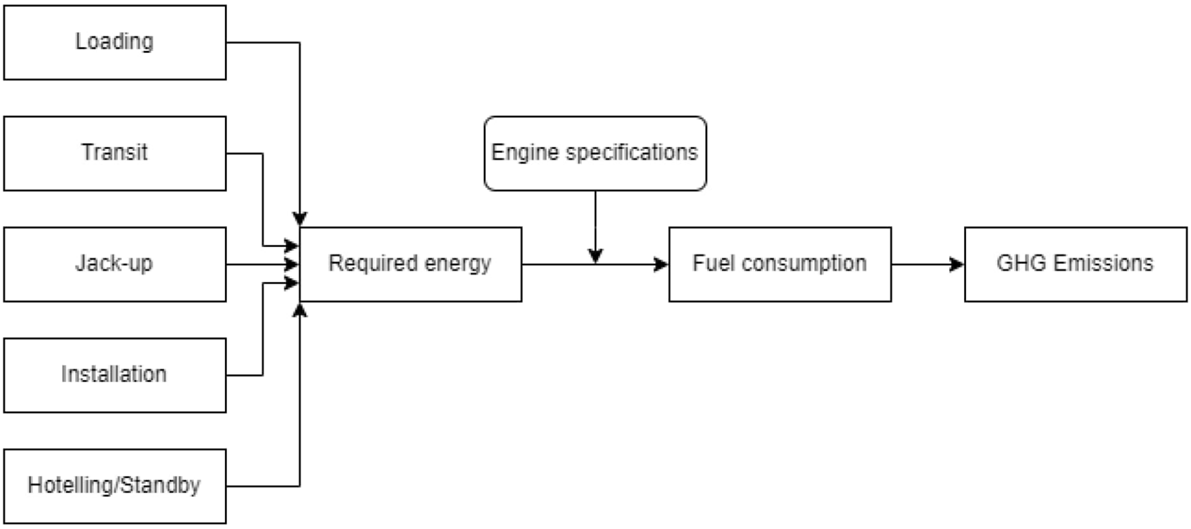

Figure 3.1.: Model approach

The implementation of the framework is done using Python. All the inputs of this model can be found in Figure 3.2 In Appendix C, the model in Python can be found. The calculations incorporated in the Python model can be found in section 3.3.

3.2. Model Assumptions

In this section the assumptions made when developing the model are discussed. By elaborating on these assumptions, the model can simplify complex calculations while still providing reasonable accuracy in predicting the overall energy consumption and GHG emissions during the wind turbine installation process.

Jacking electric

The jack-up function of a vessel can be hydraulic or electric, depending on the vessel. For this model the assumption is made the jack-up function is electrically driven. In modern designs, this is becoming more common, but for most jack-up vessels this is not yet the case. If a hydraulic jacking system is employed on the vessel, some small alterations need to me made. A hydraulic jacking system is less efficient and more energy consuming.

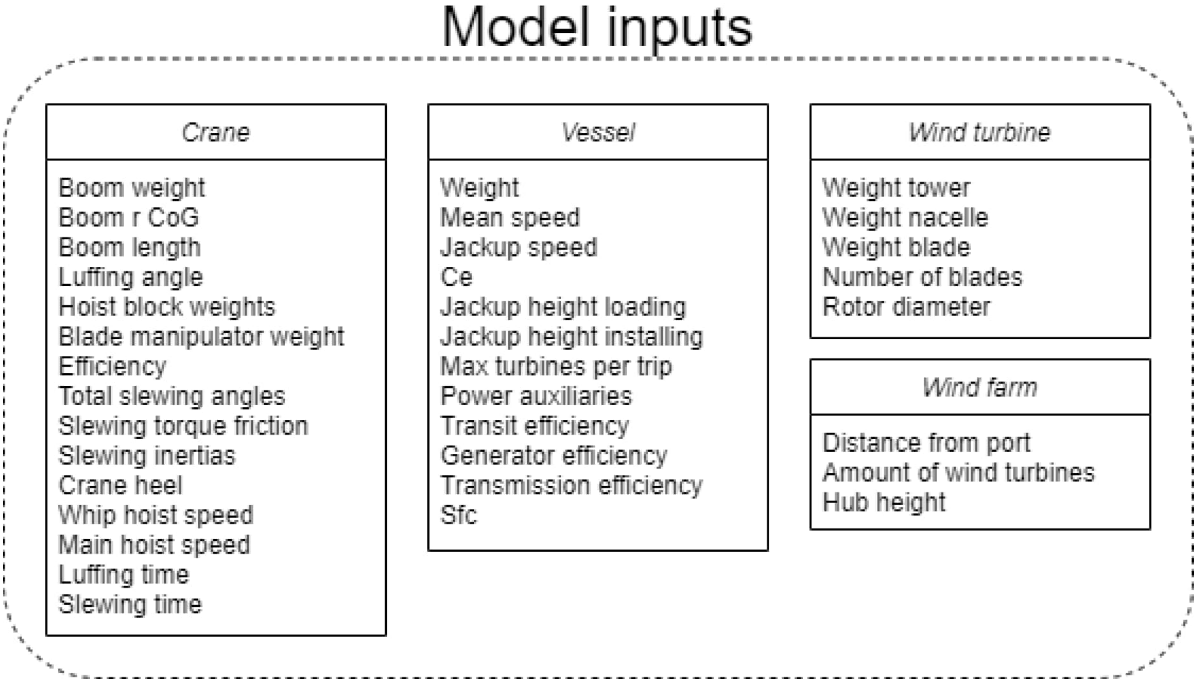

Figure 3.2.: The input variables of the developed model

Hoisting and luffing down energy neutral

When a hoist is lowered, the potential energy is transformed to another type of energy. This energy can not be stored in most offshore equipment, but it can be used immediately. This is why the hoisting and luffing down are assumed to be energy neutral. The energy it costs to move the loads is gained from the potential energy, and the energy that is left is flared.

Jacking Down Energy Neutral

The previous assumption is also made for the jacking down of a jack up vessel. The energy required for jacking down (lowering the vessel) is considered neutral, meaning it does not consume additional energy. The vessel is lowered, which provides the vessel with the energy to perform the jacking down. This assumption is based on the possibility that the jack-up system could be electric and capable of regenerating energy or simply lowering without significant power consumption, the same way the cranes can do this.

Blade Manipulator Energy is Minimal

The energy consumed by the blade manipulator during the installation process is considered minimal and therefore not included in the model. This assumption is based on the relative size and power requirements of the blade manipulator compared to the overall energy consumption of the wind turbine installation process.

Motor Inertia Not Included

The energy required to overcome the inertia of the motors is considered relatively small in comparison to other energy demands of the installation process. Therefore, motor inertia is not included in the model. This assumption simplifies the model without significantly affecting the accuracy of the overall energy consumption prediction. For example, the inertia of a crane motors usually lies between 1.5-20 $kg * m^2$, and the rotational speed can be assumed to be around 2200 rpm, which is toughly 209 rad/s. This makes the energy consumption of the start up only 0.009 - 0.1 kWh, when using the formula:

$$E = {}^{1}/_{2} * I * \omega^2 \tag{3.1}$$

Transit Forth and Back Combined

The transit energy calculation assumes that the weight of the wind turbines being transported does not significantly impact the fuel consumption of the vessel. This means that the energy required for the vessel to travel to and from the installation site is considered symmetrical and does not vary with the load. This assumption simplifies the transit energy calculations.

Slewing Angle: Half Time with Load, Half Time Without Load

The energy consumption for slewing (rotating) the crane is averaged by assuming that the crane operates half the time with a load and half the time without a load. This assumption provides a balanced estimate of the energy required for slewing operations, reflecting the varying conditions under which the crane operates.

3.3. Energy calculation

As mentioned, the first step in the model is the predicting the required energy per process. In this section for each process the calculations for the predictions will be explained. In general the total required energy of the process of a movement can be calculated with the formulas of kinetic energy (Eqn.3.2) and amount of work added (Eqn. 3.3) together.

$$E_{kin} = 1/2 * m * v^2 \tag{3.2}$$

In this equation E_{kin} the kinetic energy is expressed in joules, m in the mass in kilograms, and v is the mean speed in meters per second.

$$W = F_{res} * s \tag{3.3}$$

In this equation W is the work in joules, F_{res} is the resultant force in newtons, and s is the distance in meters. For most motions v_{start} and v_{end} are zero But because it does cost energy to accelerate, it needs to be included. The energy will be released when braking/de-accelerating, but most offshore systems do not have a possibility to storage and use this energy yet.

3.3.1. Transit

To calculate the required energy for the transit, the formulas found in the book ”Design of Propulsion and Electric Power Generation Systems” are used [17].

For the transit of a vessel, the amount of energy can be calculated with the general equations (Eqn. 3.2 and Eqn. 3.3). Only for the Work equation (Eqn. 3.3), the amount of force is dependent on various factors such as the vessel's speed and form factor. This is where the previous mentioned book comes into place. The following formulas from the book are used to calculate the force F from equation 3.3:

$$R = c_1 * v_{vessel}^2 \tag{3.4}$$

In this equation R is the total hull resistance, which is equivalent to F_{res} of the vessel, and c_1 is the proportionality factor. This equation states that the total hull resistance is proportional to the square of the ship's speed, and is only valid for a vessel sailing at relatively low speeds. This is the case for WTIVs. The next constant introduced in the book is C_E, which is called the ”Non-dimensional resistance” of a vessel. C_E depends on the ship's speed, displacement, fouling, geometry, and external factors such as sea state and water depth. The factor C_E of various ships sailing with various speeds is given in the book. For a WTIV this factor has to be estimated. Now the factor c_1 can be calculated using the following formula:

$$c_1 = C_E * \rho^{1/3} * \Delta^{2/3} \tag{3.5}$$

In this equation, ρ is the density of the sea water in kg/m^3, and Δ is the displacement of the vessel in kg, which can also be replaced by m. The kinetic energy of the vessel had to be included for the accelerating and the decelerating of the vessel, since a vessel has to rotate its propellers in order to brake. The kinetic energy contribution for a transit will thus be:

$$E_{kin_{transit}} = 2 * 1/2 * m * v_{vessel}^2 = m * v_{vessel}^2 \tag{3.6}$$

When combining all the formulas together, the following formula for the required energy of a transit is implemented into the model:

$$E_{E_{transit}} = \frac{m * v_{vessel}^2 + C_E * \rho^{1/3} * m^{2/3} * v^2 * s)}{\eta_{transit}} \tag{3.7}$$

s is the distance of a single transit of the vessel. The energy for the transit of the vessel has to be implemented for the distance between the port and the site, and also the transit between turbines. The distance between turbines can be assumed by multiplying the rotor diameter with 8 [18]. $\eta_{transit}$ is the efficiency of the process, and can also be implemented as a variable in the model.

3.3.2. Hotelling/Auxiliaries

The hotelling or auxiliary function is the function when the vessel is operating auxiliary engines only. This is for the basic energy supply, heaters, water, and other auxiliaries. For this model, the hotelling function will be an all time running function, since the basic needs will be used during the whole installation phase. The energy demand of this function can be calculated by multiplying the energy demand per hour, which is the power P_{aux}, with the total installation time t, since ship owners often know the value of this function:

$$E_{aux} = P_{aux} * t \tag{3.8}$$

3.3.3. Jacking

As mentioned, using jack-up vessels is common for the installation of wind turbines. The energy required to lift a vessel is implemented in the model with the basic work and energy equations and results in the following equation:

$$E_{jacking} = \frac{1/2 * m * v_{jacking}^2 + m_{vessel} * g * h}{\eta_{jacking}} \tag{3.9}$$

In this equation h is the jack-up height in meters and thus the distance over which the work $m_{vessel} * g$ is done, which is also pictured in Figure 3.3.

3.3.4. Loading and installation

The installation and loading procedures function focus on the energy demand of the crane on the WTIV. As discussed in the previous chapter, the crane had 3 main movements that require energy. The energy demand per movement type will be predicted separately and then added together. Since the energy required is also dependent on the load on the crane, per item installed or loaded the different movements' energy requirements will be calculated in the model.

Luffing

The first step in the lifting operations is the luffing, which is also called boom hoisting. The boom of the crane will move out of the boom rest and luffed to a desired radius from which its lifting abilities are optimal. The energy calculation is again implemented in the model by combining the kinetic energy calculation and the work executed. This must be done for the hoisting blocks on the end of the boom, and the boom itself.

$$E_{luffing} = \frac{1/2 * m_{boom} * v_{cog}^2 + m_{boom} * g * h_{cog} + 1/2 * m_{blocks} * v_{blocks}^2 + m_{boom} * g * h_{blocks}}{\eta_{luffing}} \tag{3.10}$$

In this equation, h_{cog} is the vertical displacement of the center of gravity of the boom in meters, and h_{blocks} is the vertical displacement of the main hoisting block and the whip hoisting block.

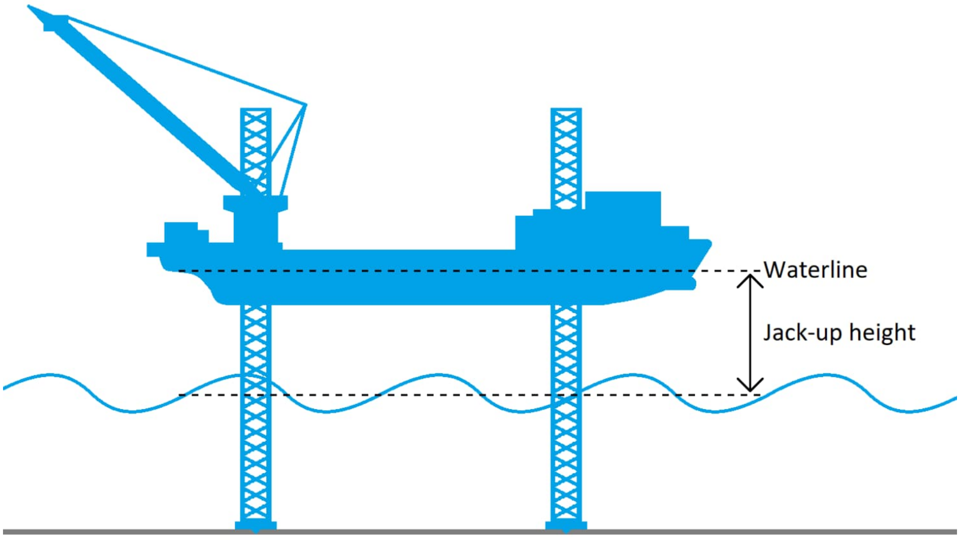

Figure 3.3.: Jack-up height

Hoisting

The required energy for the main function of the crane, the hoisting of the items, is calculated with the following formula:

$$E_{hoisting} = \frac{1/2 * m * v_{hoisting}^2 + f_{hoist} * m * g * h}{\eta_{hoisting}} \tag{3.11}$$

f_hoist is the hoist factor that should be implemented when working at sea. This factor accounts for possible extra load due to environmental conditions such a wind.

Slewing

The slewing of the crane is the rotation of the large bearing at the bottom of the crane. The required work for this operation depends on the slewing angle and the slewing torque. The slewing torque depends on the crane's heel, boom angle, and the load. The required kinetic energy depends on the crane's inertia and the rotation speed. The following formula is used for the required energy of a slewing operation:

$$E_{slewing} = \frac{1/2 * I * \omega^2 + T * \alpha}{\eta_{slewing}} \tag{3.12}$$

The inertia, I, is dependent of the load on the crane. The inertia can be retrieved from the drive sheet of the crane, when the load of the item the crane needs to slew is put in. ω is the angular velocity of the slewing movement, and α is the slewing angle. The torque T from Equation 3.12 can be calculated by adding the torque for the friction with the torque that is created by the load on the crane. This torque is the resultant horizontal force of the load in the slew bearing due to a small heel of the crane, as is pictured in Figure 3.4 The equation for the total torque is now:

$$T = T_{friction} + (m_{load} * r_{load} + m_{boom} * r_{cogboom}) * cos(\beta) * sin(\gamma) \tag{3.13}$$

$T_{friction}$ is the torque to overcome the friction in the bearing of the crane and is independent on the load on the crane. This torque is known when the crane specifications are known. β is the angle of the boom, and γ is the cranes heel angle. The mass m_{load} is the mass of the load, and the hoisting blocks. The crane usually slews a few times when picking up an item and transporting it to the desired location or height, for every predicted slewing movement the energy has to be calculated. Thus, the prediction of the different slewing angles might be an important uncertainty factor.

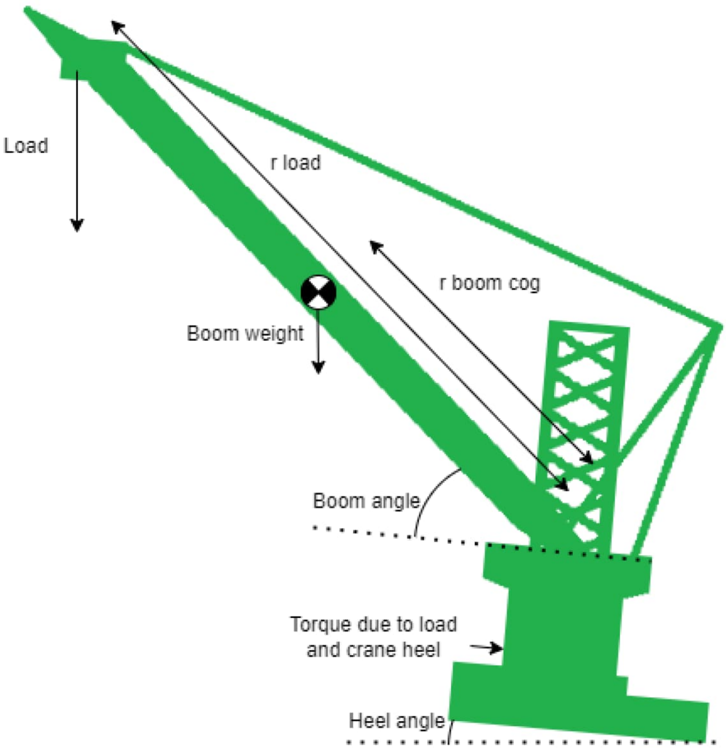

Figure 3.4.: Slewing torque due to heel of the crane

3.3.5. Efficiencies

As mentioned and written down in the equations, every function described above has an efficiency factor. The energy is not 100% translated to the movement. Therefore, in the model, every function in the model is divided by η, with η being the specific efficiency of every function, for example the hoisting of the crane. The efficiency for the function has to be estimated or calculated with known information. It is implemented in the model as an input variable.

3.4. Engines energy consumption

The required energy for the different states of the vessel now has to be translated into the required energy the engines of the vessel has to deliver. The vessel delivers mechanical energy for the thrusters that allow for the transit of the vessel, and electrical energy for the auxiliaries and equipment aboard. The required energy calculated for every energy consumption of the wind farm installation can also be called the effective energy, $E_{effective}$. The energy the engines have to deliver to get this effective energy to the different crane- and other motors can be called the brake energy E_{brake}. The translation from the required effective energy to the required brake energy has to be made now. This determines the vessels fuel consumption and thus the amount of GHG emissions for the installation procedure. The total required brake energy has to be separated between the energy for the transit and the energy for the other functions.

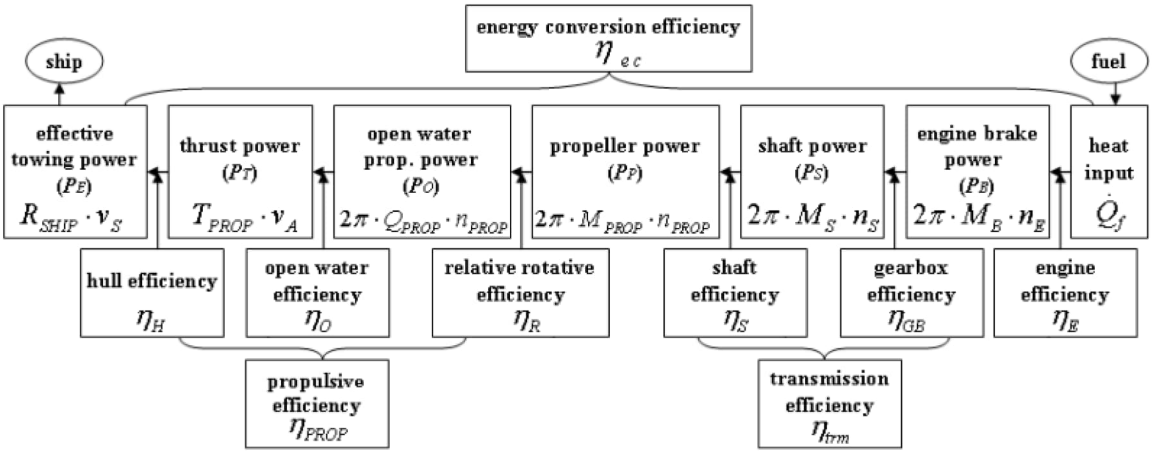

Figure 3.5.: Propulsion chain: Overview of powers and efficiencies [17]

3.4.1. Brake energy and fuel consumption transit

In section 3.3.1 the required energy for the propulsion was explained, this can be called the effective energy. The actual power the engine delivers can be called the brake power, P_b. According to Figure 3.5 from [17], there are six more efficiencies that have to be accounted for between the brake power and the effective towing power. The hull efficiency, open water efficiency, and relative rotative efficiency are often added together and the value of this propulsive efficiency can be estimated to be 0.75 [17]. This efficiency, along with the shaft and gearbox efficiency can be found in Table 3.1. The new formula for the transit energy will now be:

$$E_{B_{transit}} = \frac{E_{E_{transit}}}{\eta_{tot}} = \frac{E_{E_{transit}}}{0.72} \tag{3.14}$$

From this $E_{B_{transit}}$, finally the amount of fuel the vessel needs for the transit can be calculated. To do so, the specific fuel consumption of the engines is required. The specific fuel consumption sfc is by definition the fuel consumption of the engine related to brake power [17]. The fuel consumption can now be derived from the following formula:

$$m_{fuel_{transit}} = \frac{sfc * E_{B_{transit}}}{1000} \tag{3.15}$$

In this formula, the amount of fuel is expressed in kg, the amount of energy in kWh and the specific fuel consumption in g/kWh. The specific fuel consumption is engine related and known by the vessel owners.

3.4.2. Brake energy and fuel consumption electrical energy

The electrical energy demands determined need to be related to engine brake power of the engines. For the fuel consumption of the electrical energy generated, some losses have to be taken into account to get from the required energy towards the generated energy to accomplish this requirement: from the transmission and the generator. The transmission losses consist of shaft bearing and seal losses [17]. These losses are implemented as efficiencies, and assumptions for those efficiencies are given by [17]. The efficiencies used in the model can be found in Table 3.1. The formula for the required generated energy is now:

$$E_{B_{electrical}} = \frac{E_{E_{electrical}}}{\eta_{gen} * \eta_{trans}} = \frac{E_{E_{electrical}}}{0.91} \tag{3.16}$$

Then, again, the fuel consumption for the electrical energy can be calculated.

$$m_{fuel_{electrical}} = \frac{sfc * E_{B_{electrical}}}{1000} \tag{3.17}$$

Table 3.1.: Efficiencies engines

Variable	η
Propulsive efficiency	0.75 [17]
Shaft efficiency	0.99 [17]
Gearbox efficiency	0.97 [17]
Generator efficiency	0.95 [17]
Transmission efficiency	0.96 [17]

3.5. Emissions Calculations

Using the predicted fuel consumption, GHG emissions are calculated. Typically, Marine Diesel Oil (MDO) is used, with a carbon intensity of approximately 3.2 kg CO2 per kg. The total amount of CO2 emissions can now be calculated:

$$\text{Total GHG emissions} = m_{\text{fuel}} * \text{Carbon intensity} \tag{3.18}$$

3.5.1. Calculating Other GHG Emissions

Emissions of CH_4, N_2O, SO_x, and NO_x are estimated based on fuel consumption. These estimates are typically given in grams of pollutant per kilogram of fuel burned (g/kg fuel).

Assuming the following emission factors based on average marine diesel engines according to IMO [19]:

- CH_4: 0.2 g/kg fuel
- N_2O: 0.3 g/kg fuel
- SO_x: 1.5 g/kg fuel
- NO_x: 20 g/kg fuel

For the transit and electrical energy fuel consumption calculated previously:

$$\text{Total GHG emissions}_x = m_{\text{fuel}} * \text{emission factor x} \tag{3.19}$$

3.6. Concluding remarks

This chapter has detailed the development of a model aimed at predicting the GHG emissions associated with the installation of wind farms. The objective was to develop a model adaptable for various marine contractor installations, with a primary focus on wind turbine installation for validation and results. This is done by employing a bottom-up approach to calculate the energy required for each vessel activity, then translating this energy requirement into fuel consumption and GHG emissions. Several carefully considered assumptions were made to simplify complex calculations while aiming to remain accurate.

4

Results

In this chapter, the results of the developed model will be presented, discussed, and analysed. Initially, the input selection process will be described, highlighting the key variables used. Subsequently, the results generated by running the model with these inputs will be showcased and examined. Finally, a sensitivity analysis will be conducted to provide deeper insights into the significance of the input variables. This will also answer the subquestion *"Which variables influence the amount of energy needed for an offshore wind turbine installation?"*.
As discussed in Chapters 1 and 2, in the installation of a wind farm, different contracts apply for the different installation phases. For the results, analysis, and validation, the installation of wind turbines by a jack-up vessel will be the inputs of the model. In order to run the model, and get some results and insight, ballpark variables have to be chosen.

4.1. Input variables

The selected values for the various variables will be reviewed. This will be done for the crane, vessel, wind farm and wind turbine separately. The full table with all input variables can be found in Appendix D.

4.1.1. Input crane

For the input variables of the crane, values of some cranes were compared and a reasonable value within the same range is chosen. The total slewing angle per turbine unit needs to be assumed. In Figure 4.1, a layout of the deck of a WTIV is shown. Based on the location of the various items the slewing angles are predicted and shown in Table 4.1. More insights in the slewing angles will be given in Chapter 5.

Table 4.1.: Crane Slewing angles

Variable	**Angles**
Total slewing angle tower	360 deg
Total slewing angle nacelle	200 deg
Total slewing angle blade	400 deg

4.1.2. Input vessel

For the vessel input, most values could be assumed within a reasonable range, but for a few values, there is some uncertainty. As discussed in the previous chapter, to determine the transit energy, the vessels C_e needs to be known. Some values of C_e for different ships were given, but for a WTIV this was not the case. By checking for similarities between the ships with a given C_e factor, it is now assumed to be 8/1000. In the section 'Sensitivity analysis', this value will be further investigated.

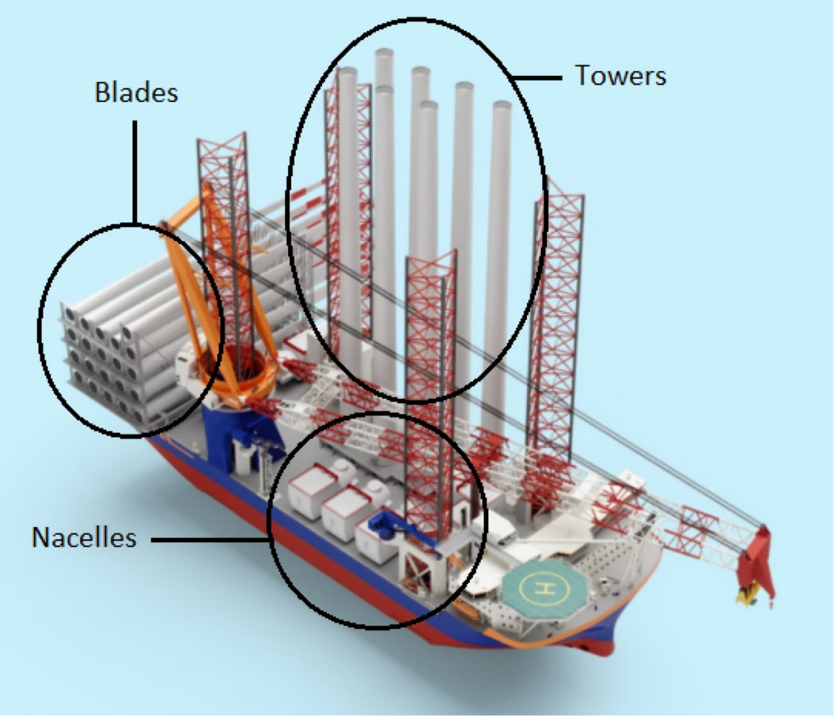

Figure 4.1.: Wind Turbine Installation Vessel layout

Another value that had to be assumed is that of the auxiliaries/hotelling function consumption per hour.

4.1.3. Input Wind Farm & Turbine

The inputs for the wind farm and wind turbine variables are based on a real wind farm, chosen from the database of 'Esgian'. The windfarm consists of 50 wind turbines located 28 km from the port. The turbine model installed in this windfarm is the 'Vestas V174-9.5', of which its input values also are retrieved from Esgian. The wind farm and wind turbone values can be found in the table in Appendix D.

4.2. Results

For the results, graphs are plotted of the effective energy predictions. In the model, the total effective energy required per installation stage is converted to the brake energy requirements, fuel and then the GHG emissions. The results of a single trip for the WTIV are first shown, and then the results for the full procedure will be discussed.

4.2.1. Single trip

Of a single trip of the WTIV, meaning one trip the vessel performs from loading at the port until arriving back at the port, various results will be looked into. Graph of the mean effective power per stage is shown in Figure 4.2. This is represented as a step function because for every stage the effective energy is predicted based on physics, and not time related (except for the auxiliaries/hotelling which is assumed to have a constant power). The total energy per stage is divided by the time per stage to acquire this graphical representation. The peaks during the "Transit" stages are the highest, but they are short-lived. This means that while transit requires a high power output during its operation, it does not necessarily consume the most energy overall because the duration is relatively short. The mean power for the loading and installation are barely visible in this graphical representation. In Figure 4.3 Figure 4.4 shows the cumulative energy over time for one trip, broken down by stage. This plot provides a detailed look at the energy consumption pattern for a single trip. It is clear from this graph that the auxiliaries are predicted to require the most energy, followed by jacking up. Transit is the third highest energy consumer, so the high peaks seen in Figure 4.2 are short-lived enough to not give the highest energy requirements.

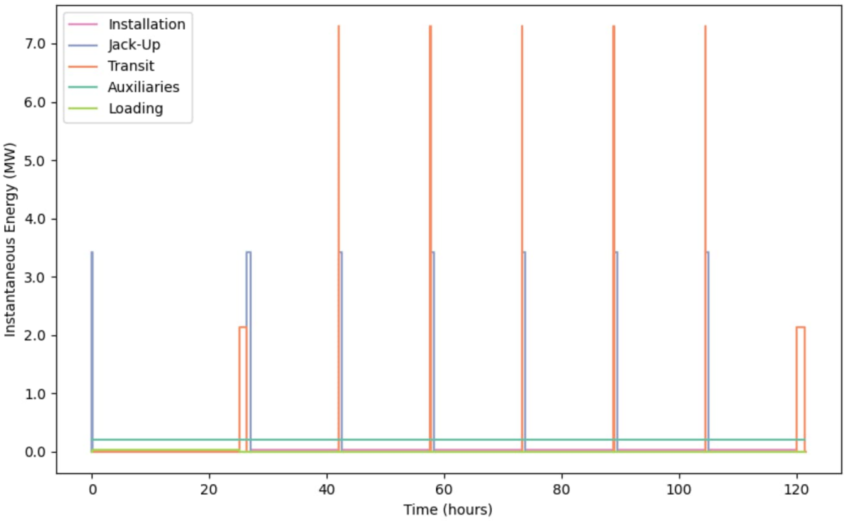

Figure 4.2.: Mean Power one trip

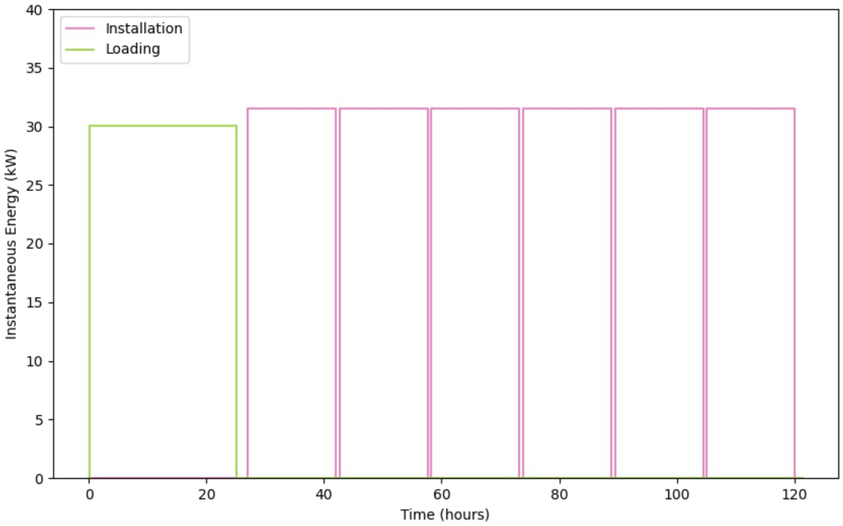

Figure 4.3.: Mean Power one trip - Crane

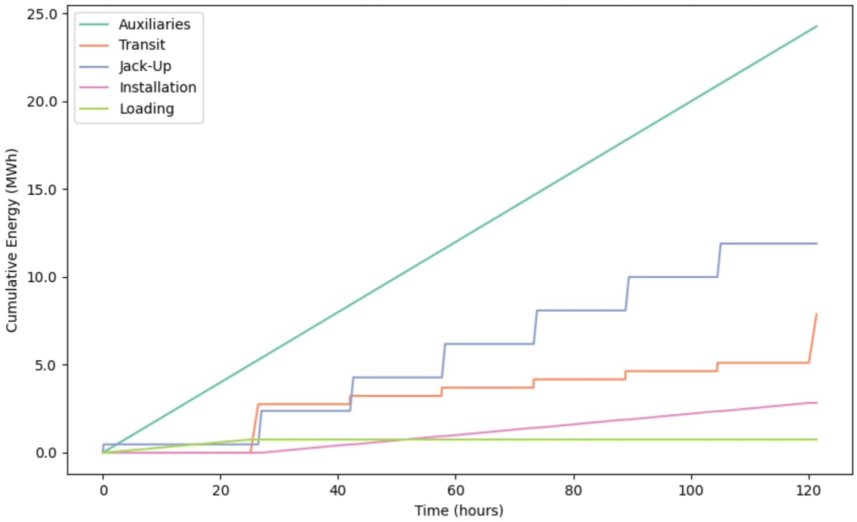

Figure 4.4.: Energy consumption per stage of one trip

4.2.2. Full Wind Farm installation

Now the results for the full wind farm installation will be analysed. Figure 4.5 presents a stacked plot illustrating the cumulative effective energy consumption over time for various stages, while Figure 4.6 displays the same consumption data in a non-stacked format. The plots illustrate how each stage contributes to the total energy consumption over time. The total cumulative energy consumption reaches just over 400 MWh by the end of the installation process. Auxiliaries consume the largest portion of energy throughout the installation process. This indicates that auxiliary activities are the most energy-intensive. The energy consumption for each activity increases linearly over time. As mentioned before, this is because the model is not time based but physics based and the energy consumption per stage is computed linearly. The total effective energy per installation step is also pictured in a barplot shown in Figure 4.7. This plot also shows the auxiliaries energy consumption is the most significant.

The model transformed the effective energy to the brake energy via the engine specifications. Table 4.2 shows both the effective and the brake energy of the stages for the full wind farm installation. The brake energy is translated to the total fuel consumption. This was done for the electrical consumption and the transit separately due to different types of efficiencies. These values can be found in Table 4.3.

Table 4.2.: Predicted energy requirements per installation step of full wind farm installation

Stage	**Effective energy**	**Brake energy**
Transit	69.1 MWh	95.9 MWh
Jack-up	99.6 MWh	115.1 MWh
Installation	29.5 MWh	34.2 MWh
Loading	6.31 MWh	7.30 MWh
Hotelling	205.9 MWh	238.2 MWh

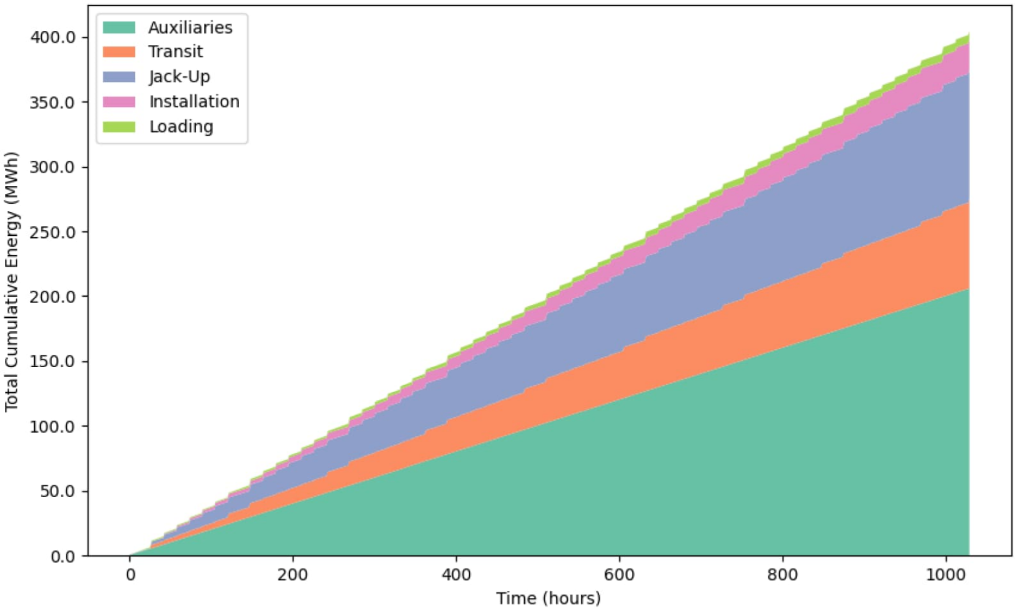

Figure 4.5.: Stacked Effective Energy

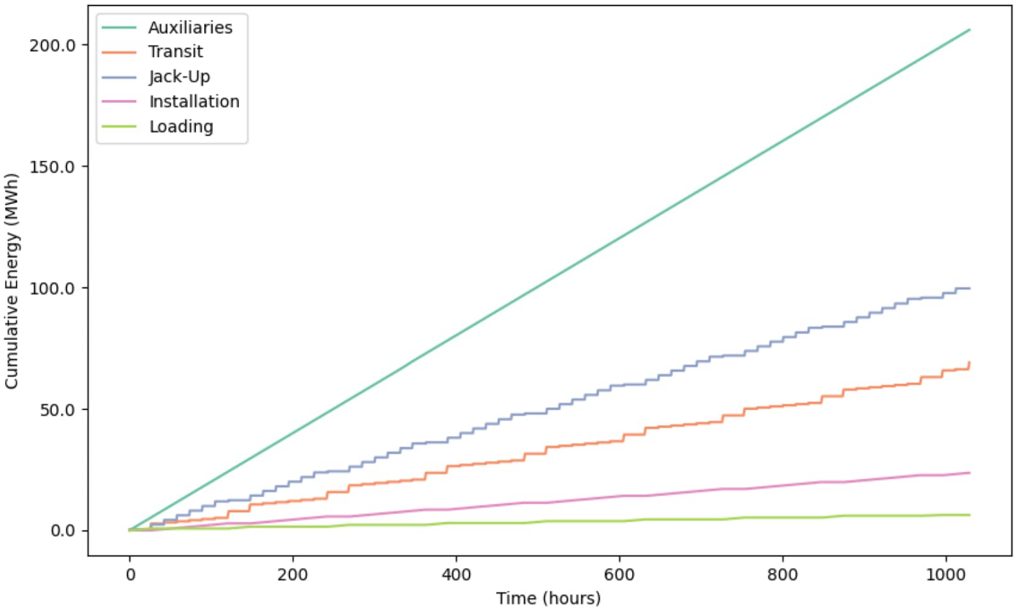

Figure 4.6.: EnergyOvertime

4.2.3. Insights on amount of emissions

The total needed predicted fuel for the installation process is 98150.70 kg. This leads to the total amount of predicted GHG emissions as pictured in Table 4.4.

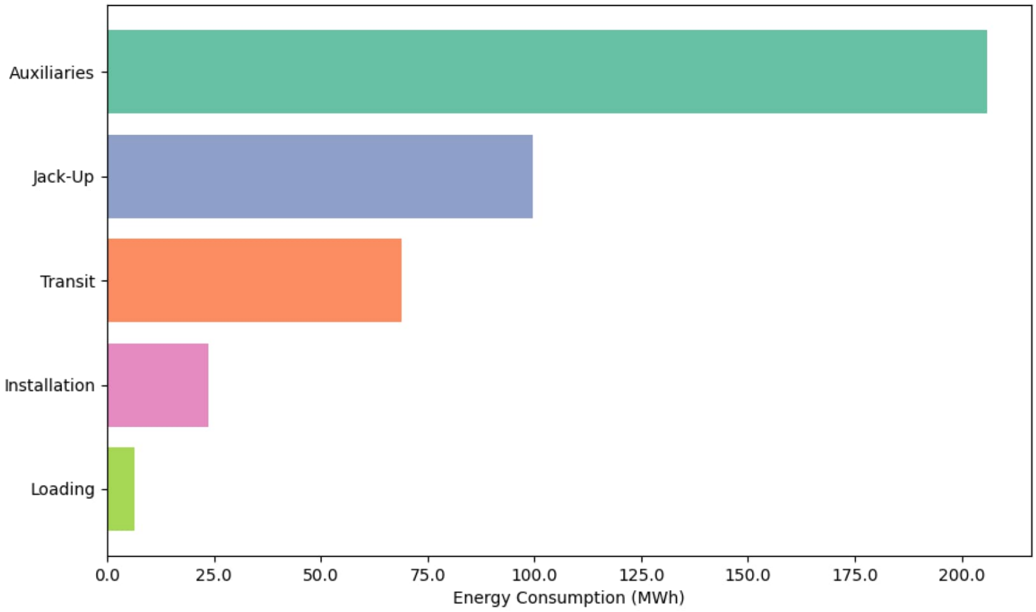

Figure 4.7.: Energy requirements per installation step of the full wind farm installation

Table 4.3.: Brake Energy and fuel consumption for Transit and Electrical

Stage	Brake Energy	Fuel consumption
Transit	95.9 MWh	19.18 mt
Electrical	394.8 MWh	78.97 mt

Table 4.4.: Predicted GHG Emissions of the installations of a wind farm

Emission Type	Total Emissions [kg]
CO2	312533
CH4	19.5
N2O	29.3
SOx	146.5
NOx	1953

From the results can be concluded that the model estimates the amount of CO2 emissions of 50 wind turbines to be 312533 kg. The efficiency of a coal-fired power station is around the 0.745 kg/kWh. So instead of installing 50 wind turbines, 419507 kWh could have been produced in the coal fired power station. One wind turbine can generate about 10 MW. For the wind park to generate the amount of energy that could have been made by a coal-fired power station during the installation procedure, it would cost less than one hour!

4.3. Sensitivity analysis

Now the primary results are calculated and discussed, it is time to look into the sensitivity of the developed model. Since for the input values, some assumptions had to be made, it is good to look into the difference in results if slightly different assumptions were made. The primary goal is to identify which parameters have the most significant effect on the model's output, thus highlighting areas where accuracy in input data is most critical or where changes could be made to improve the overall efficiency.

Typically, in a sensitivity analysis, each model parameter is varied in turn by a small amount within the region of a best estimate or standard case. For each parameter, the resulting relative change in the state variable is divided by the relative variation in the parameter to obtain sensitivity coefficients [20].

For the sensitivity analysis, different input values will be tested for their sensitivity. This will be done for variables that were estimated with the most uncertainty and for variables that are interesting to check because of their potential impact on the overall results. Table 4.5 shows the variables chosen to perform a sensitivity analysis on, and their used ranges.

Table 4.5.: Variable Ranges and Initial Values

Variable	**Initial value**	**Value range**
C_E	$\frac{7}{1000}$	$\frac{4}{1000}$-$\frac{10}{1000}$
Distance port	28 km	15-50 km
Weight vessel	35000000 kg	33000000-3600000 kg
Speed vessel	6 m/s	4-8 m/s
Jack up height installing	20 m	10-25 m
Slewing torque friction	7000 kN	3000-9000 kN
Installation time	15 h	10-25 h
Loading time	25 h	20-35 h
Efficiency crane	85%	80-95%
SFC	200 g/kWh	180-230 g/kWh

In Figure 4.8 the plots of the sensitivity analysis are shown. The y axis represents the amount of predicted fuel consumption and the x axis shows the range of the changed input variable. The red dot represents the outcome of the primary results discussed in the previous section. The slope of each of those graphs is calculated. The results are shown in Table 4.6. For more insights and comparison the standardised slope is also calculated. This is also called the standardized regression coefficient and can be found by multiplying the slope with the ratio of the standard deviation of the parameter to the standard deviation of the output [21].

The vessel weight has a minimal impact on the amount of fuel needed for the wind turbine installation process. This also confirms one of the assumptions made in Chapter 3 about not taking into account the change in vessel weight when the transit is performed with or without turbines. C_e has the biggest slope, but its standardised slope is not as big. The standardised slopes correspond more to the graphical representations shown. The installation time has the biggest impact on the fuel consumption. This is likely due to the auxiliaries being the most energy consuming, and a longer installation time means the auxiliaries consume for a longer time as well.

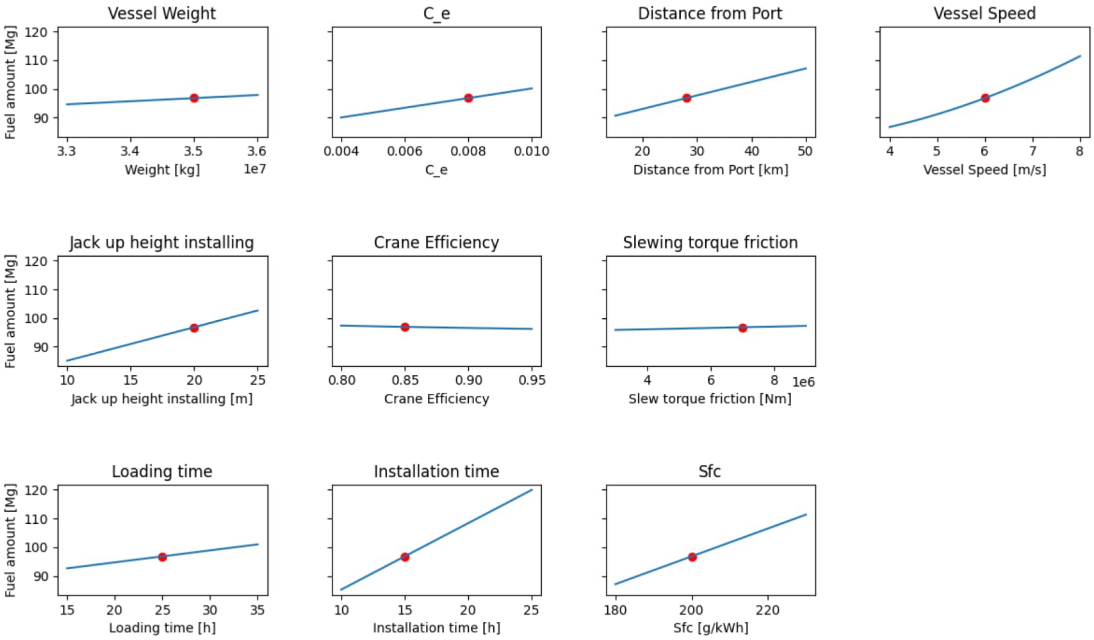

Figure 4.8.: Sensitivity plots

Table 4.6.: Slope values of variables

Variable	**Slope**	**Standardised slope**
Installation time	2.3135	0.0201
Vessel Speed	6.1786	0.0142
Sfc	0.4908	0.0141
C_E	1680.8684	0.0058
Distance from Port	0.4700	0.0095
Jack up height installing	1.1664	0.0101
Loading time	0.4164	0.0048
Vessel weight	0.0000	0.0019
Slewing torque friction	0.0000	0.0008
Crane Efficiency	-9.0657	-0.0007

4.4. Concluding remarks

In this chapter the outcomes generated by the developed model were presented, discussed, and analysed. The focus was on predicting the GHG emissions during the installation of wind farms. First, the input variables were selected. Then the results for a single trip and the full wind farm installation were analysed. Finally, a sensitivity analysis was conducted to evaluate the impact of various input parameters on the model's output. Overall, the results provide a solid basis for predicting the GHG emissions involved in wind farm installations. The sensitivity analysis revealed how different input variables impact the model's output, highlighting the importance of accurate data for certain key parameters.

5

Validation

The created model needs to be verified to determine if the predicted emission levels accurately reflect the actual emissions produced during an installation project. Since there is a limited amount of data available and Huisman Equipment, the company that collaborated on this thesis assignment, is specialised in the cranes equipped on the WTIVs, the validation in for this thesis will be solely focused on the energy consumption of the crane. First, the case study will be discussed. This will answer the subquestion *"What case study can be used to validate the model?"*. For this case study the relevant data will be retrieved. Then, the model results for the energy consumption of the main hoist, whip hoist, luffing, and slewing will be compared to the real data. Next, the results of the crane part will be further analysed and compared with the available data.

5.1. Case Study: Crane

For the decision making of determining the case study these factors have been taken into account:

- The WTIV has to be equipped with a Huisman crane with availability of data.
- There has to be data available on Esgian on the contracts, the WTIV, the installation times, the wind farm specifications, and the wind turbine specifications.

These preconditions led to the eventual case study. The required inputs of the crane and the wind farm can be found in Appendix D.2.

Crane data from the installations is compared with the effective energy calculated in the model. In the model, the distinction was made between the slewing, luffing, and hoisting of the crane. For the validation, the same will be done. The actual crane data is divided into these different functions, and each function will be plotted and compared with the model's output.

For the case study the data is retrieved from a database. To do so, first the times of the installation and loading of the crane have to be manually picked from the data dashboard of Huisman Equipment. The data of the installation of 53 wind turbines is retrieved. The data for the power of the main hoist, whip hoist, boom hoist (luffing), and slewing is obtained, and then integrated over time to get the total energy consumption per movement. Executing the model developed in Chapter 3 with the case study parameters in the crane energy consumption output depicted in Figure 5.1.

The boxplot of the energy consumption per movement of the 53 installed wind turbines is shown in Figure 5.2, as well as the model prediction. In Table 5.1 the mean energy consumption per movement and the model output can be compared to each other.

Hoisting comparison

It is evident that for the main hoisting, the predicted energy consumption is quite accurate, falling within the central 50% of the data. For the whip hoist, the predicted energy aligns very well with the data from the 53 wind turbine installations. The slightly lower predicted consumption for the main hoist compared to the actual consumption may be due to the crane operator's hoisting operations not being 100% efficient.

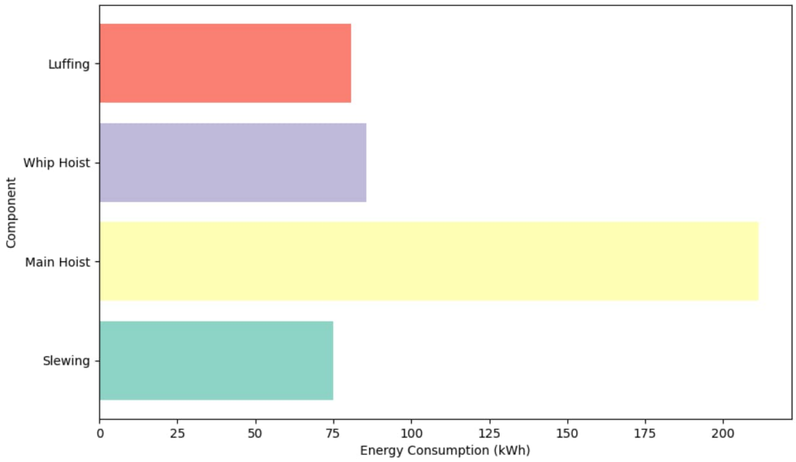

Figure 5.1.: Predicted crane energy distribution Case Study

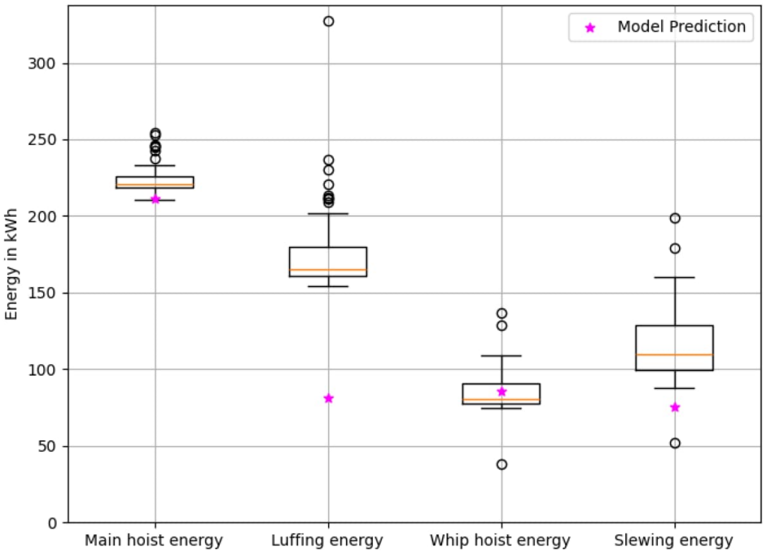

Figure 5.2.: Boxplot of the data and the predicted model energy consumption

Table 5.1.: Comparison of Mean Energy Consumption and Model Predictions for Different Installation Types

Installation Type	Mean Energy Consumption	Model Prediction
Slewing	114 kWh	75 kWh
Luffing	177 kWh	81 kWh
Main hoist	224 kWh	211 kWh
Whip hoist	85 kWh	86 kWh

Luffing comparison

For the luffing, the predicted energy consumption is significantly lower than the actual energy consumption of the crane, by more than a factor of 2. This discrepancy indicates a need for further research into the crane's luffing motions.

Figure 5.4 displays a boxplot formed from the data of positive luffing angle changes per installation for 53 wind turbines, compared to the predicted luffing used as input for the results. Only positive angle changes are considered, based on the assumption made in Chapter 3 that only positive luffing angle changes require energy. For this crane movement, there is a notable difference between the predicted and actual angles. Figure 5.6 shows a graph of the luffing angle during one of the wind turbine installations. It is clear that there is significant luffing around the 75 ° and 85 ° marks. This indicates that extra luffing occurs when the crane is already high in the air, meaning the change in the boom's center of gravity would be smaller compared to luffing from a smaller angle. The additional amount of luffing during a wind turbine installation is approximately 160°. The reason for this amount of extra luffing could be because in the model, only the effective needed angles were taken into account. When operating a crane offshore to install wind turbine parts, extra movements can be needed to get an asset very precisely to its desired location.

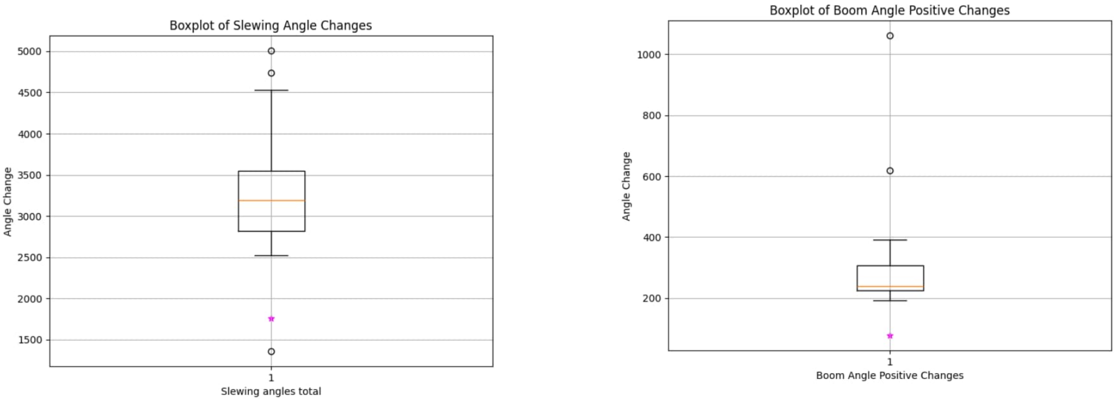

Figure 5.3.: Boxplot of the slewing angles

Figure 5.4.: Boxplot of the positive luffing angle changes

Figure 5.5.: Boxplots of the Slewing angles and Luffing angles

Slewing comparison

For the slewing motions, the model predictions are also inaccurate. The predicted energy consumption is too low and falls outside the central 50% range of the data. The predicted slewing is almost half of what the actual data indicates. Further investigation into the slewing motions is necessary. Figure 5.3 presents a boxplot of the total slewing angle data per installation for 53 wind turbines, alongside the predicted slewing angles used in the model. The data reveals significantly more slewing activity than predicted, with a discrepancy of nearly 1500 °. This is about 80% more than the original input slewing angles used.

The reason for this amount of extra luffing and slewing could be because in the model, only the effective needed angles were taken into account. When operating a crane offshore to install wind turbine parts, extra movements can be needed to get an asset very precisely to its desired location.

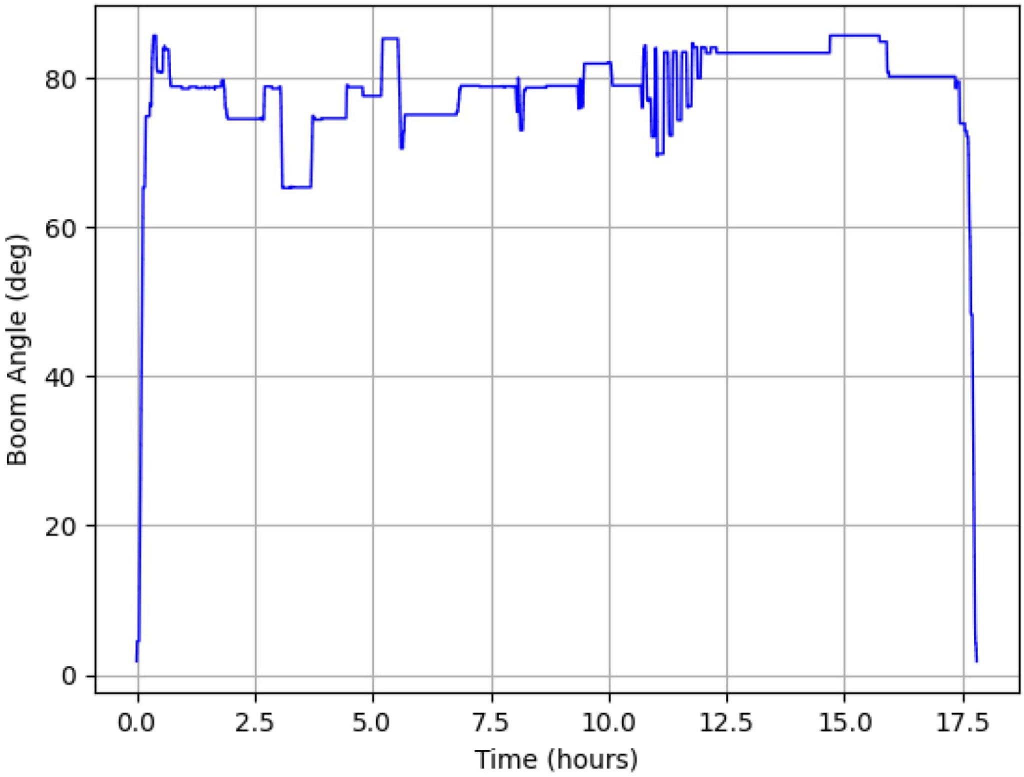

Figure 5.6.: Luffing angle over time of one WT installation

5.1.1. Adapt new angles into model

Since the angles for both the slewing and the luffing motions appear to be incorrectly predicted, it is interesting to see what happens do the models energy prediction when the right angles are implemented. This will now be looked into.

For the luffing to take into account the extra amount in the model, the following equation can replace equation 3.10:

$$E_{luffing} = \frac{(1/2 * m_{boom} * v_{cog}^2 + m_{boom} * g * (h_{cog} + extraheightboom)}{\eta_{luffing}} + \frac{1/2 * m_{blocks} * v_{blocks}^2 + m_{boom} * g * (h_{blocks} + extraheightblocks)}{\eta_{luffing}} \tag{5.1}$$

With the extra heights being:

$$extraheightx = 16 * ((sin(80°) - sin(70°)) * lengthx \tag{5.2}$$

In which length x represents the distance of the cog for the boom, and x represents the length of the boom for the blocks. 16 times a 10 degree change makes the total luffing angle in the model to be in the same range as the data.

If the slewing angles input in the model are multiplied by 1.8, the total slewing angle would be 3520 °, which is only 40 ° off from the mean slewing angle derived from the data.

The model is executed again and the new results are shown in the boxplot in Figure 5.7. The new luffing and slewing energy predictions are much closer to the actual data, indicating that the model can accurately predict the crane's energy requirements with the correct input. It appears that luffing and slewing occur more frequently than previously predicted.

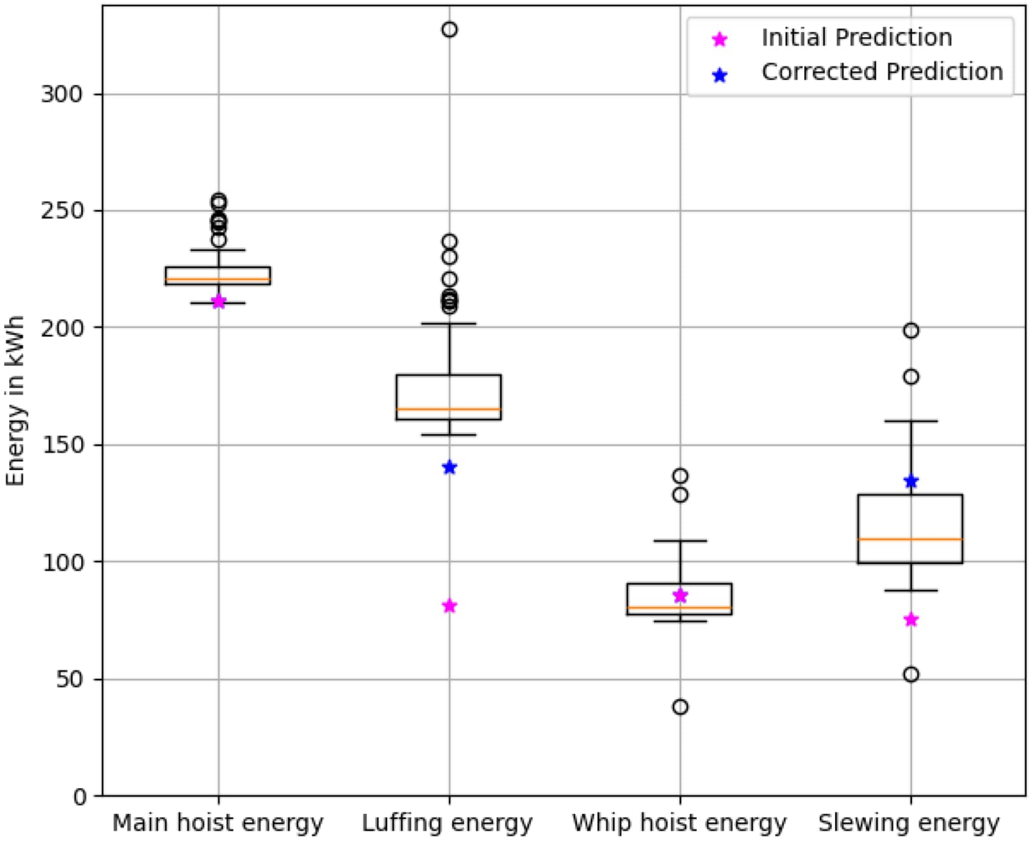

Figure 5.7.: Boxplot of the data and the predicted model energy consumption after angle alterations

5.2. Concluding remarks

The validation of the developed model is a crucial step to ensure that the predicted emission levels accurately reflect the actual emissions produced during an installation project. Given the limited data availability the validation in this thesis focuses solely on the energy consumption of the crane. The validation compared the model's predicted energy consumption for slewing, luffing, and hoisting with actual crane data from the installation of 53 wind turbines. The predicted energy consumption for the hoisting was proven to be accurate. For the slewing and the luffing, wrong angles were used as an input in the model. After adjusting, the results of the developed model matched the data better. This validation confirms the model's capability to reliably estimate the energy consumption of crane operations during wind turbine installations, providing a solid foundation for further refinement and application in real-world scenarios.

6

Conclusions and Recommendations

This chapter provides a look back onto the research in this thesis. The aim was to develop an easily adaptable model that can provide a framework towards the prediction of the amount of greenhouse gas emissions that are emitted by a wind turbine installation vessel. First, it is time for the conclusions. All subquestions will be briefly answered, and then the answer on the main research question will be given. The next section, the recommendations, will discuss the limitations of this thesis and suggests future work to be done.

6.1. Conclusions

This research was done for the emissions of WTIVs, which are employed by marine contractors. The parts of the Wind Farm installation processes taken into consideration were the installation of the offshore substation, the monopile foundation, and the turbine itself. In this conclusion per subquestion the answers will be discussed. This leads to the eventual answer on the main research question of this study.

The first subquestion of this thesis was: *How can the GHG emissions of marine operations be computed?* The answer of this subquestion was tracked down by performing literature research. The EU ETS obliges the offshore sector to report their emissions. Greenhouse Gas emissions should be calculated by multiplying the fuel consumption with the emission factor. The fuel consumption of a vessel should be calculated with one of the following four methods:

- Bunker Fuel Delivery Note combined with periodic stocktakes of fuel tanks based on tank readings.
- Bunker fuel tank monitoring on board.
- Flow meters for applicable combustion processes.
- Direct CO2 emission measurements.

The method currently most used is the first one. This is why it was decided that in order to predict the amount of GHG emissions, the fuel consumption should thus be calculated.

The second subquestion introduced was: *What are the installation procedures of an bottom fixed offshore monopile wind turbine?* This subquestion was also answered with literature research. Different scheme's were compiled to picture all the steps performed to install an offshore wind farm. For a wind farm the main steps were:

- Install foundations
- Install transition pieces
- Install wind turbines
- Install substations

The foundations and transmission pieces have to be installed before the wind turbines can be placed, and the offshore substation(s) can be placed independently. The trip of a Wind Turbine Installation Vessel has these main steps to perform:

- Loading assets
- Transit to site
- Install asset
- Transit to next wind turbine spot, when applicable, and repeat previous step
- Transit back to port and, when applicable, load up the vessel again

Another way to load up the wind turbine installation vessel is by feedering. Currently feedering is not commonly practiced.

The third subquestion for this thesis was: *What are the energy consumers during the installation procedures?*. To answer this question, the trips of a Wind Turbine Installation Vessel should be split into the different operations: Loading, Transit, Jack Up (if applicable), and Installing the asset itself. During all those tasks, the auxiliaries/hotelling system of the vessel is running for its basic power supply. For the transit, the thrusters of the vessel that allow for the forward propulsion are the energy consumers. For the loading and installing, the crane and when necessary other equipment are the main energy consumers. For the jack up function, the jack up pillars consume the energy.

The next two subquestions were *Which variables influence the amount of energy needed for an offshore wind turbine installation?* and *How can a model be generated for the emissions of (part of) the installation procedure?* Those subquestions are answered in Chapter 3: the model development. A bottom-up approach is used to create a model that predicts the amount of emissions it costs to install an offshore wind farm. This is achieved by predicting the required energy for each operation using physics formulas, then translating this into the amount of fuel needed based on engine characteristics. This allows for the calculation of the eventual emissions. Every formula explained in Chapter 3 provides the variables needed for the model to make a prediction. Specifications of the crane, the vessel, the wind turbines, the wind farm, and the installation times need to be known to make a prediction.

More of subquestion five is answered in the sensitivity analysis. Values were changed within their plausible range and the change in needed fuel was analysed. Change rate was pictured in graphs and their slopes were calculated. The vessel's factor C_e has the biggest influence on the total amount of fuel consumption when installing offshore wind turbines.

Next, the sixth subquestion is answered: *What case study can be used to validate the model?* Multiple requirements were made and a case study of which crane data is available was found. The validation is only performed for the crane, since there is no other data available. Data from the installation of over 50 wind turbines was retrieved for this comparison. For the crane, the slewing and luffing angles were misjudged in the model. After changing these, the model provides an outcome for the crane energy consumption that is within a desired range of the actual energy consumption.

The last subquestion formed at the start of this research was *What are the opportunities to reduce emissions?*, which is already partially answered in this conclusion. Opportunities to reduce the emissions can be found in the sensitivity analysis. As mentioned, C_e is a factor that influences the amount of emissions immensely, so obtaining a vessel with a C_e factor as low as possible would reduce the amount of emissions the most. Also, in the model development the jacking down, hoisting down, and luffing down were considered energy neutral. With these downward motions the potential energy is released, and unfortunately this can not be reused and is flared. If this energy could be stored, this would allow for the energy to be reused, which would reducer the amount of energy needed from the generators, and therefore reduce the emissions. The main research question of this thesis is *How can the greenhouse gas emissions of the installation of an offshore wind farm by wind turbine installation equipment be predicted?*. This is answered step by step by compiling the subquestions and answering those. By predicting the amount of energy required for each step in the operation, and then translating that to the required amount of fuel by the vessel's engines, the amount of emissions for the operation can be predicted. For the case study being the installation part done by the crane, this is validated. Predicting the required energy through physics formulas proves to be a viable solution. Further validations are necessary, but more details on this will be provided in the next section. Overall the developed model for the prediction of greenhouse gas emissions proves to be a stable framework that could be used in the future by marine contractors when negotiating contracts and installation costs.

6.2. Recommendations

This thesis aimed to develop a model that could predict the amount of greenhouse gases emitted when installing an offshore wind farm. However, this research has its limitations and therefore some recommendations for improvement and future work are made:

Energy restitution

As mention in chapter 3, the potential energy that is released when lowering loads is flared. More research should be done about the possibilities to store this energy. If in the future systems such as batteries would be installed on WTIVs, this might reduce the amount of required energy from the generator, which would be very beneficial to the amount of emissions. Especially since the predicted jack up energy requirements are relatively high, improvements here are recommended.

Validation

The developed model is validated for the crane part only due to limited availability of data. It is recommended that the rest of the model also gets validated in order to determine if the amount of greenhouse gases corresponds to the actual amount of emissions. For this, retrieving data from the marine contractors is necessary. The input variables for the vessel have to be known, as well as the amount of fuel consumed, to perform a validation on this part of the model.

Sensitivity analysis

In this research the sensitivity analysis was performed on the 10 input variables, assumed to be the most valuable to get more insights of. However, more sensitivity could be performed on other input variables in the future.

Feedering

It was briefly explained in chapter 2, but the assets a wind turbine installation vessel installs could also be feedered to the vessel, instead of the vessel making all the transits. Since the model predicts the energy consumption is mostly due to auxiliaries, it might be interesting to look more into the feedering. If there is less time needed for the installation procedure, the amount of emissions for the vessel will reduce. But the amount of emissions the feedering boat emits has to also be incorporated for a good overall prediction.

Expansion of the model

The developed model is specifically applied to the installation of wind turbines. However, it is highly adaptable and can be easily modified to predict the amount of emissions associated with the installation of substations or monopile foundations. It is recommended to make these adaptations so that comprehensive predictions can be made for the entire installation process, ensuring a complete and accurate assessment of emissions across all components of the project.

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A

Research Paper

A Methodology to predict the Greenhouse Gas Emissions of Offshore Wind Farm Installations

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Abstract

The need to reduce greenhouse gas emissions has led to the use of renewable energy sources, such as offshore wind energy. This study looks at the emissions from installing offshore wind farms, focusing on Wind Turbine Installation Vessels (WTIVs) with cranes by Huisman Equipment BV. The study aims to create an adaptable model to predict GHG emissions during the installation process. The developed model calculates the energy needed for various stages, including transit, jacking, crane operations, and auxiliary functions. For installing 50 wind turbines, the model predicts a total energy requirement of about 408,000 kWh, resulting in GHG emissions of around 312,500 kg CO2. Sensitivity analysis identifies key parameters like vessel speed, jack-up height, and crane efficiency. Validation of the crane's energy requirements shows the model can accurately predict energy needs if the right angles for input are used. Recommendations include more validation, technology upgrades, and exploring other loading methods to reduce emissions.

Index Terms—GHG emissions, offshore wind farms, WTIV, renewable energy, wind park installation

I. Introduction

The urgent need to combat climate change has accelerated the shift towards renewable energy sources. International agreements, such as the Paris Agreement, underscore the critical importance of reducing greenhouse gas (GHG) emissions to mitigate global warming. In line with these commitments, the European Union aims to achieve climate neutrality by 2050, with an interim goal of reducing GHG emissions by at least 55% by 2030. Offshore wind energy plays a pivotal role in this transition.

To align with the Net Zero Emissions by 2050 Scenario, which anticipates approximately 7400 TWh of wind electricity generation by 2030, the average annual growth rate of wind energy generation must increase to about 17% [1]. Offshore wind energy is particularly notable for its potential and efficiency in harnessing wind power.

However, the installation of offshore wind farms involves complex marine operations that contribute to GHG emissions. These operations include the transportation of heavy components, jacking up vessels to create stable platforms, and using cranes to lift and assemble wind turbines. Each of these activities consumes substantial energy, primarily derived from fossil fuels, leading to significant GHG emissions.

The goal of this study is to develop a model to predict GHG emissions during the installation of offshore wind farms. The main research question is: ”How can the greenhouse gas emissions from the installation of an offshore wind farm by wind turbine installation equipment be predicted?” To address this question, the study examines several aspects related to emissions calculations, installation procedures, energy consumption, and potential emission reduction strategies.

By analysing the emissions from offshore wind farm installations, this study aims to provide valuable insights for marine contractors in the renewable energy sector.

II. Methods

The EU Emissions Trading System (ETS) is a key part of the EU's plan to fight climate change and is the world's first major carbon market [2]. It uses a cap-and-trade system, setting a limit on the total amount of GHG emissions that sectors covered by the system can emit. Companies get or buy emission allowances, which they can trade. The cap is lowered over time, ensuring total emissions decrease.

Technical standards for monitoring and reporting emissions from maritime operations are crucial for compliance with the EU ETS. Directive 2003/87/EC and Regulation 2015/757 outline methods for calculating CO2 emissions from fuel consumption. These methods include Bunker Delivery Notes (BDN), periodic fuel tank checks, flow meters for combustion processes, and direct CO2 emissions measurements. Each method has its pros and cons, and their use depends on the specific circumstances of the marine operation [3].

The installation of offshore wind farms involves several complex procedures requiring different vessels and equipment. Key steps include installing monopile foundations, offshore substations, and wind turbines. This is also pictured in Figure 1. Major energy consumers during installation of these assets include thrusters, cranes, jack-up pillars, auxiliary systems, engines, and generators. Each component's energy requirements are analysed.

The methodology for this study involves creating a physics-based predictive model to estimate the GHG

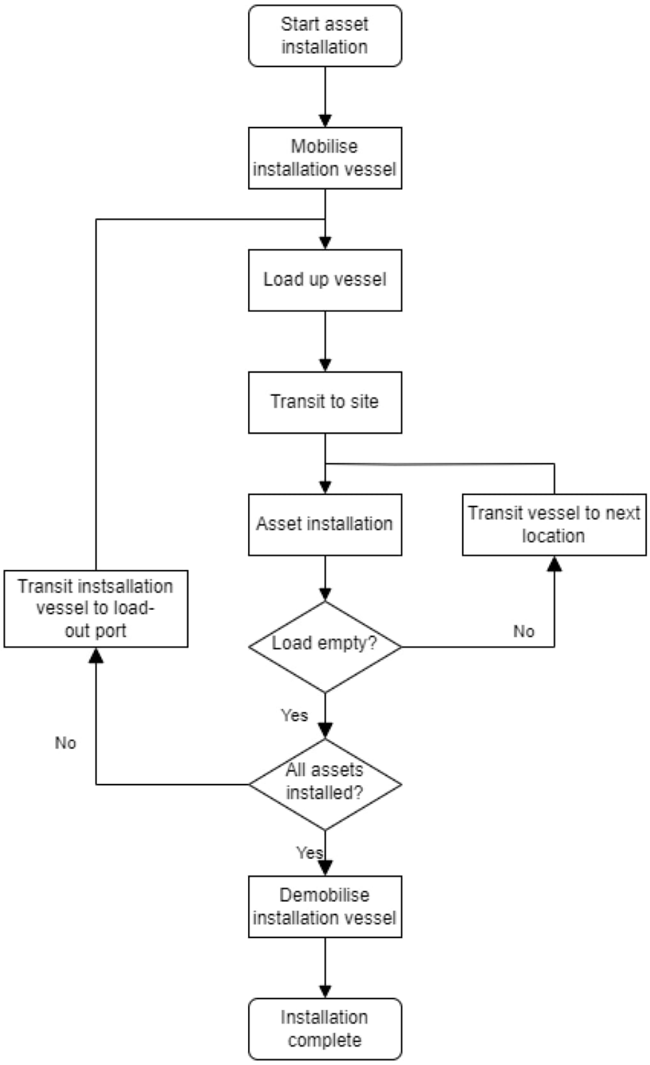

Fig. 1. Installation procedure WTIV

emissions generated during the installation of offshore wind farms. The model is built using Python and includes factors that influence energy consumption and emissions, such as vessel transit, jacking operations, crane activities, and auxiliary functions.

A. Model Development

The model uses a bottom-up approach, breaking down the installation process into its main components and calculating the energy needed for each. This process based approach, pictured in Figure 2, allows for physics based predictions of energy consumption and emissions.

B. Model Assumptions

The model uses data from various sources, including technical specifications from Huisman Equipment BV, literature on marine fuel consumption, and standards for emissions calculations. Assumptions for this model include: Hoisting down, luffing down, and jacking down are energy neutral; Energy needed by the blade manipulator is minimal; Energy required due to motor inertia is minimal.

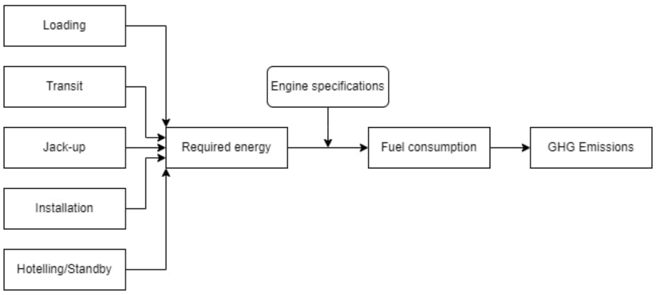

Fig. 2. Model structure for predicting GHG emissions.

C. Transit Energy Calculation

The energy needed for transit is calculated using marine engineering formulas [4], considering factors like hull resistance, vessel speed, and propulsion efficiency. The transit phase involves moving the WTIV from the port to the installation site, and moving the vessel to the next turbine location.

D. Jacking Energy Calculation

The model calculates the energy required to lift the vessel above the water to provide a stable platform for turbine installation. This calculation includes the potential energy based on the vessel's mass and the height it needs to be raised, as well as the kinetic energy, which depends on the jack-up speed and mass. Additionally, the energy consumption is influenced by the efficiency of the jacking system.

E. Crane Energy Calculation

The energy requirements for crane operations are calculated by considering the movements: luffing, slewing, and hoisting. Each movement involves specific loads and distances, and the model takes these factors into account to estimate the total energy consumption. For each type of movement, the model combines the work done (based on the load and distance) and the kinetic energy (considering the speed and mass) to predict the required energy.

F. Auxiliary Energy Calculation

The energy consumption of auxiliary systems, like power generation, airco, and water treatment, is modeled based on continuous operation during the installation process. These systems are essential for maintaining onboard conditions and ensuring the vessel's functionality. The mean power is multiplied with the total time the vessel is mobilised.

G. Translation to emissions

The energy requirements for the vessel's various operations must be converted into the energy that the vessel's engines need to deliver. The vessel supplies mechanical energy for the thrusters, which enable it to move, and electrical energy for the onboard auxiliaries and equipment. The energy calculated for each energy-consuming activity during wind farm installation is termed effective energy. The energy the engines must deliver to produce this effective energy is termed brake energy. This conversion helps determine the vessel's fuel consumption and, consequently, the GHG emissions during the installation process. The total required brake energy is divided between the energy needed for transit and the energy needed for other functions.

For transit operations, the effective energy is adjusted for various efficiencies, such as hull, open water, and relative rotative efficiencies, which collectively have an estimated value. This adjustment determines the brake power needed from the engines. The specific fuel consumption of the engines is then used to calculate the fuel needed for transit.

For the electrical energy demands, the model considers transmission and generator losses. These losses are accounted for by adjusting the effective energy to determine the brake energy required from the engines. The fuel consumption for generating electrical energy is then calculated similarly to transit fuel consumption.

Efficiencies for different components, such as propulsive efficiency, shaft efficiency, gearbox efficiency, generator efficiency, and transmission efficiency, are factored into the calculations.

Using the predicted fuel consumption, GHG emissions are calculated, typically assuming the use of marine diesel oil (MDO) with a known carbon intensity. Emissions of other pollutants, such as methane (CH_4), nitrous oxide (N_2O), sulphur oxides (SO_x), and nitrogen oxides (NO_x), are also estimated based on fuel consumption and standard emission factors for marine diesel engines.

III. Results

The results of the predictive model give a overview of the energy consumption and GHG emissions from installing offshore wind farms using WTIVs. The analysis covers both a single trip and the full installation process for 50 wind turbines, with a vessel capacity of 6 wind turbines.

A. Single Trip Analysis

The single trip analysis shows the average power needed for each stage of the installation process. Transit and auxiliary functions are the most energy-intensive stages. During transit, the high energy demand is mainly due to the vessel's propulsion system, which must overcome significant hull resistance. Auxiliary functions, which operate continuously, account for a large portion of energy consumption. The results of the single trip analysis are pictured in Figure 3.

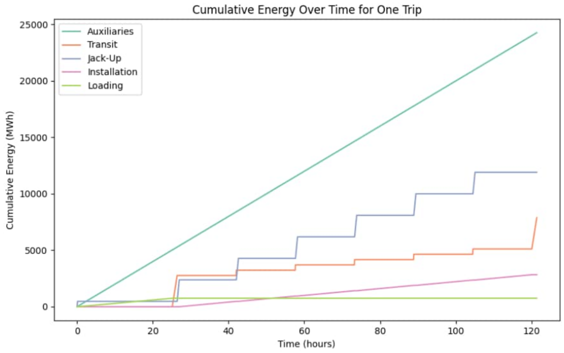

Fig. 3. Results single trip

B. Full Installation Process

For the complete installation of 50 wind turbines, the model predicts a total energy requirement of about 400,000 kWh. The breakdown of effective energy consumption by stage is as follows:

- Transit: 69,074 kWh
- Jacking: 99,565 kWh
- Crane Operations: 29,539 kWh
- Auxiliary Functions: 205,935 kWh

This is also pictured in Figure 4

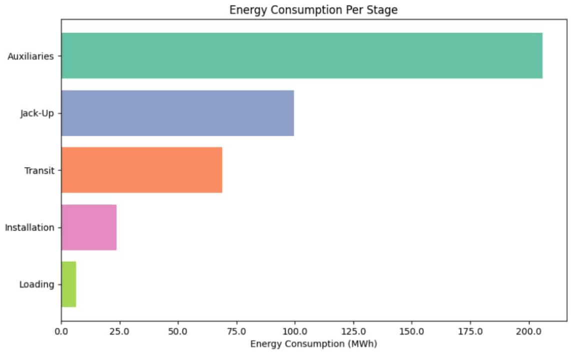

Fig. 4. Energy consumption breakdown by installation stage.

The total fuel consumption is estimated to be 98,151 kg, leading to GHG emissions of around 341,000 kg CO2. These emissions are significant, highlighting the need for strategies to reduce the carbon footprint of offshore wind farm installations.

C. Sensitivity Analysis

A sensitivity analysis identifies the most critical variables affecting the model's accuracy. Changes in vessel speed, jack-up height, and crane efficiency can significantly impact energy consumption and emissions. For example, increasing vessel speed leads to higher energy consumption due to increased hull resistance, while variations in jack-up height affect the energy needed to lift the vessel. The results of the sensitivity analysis, performed on 10 input variables is shown in Figure 5 and Table I. The standardised slopes reflect the influence of the variables on the amount of greenhouse gas emissions for the installation process.

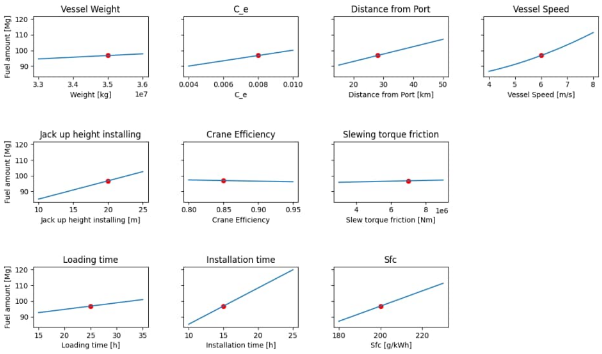

Fig. 5. Sensitivity analysis performed on 10 input variables

TABLE I
Slope values of variables

Variable	Slope	Standardised slope
Installation time	2.3135	0.0201
Vessel Speed	6.1786	0.0142
Sfc	0.4908	0.0141
C_E	1680.8684	0.0058
Distance from Port	0.4700	0.0095
Jack up height installing	1.1664	0.0101
Loading time	0.4164	0.0048
Vessel Weight	0.0000	0.0019
Slewing torque friction	0.0000	0.0008
Crane Efficiency	-9.0657	-0.0007

The weight of the vessel has a minimal impact on the fuel required for the wind turbine installation process, confirming the earlier assumption that changes in vessel weight during transit, whether with or without turbines, can be ignored. The installation time has the greatest effect on fuel consumption, likely because the auxiliaries, which consume the most energy, operate for a longer duration during extended installation periods.

D. Validation

The developed model is validated for the cranes energy consumption only due to limited availability of data. The data of over 50 installed wind turbines was analysed and compared with the models results. Initial results were good for the hoisting procedures of the crane. For the luffing and slewing, the energy consumption was predicted significantly small. Further insights in the movements were gained, and for the models results the assumed angles the crane makes were wrongly assumed. This is due to the input of the model only containing the effectively needed angles for slewing and luffing, but more movements are made for precision. By adjusting the model accordingly, the results were aligned with the data. The final boxplot which shows the datas energy consumption along with the models predicted energy consumption is shown in Figure 6

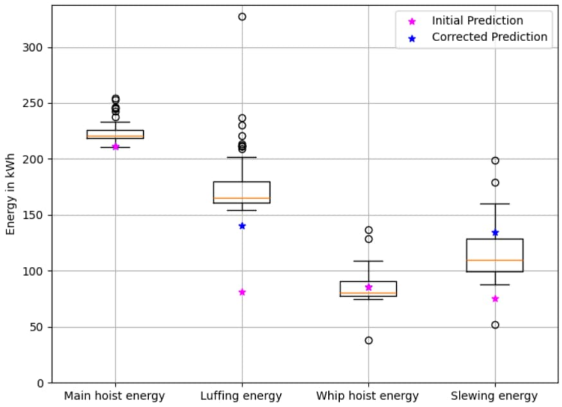

Fig. 6. Validation of the model compared to real data

IV. Discussion

The model's predictions show that auxiliary functions are the largest contributors to energy consumption and emissions during the installation process. This emphasizes the need for optimizing auxiliary systems, like power generation, HVAC, and water treatment, to reduce their energy demand. The high energy consumption during transit also highlights the importance of efficient vessel operations, including optimizing transit routes and reducing idle times.

The sensitivity analysis shows that vessel speed, jack-up height, and crane efficiency are key variables influencing energy consumption and emissions. By optimizing these variables, it is possible to achieve significant reductions in GHG emissions. For example, optimizing vessel speed can reduce fuel consumption during transit, while improving crane efficiency can lower the energy needed for lifting and positioning turbine components. Adjusting jack-up height based on site-specific conditions can also enhance energy efficiency during installation.

Investing in advanced technologies can further reduce the environmental impact of offshore wind farm installations. Upgrading to more efficient cranes with better performance motors and energy recovery systems can lower energy demand. Similarly, adopting more efficient auxiliary systems, such as advanced HVAC and power generation units, can reduce the continuous energy consumption needed to maintain onboard conditions.

A. Conclusion

This study provides a detailed analysis of the GHG emissions from installing offshore wind farms using WTIVs equipped with cranes by Huisman Equipment BV. The developed predictive model offers valuable insights into the energy consumption and emissions generated during different stages of the installation process. The findings underscore the importance of optimizing marine operations and adopting more efficient technologies to minimize the environmental impact of offshore wind energy installations.

The model's predictions show that auxiliary functions and transit stages are the most energy-intensive parts of the installation process. The total GHG emissions for installing 50 wind turbines are estimated to be around 341,000 kg CO2. These emissions highlight the need for strategies to reduce the carbon footprint of offshore wind farm installations, contributing to the overall sustainability of renewable energy projects.

B. Recommendations

Energy restitution: The potential energy that is released when lowering loads is flared. More research should be done about the possibilities to store this energy. If in the future systems such as batteries would be installed on WTIV, this might reduce the amount of required energy from the generator, which would be very beneficial to the amount of emissions. Especially since the predicted jack up energy requirements are relatively high, improvements here are recommended.

Validation: The developed model is validated for the crane part only due to limited availability of data. It is recommended that the rest of the model also gets validated in order to determine if the amount of greenhouse gases corresponds to the actual amount of emissions. For this, retrieving data from the marine contractors is necessary. The input variables for the vessel have to be known, as well as the amount of fuel consumed, to perform a validation on this part of the model.

Sensitivity analysis: In this research the sensitivity analysis was performed on the 10 input variables, assumed to be the most valuable to get more insights of. However, more sensitivity could be performed on other input variables in the future.

Feedering: The assets a wind turbine installation vessel installs could also be feedered to the vessel, instead of the vessel making all the transits. Since the model predicts the energy consumption is mostly due to auxiliaries, it might be interesting to look more into the feedering. If there is less time needed for the installation procedure, the amount of emissions for the vessel will reduce. But the amount of emissions the feedering boat emits has to also be incorporated for a good overall prediction.

Expansion of the model: The developed model is specifically applied to the installation of wind turbines. However, it is highly adaptable and can be easily modified to predict the amount of emissions associated with the installation of substations or monopile foundations. It is recommended to make these adaptations so that comprehensive predictions can be made for the entire installation process, ensuring a complete and accurate assessment of emissions across all components of the project.

By implementing these recommendations, marine contractors in the offshore wind industry can enhance the sustainability of wind farm installations and contribute to global efforts to mitigate climate change. The study's findings and recommendations provide a foundation for ongoing improvements in marine operations and the development of cleaner, more efficient renewable energy projects.

References

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B

Extension literature on GHG emissions

This appendix provides more explanation regarding GHG emission metrics, and protocols, standards, and legislation around them. This is a more thorough literature review, further answering the firtst subquestion of this thesis: *How can the GHG emissions of marine operations be computed?*

Chapter 3: Emissions metrics

Chapter 4: Protocols and standards

Chapter 5: Legislation

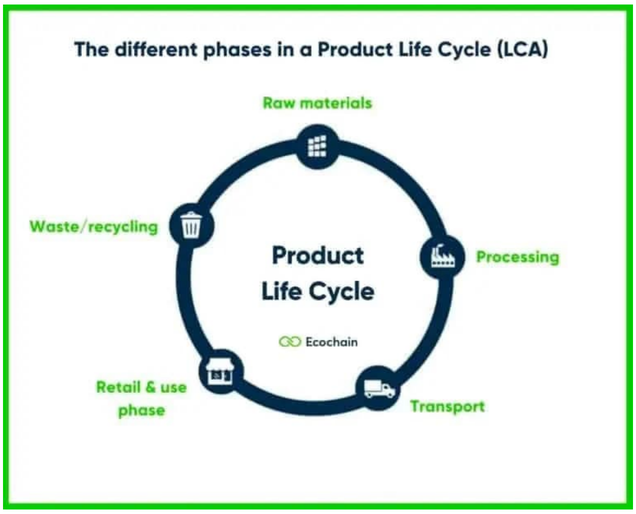
3. Emission metrics

3.1. Definitions

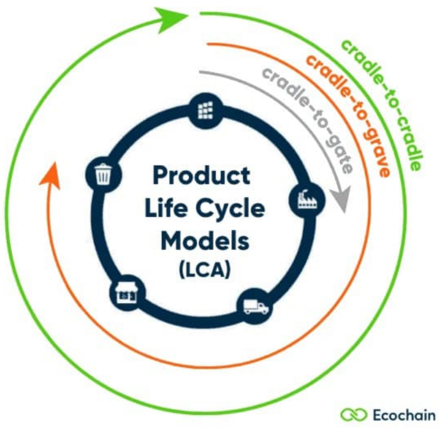
When it comes to determining the emissions of the life cycle of a product, different definitions exist to make an report about it. LCA is the fist definition. LCA is a structured, comprehensive and internationally standardised method. It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services ("products") [5]. Life Cycle Assessment takes into account a product's full life cycle: from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste. Critically, LCA studies thereby help to avoid resolving one environmental problem while creating others: This unwanted "shifting of burdens" is where you reduce the environmental impact at one point in the life cycle, only to increase it at another point. Therefore, LCA helps to avoid, for example, causing waste-related issues while improving production technologies, increasing land use or acid rain while reducing greenhouse gases, or increasing emissions in one country while reducing them in another. Life Cycle Assessment is therefore a vital and powerful decision support tool, complementing other methods, which are equally necessary to help effectively and efficiently make consumption and production more sustainable [5]. The ISO 14040 and 14044 standards provide the indispensable framework for Life Cycle Assessment. The International Reference Life Cycle Data System (ILCD) has been developed to provide guidance for consistent and quality assured Life Cycle Assessment data and studies [5].

Another definition that can be used when calculating the life cycle emissions of a product is carbon footprint. This is defined by Noelle Eckley Selin as the amount of carbon dioxide emissions associated with all the activities of a person or other entity. It includes direct emissions, such as those that result from fossil-fuel combustion in manufacturing, heating, and transportation, as well as emissions required to produce the electricity associated with goods and services consumed. In addition, the carbon footprint concept also often includes the emissions of other greenhouse gases, such as methane, nitrous oxide, or chlorofluorocarbons (CFCs). Carbon footprint is usually expressed as a measure of weight, as in tons of CO2 or CO2 equivalent per year [6]. Carbon footprints are different from a country's reported per capita emissions (for example, those reported under the United Nations Framework Convention on Climate Change). Rather than the greenhouse gas emissions associated with production, carbon footprints focus on the greenhouse gas emissions associated with consumption. They include the emissions associated with goods that are imported into a country but are produced elsewhere and generally take into account emissions associated with international transport and shipping, which is not accounted for in standard national inventories. As a result, a country's carbon footprint can increase even as carbon emissions within its borders decrease [6]. Commonly used methodologies for calculating organizational carbon footprints include the Greenhouse Gas Protocol and ISO 14064 [6]. Two other core standards around carbon footprint analysis are ISO 14067 and Publicly Available Specification (PAS) 2050 [7].

When doing an assessment on the emissions of greenhouse gases, LCA and carbon footprint are sometimes mixed up. Carbon footprint analysis is actually a subset of a complete life cycle analysis [7]. According to Ben Miller, LCA takes environmental releases—including GHG — and all other material inputs throughout the life cycle into account and assesses all the potential direct and indirect impacts on the environment. Thus, LCA is a multi-criteria analysis that evaluates numerous environmental impacts. On the other hand, carbon footprint analysis is a mono-criterion analysis focused on only one environmental impact: climate change by GHG emission [7]. According to Martin Lehmann a life cycle assessment at product level is referred to as carbon footprinting, as the focus is specifically placed on the greenhouse gas emissions generated Product Carbon Footprint (PCF) [8].



(a) Life Cycle of a product [9]



(b) Life Cycle models [9]

3.2. Life Cycle

As can be seen in Figure 1a, a life cycle consists of several stages and the emissions of all the phases together form the carbon footprint of a product. However, there are different kind of Life Cycle Assessments: cradle to gate, cradle to grave, and cradle to cradle. A illustration of those assessments can be seen in Figure 1b.

- Cradle-to-gate: assesses a product until it leaves the factory gates – before it is transported to the consumer (Stages 1 & 2).

- Cradle-to-grave: includes all 5 life cycle stages in your measurements. This gives you the complete environmental footprint, from start to end. (Stages 1-5)

- Cradle-to-cradle: is a variation of Cradle-to-grave, but exchanges the waste stage with a recycling/upcycling process that makes materials or components reusable for another product – essentially "closing the loop". (Stages 1-5, with 5 being equivalent to another Stage 1) [9]

Maritime
Another term for type of assessment is 'well-to-wake'. This term refers to the entire process of fuel production, delivery and use onboard ships, and all emissions produced therein. This approach is considered critical to assessing life cycle GHG emissions from marine fuels. By understanding the steps and challenges of well-to-wake emissions monitoring, marine stakeholders can gain a comprehensive view of their impact, as well as that of their partners [10]. The stages of a well-to-wake approach are pictured in Figure 2. As can be seen from this figure, the stages of this approach are similar to a cradle-to-grave approach. The well-to-wake approach is sometimes used for cargo or passenger transport ships.

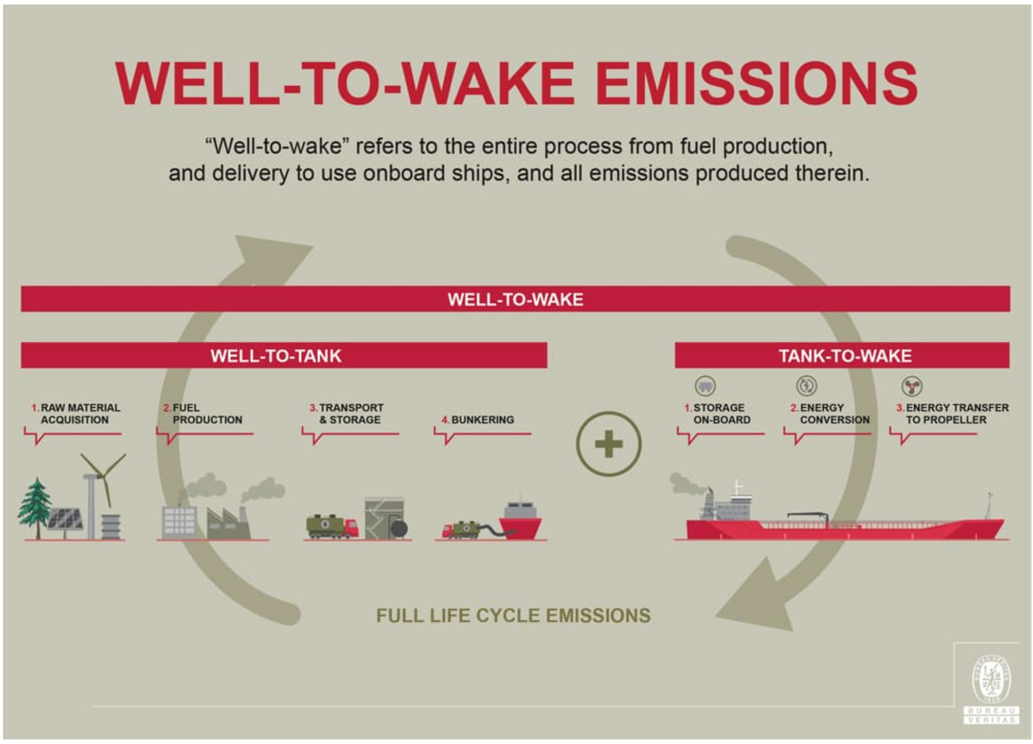


Figure 2: Well-to-wake approach [10]

3.3. Carbon Footprint scopes

When calculating the Carbon Footprint, a distinction is also made between direct and indirect emissions (Scope 1-3) [12]. This is also illustrated in Figure 3.

Scope 1
Direct GHG emissions – these occur from sources that are owned or controlled by the company, for example emissions from combustion in owned or controlled boilers, furnaces, vehicles, etc. or emissions from chemical production in owned or controlled process equipment [13].

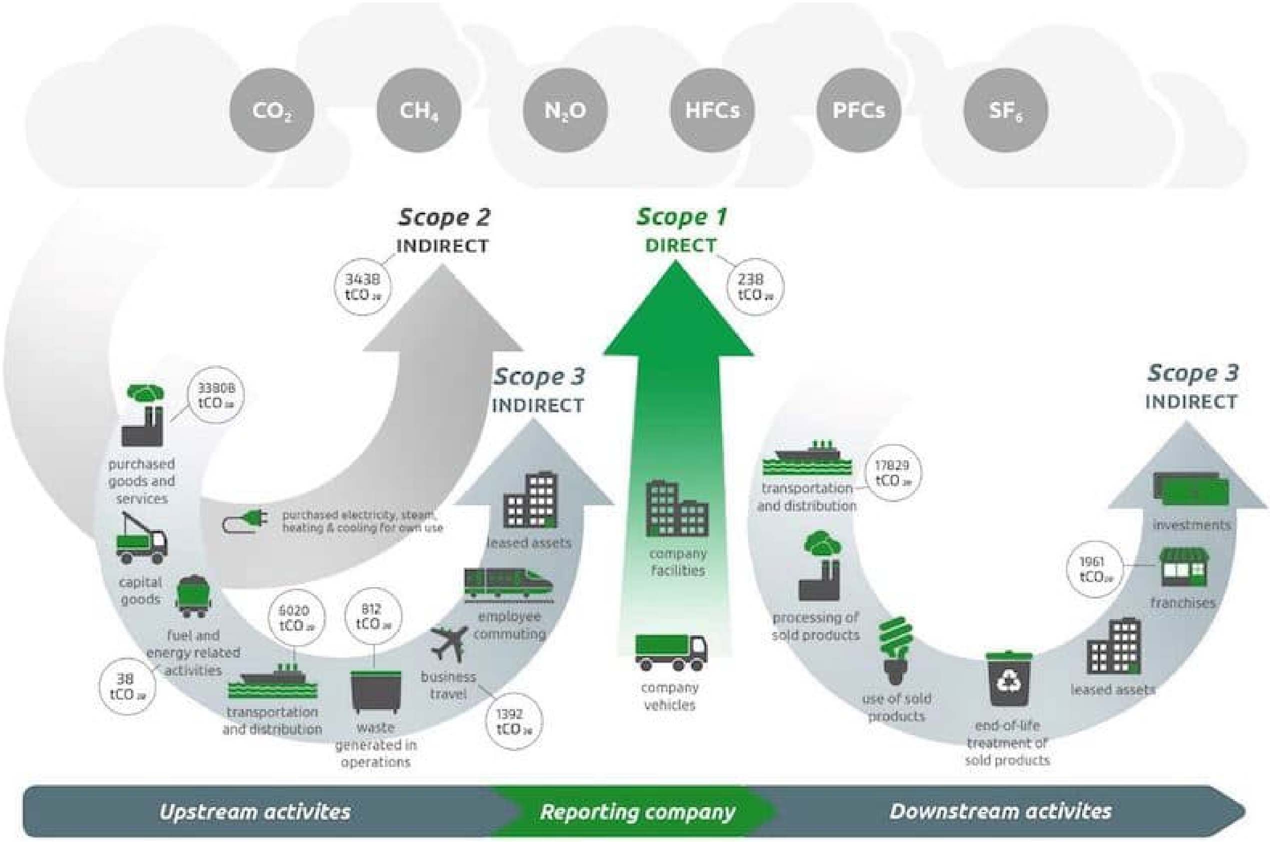


Figure 3: Different Carbon Footprint scopes [11]

Scope 2
Owned indirect GHG emissions like electricity and heat - this accounts for GHG emissions from the generation of purchased electricity and heat consumed by the company. Purchased electricity is defined as electricity that is purchased or otherwise brought into the organizational boundary of the company. Scope 2 emissions physically occur at the facility where the electricity is generated [13].

Scope 3
Not owned indirect GHG emissions [11]. This is a reporting category that allows for the treatment of all other indirect emissions. Scope 3 emissions are a consequence of the activities of the company, but occur from sources not owned or controlled by the company. Some examples of Scope 3 activities are the extraction and production of purchased materials, the transportation of purchased fuels and the use of sold goods and services [13].

As can be seen in Figure 3, for scope 3 also a distinction is made between upstream- and downstream activities. Upstream emissions come from the production of your business's products or services, while downstream emissions come from their use and disposal [14].

4. Protocols and Standards

In the previous section, different terms and definitions regarding the calculation of emissions are discussed. These definitions are used for the different standards on the environmental performance of products and operations. This section will dive into these.

Regarding the emissions of greenhouse gases, there are several protocols and standards which specify the procedures of LCAs and Carbon Footprint calculations. Table 1 gives an overview of standards, including the year they were written and last amended. Upon furhter investigation, ISO 14064, which is mentioned in the previous Chapter, was left out of scope because this standard is about organization level and product level reductions and removals only. Some other interesting ISO standards were found instead. The relationship between the different standards can be found in Figure 4.

Table 1: Standards

Standard	**Name**	**First published**	**Latest version**
ISO 14040	Environmental management - Life cycle assessment - Principles and framework	1996	2020
ISO 14044	Environmental management - Life cycle assessment - Requirements and guidelines	2005	2020
ISO 14067	Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification	2013	2018
ISO 14083	Greenhouse gases — Quantification and reporting of greenhouse gas emissions arising from transport chain operations	2023	2023
EN 15804	Sustainability of construction works - Environmental product declarations Core rules for the product category of construction products	2008	2019
ILCD	General guide for Life Cycle Assessment	2010	2010
PAS 2050	Specification for the assessment of the life cycle greenhouse gas emissions of goods and services	2008	2011
GHG Protocol	Greenhouse Gas Protocol - Product standard	2011	2015
PEF Method	Product Environmantal Footprint method	TBA	TBA

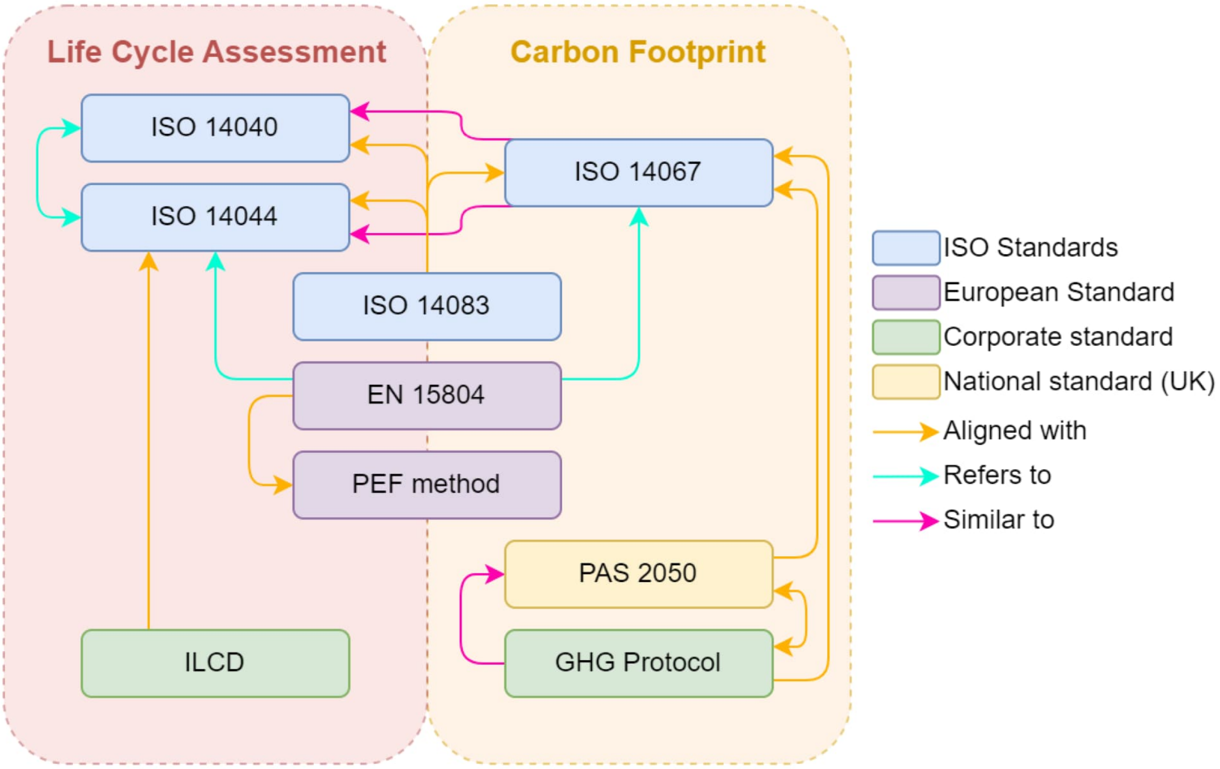


Figure 4: Relationship Different Standards

4.1. ISO standards

Most of the ISO standards are part of the ISO 14000 group. The ISO 14000 is a family of ‘standards’ - the standard (14001) + guidelines - related to environmental management that exists to help organizations minimize how their operations (processes, etc.) negatively affect the environment (i.e. cause adverse changes to air, water, or land); comply with applicable laws, regulations, and other environmentally oriented requirements; and continually improve in the above [15]. The ISO 14040 series of standards define LCA guidelines and establish four stages to an LCA: goal and scope definition; inventory analysis; impact assessment; and interpretation of results.

In Appendix A the different ISO standards mentioned in Table 1 can be partially found. Those standards form the base for every other standard or guide mentioned. The first three chapters of every ISO standard are ’Scope’, ’Normative references’, and ’Terms & definitions’. These are not included in the Appendix because of irrelevance. The chapters included are in the Appendix contents highlighted with a red rectangle.

As can be seen in Appendix A.1, Chapter 4 of ISO 14040 provides a general description of life cycle assessment. At the start of this chapter is stated that LCA is a relative approach and a iterative technique, so comprehensiveness and transparency are important guiding principles in executing LCAs in order to ensure a proper interpretation of the results. An LCA study comprises four phases: Goal & scope definition, inventory analysis, impact assessment, and interpretation. Intended direct applications of the LCA study are i.a. product development & improvement, stragetic planning, public policy making, and marketing. A excessive list in 4.3 of ISO 14040 summarizes the key features of the LCA methodology. For this paper the interesting features are a) LCA assesses, in a systematic way, the environmental aspects and impacts of product systems, from raw material acquisition to final disposal, in accordance with the stated goal and scope; g) there is no single method for conducting LCA. Organizations have the flexibility to implement LCA as established in this International Standard, in accordance with the intended application and the requirements of the organization; i) LCA addresses potential environmental impacts; LCA does not predict absolute or precise environmental impacts due to

- the relative expression of potential environmental impacts to a reference unit,
- integration of environmental data over space and time,
- the inherent uncertainty in modelling of environmental impacts, and
- the fact that some possible environmental impacts are clearly future impacts;

Life Cycle Interpretation (LCI) is used as a method to o identify, qualify, check, evaluate and present the conclusions based on the findings of an LCA, in order to meet the requirements of the application as described in the goal and scope of the study. LCI uses an iterative procedure both within the interpretation phase and with the other phases of an LCA, and it makes provisions for links between LCA and other techniques for environmental management by emphasizing the strengths and limits of an LCA in relation to its goal and scope definition [16].

Chapter 5 of ISO 14040, which is called ’Methodological framework’ refers to ISO 14044. So, those standards both need to be used simultaneously. As can be seen in Appendix A.2, the main chapter of ISO 14044 (Chapter 4) is thus called ’Methodological framework for LCA’, and is followed by a small chapter on the general reporting requirements. Also can be noticed chapter 4 of ISO 14044 starts with a reference to ISO 14040. Furthermore, it describes the four phases of the LCA in detail.

Chapter 5 of ISO 14044 is on the reporting of the LCA, which is interesting, but mostly out of scope for this report since the research question is about the methods of calculations itself [17].

As mentioned in Table 1, ISO 14067 provides the requirements & guidelines of PCF. As can be seen in Appendix A.3, chapter 5 and 6 are the main chapters of this standard, about the principles and methodology of the PCF. Chapter 5 ’Principles’ is similar to Chapter 4 of ISO 14040. Most of the sub clauses are adapted from this other standard. One extra subclause not found in ISO 14040 is about avoiding double-counting. However, this principle is mentioned in ISO 14044. Chapter 6, about the methodology for quantification starts with ”A PCF study in accordance with this document shall include the four phases of LCA”. Those phases are further explained in chapter 6.3 to 6.6, and are therefore similar to ISO 14044. However, there are some differences: ISO 14067 has some additional subsections in the Life Cycle inventory analysis; ”PCF performance tracking”, ”Assessing the effect of the timing of GHG emissions and removals”, and ”Treatment of specific GHG emissions and removals” [18].

As can be seen in Appendix A.4 ISO 14083 is a standard about the emissions of the transport of passengers and freight. It is aligned with ISO 14067, ISO 14040, and ISO 14044. Chapter 10 is called ”Calculation of GHG emissions for a Transport Chain Element (TCE)”, which is about the calculation for a specific mode on its own, such as sea transport. Annex G further details the sea transport specifics. Both Chapter 10 and Annex G can be found in the Appendix. This ISO standard can be used for the transportation of containers, which can be considered as an offshore operation [19].

4.2. EN 15804

EN 15804 provides core Product Category Rules (PCR) for Type III environmental declarations for any construction product and construction service. The assessment of social and economic performances at product level is not covered by this standard. The core PCR defines the indicators to be declared, information to be provided and the way in which they are collated and reported. Also, it describes which stages of a product's life cycle are considered in the Environmental Product Declarations (EPD) and which processes are to be included in the life cycle stages. Next, it defines rules for the development of scenarios, and it includes the rules for calculating the Life Cycle Inventory and the Life Cycle Impact Assessment underlying the EPD, including the specification of the data quality to be applied. Furthermore, it includes the rules for reporting predetermined, environmental and health information, that is not covered by LCA for a product, construction process and construction service where necessary. Finally, it defines the conditions under which construction products can be compared based on the information provided by EPD. For the EPD of construction services the same rules and requirements apply as for the EPD of construction products.

As mentioned in Table 1, this standard is about the sustainability of construction products and services. In this standard a construction product is considered "an item manufactured or processed for incorporation in construction works". When further reviewing this standard, it does not seem as if the standard is produced for anything other but the construction of houses and buildings. ISO 14044 and ISO 14067 are mentioned as normative references in this standard, and are thus considered indispensable for the application of this standard. Since offshore operations such as installing a wind turbine can be considered a construction service, this standard may be useful when making another standard which includes offshore constructions. [20]

4.3. ILCD

The ILCD Handbook provides detailed guidance for planning, developing, and reporting both life cycle emission and resource consumption inventory (LCI) data sets and Life Cycle Assessment studies [5]. The document further details the ISO 14044 provisions and differentiates them for the three main types of questions that are addressed with LCA studies: "Micro-level decision support", "Meso/macro-level decision support", and "Accounting". Focus is given to methodological issues that result in relevant differences in current practice of developing Life Cycle Inventory data sets and performing LCA studies [5].

The ISO 14040 and 14044 standards provide the indispensable framework for Life Cycle Assessment. This framework, however, leaves the individual practitioner with a range of choices, which can affect the legitimacy of the results of an LCA study [5]. For each phase of the LCA described in ISO 14044 there is a detailed chapter in this handbook. Since it is in alignment with ISO 14044, using this handbook for LCA assures a clearer outcome and a more detailed guidance, especially when a comparison between different LCA's of products needs to be made. The ILCD consists of 417 pages, so is not included in the Appendix, but can easily be found online.

4.4. PAS 2050 & GHG Protocol

PAS 2050 was developed by the British Standards Institute (BSI). PAS 2050 came into effect in October 2008 and was revised in 2011. PAS 2050 is widely used and is considered the first carbon footprint standard used internationally [14]. The GHG Protocol Product Standard was created by the WRI/WBCSD and published in October 2011. It was developed to be consistent with the first version of PAS 2050, with the difference that the GHG Protocol Product Standard includes requirements for public reporting. The GHG Protocol also provides additional standards for corporate assessments and project-related calculations [14].

Pas 2050 and the GHG Protocol are similar standards. Pas 2050 was introduced in 2008 (revised in 2011) with the aim of providing a consistent internationally applicable method for quantifying product carbon footprints. The GHG Protocol Product Standard was released in 2011 and in addition to providing requirements to quantify the GHG inventories of products, also includes requirements for public reporting. Both standards are broadly consistent in their quantification methods, but their differing purpose and standard development processes has lead to two different documents [21]. ISO 14067 is quite similar to these standards, and although the methodologies aren't identical, their developers (BSI, WRI/WBCSD, ISO, AFNOR and the European Commission) aimed to increase alignment across their methodologies [14]. All methodologies provide requirements for dealing with specific issues relevant for carbon footprints, including land-use change, (biogenic) carbon uptake and emissions, offsetting, soil carbon stock, green electricity and characterization factors to be used for biogenic carbon [14]. ISO 14067 is an example of a more general standard, while PAS 2050 and the GHG Protocol provide more detailed requirements with less space for interpretation [14].

4.5. PEF Method

The European Commission has proposed the Product Environmental Footprint (PEF) method as a common way of measuring environmental performance. In December 2021, the Commission adopted a revised Recommendation on the use of Environmental Footprint methods, helping companies to calculate their environmental performance based on reliable, verifiable and comparable information. It also allows other actors (public administrations, NGOs, business partners, for example) to have access to such information. The European Commission's Joint Research Centre has been driving the scientific and technical developments to ensure robustness and impartiality [22]. EN15804 is actually a part of the PEF method.

The Product Environmental Footprint, also the PEF methodology, is an important initiative from the European Commission. It's a new and improved method on how companies should measure the environmental performance of any product throughout its Life Cycle (taking into account all the upstream supply chain and downstream activities). The PEF is based on the scientific method for measuring environmental footprints called Life Cycle Assessments.

The PEF outlines an improved common framework for all the steps and specific rules that are necessary to make an appropriate and comparable Life Cycle Assessment. Its mission is to strengthen the (European) market for green alternatives and ensure that environmental impacts are transparently assessed and, in the end, of course; reduced [23].

The PEF being a single LCA method used by everyone- helps improve the validity and comparability of the environmental performance evaluation of EU member states and the private sector. Especially compared to the existing methods. Having this new organisational standard in environmental impact measurements will tackle greenwashing and false sustainability claims. Motivating companies to stay on the 'right sustainability path'- and helping consumers recognise to what extent a product, company, or service is environmentally friendly. The PEF methodology is still in progress and in the so-called 'transition phase' (pilot phase). This transition phase is planned to be completed by the end of 2024. This means that using the PEF isn't mandatory yet. The European Commission is still further developing the details for the PEF Product Category Rules (also PEFCR's or PCR's) in order to finalise the PEF methodology developments. These category rules will define footprint measurement rules specific to industries. Only for the European construction sector, has the PEF already resulted in some mandatory changes in LCA's. This is due to the earlier mentioned PEF norm EN15804 [23]. A big difference between a LCA and the PEF method is the PEF method and its database offers comparability, and is suitable for benchmarking products in the same product groups. The PEF will most likely be finalised, launched, and implemented in the end of 2024.

5. Legislation

In the previous section different standards have been discussed for accounting Greenhouse Gases. To further analyse which method should be used it is also good to know what standards or methods should be used according to different regulations and recommendations. Table 2 provides different legislations about the accounting of greenhouse gases.

Table 2: Legislation

Legislation	Name	Type	Last amended
EU 2003/87	Establishing a system for greenhouse gas emission allowance trading within the Union	Directive	June 2023
EU 2009/16	On port state control	Directive	December 2019
EU 2013/34	On the annual financial statements, consolidated financial statements and related reports of certain types of undertakings	Directive	January 2023
EU 2014/95	Amending Directive 2013/34 as regards disclosure of non-financial and diversity information by certain large undertakings and groups	Directive	October 2014
EU 2015/757	On the monitoring, reporting and verification of carbon dioxide emissions from maritime transport	Regulation	June 2023
EU 2021/2279	On the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations	Recommendation	
C/2019/4490	Guidelines on non-financial reporting: Supplement on reporting climate-related information	Communication	-

As can be seen in Table 2, there are different types of legislation. The aims set out in the EU treaties are achieved by several types of legal act. Some are binding, others are not. Some apply to all EU countries, others to just a few [24].

Regulations

A ”regulation” is a binding legislative act. It must be applied in its entirety across the EU. For example, when the EU’s regulation on ending roaming charges while travelling within the EU expired in 2022, the Parliament and the Council adopted a new regulation both to improve the clarity of the previous regulation and make sure a common approach on roaming charges is applied for another ten years [24].

Directives

A ”directive” is a legislative act that sets out a goal that EU countries must achieve. However, it is up to the individual countries to devise their own laws on how to reach these goals. One example is the EU single-use plastics directive, which reduces the impact of certain single-use plastics on the environment, for example by reducing or even banning the use of single-use plastics such as plates, straws and cups for beverages[24].

Recommendations

A ”recommendation” is not binding. When the Commission issued a recommendation that EU countries’ media service providers improve their ownership transparency and safeguard their editorial independence, this did not have any legal consequences. A recommendation allows the institutions to make their views known and to suggest a line of action without imposing any legal obligation on those to whom it is addressed [24].

5.1. EU 2003/87

As mentioned in the introduction, the EU ETS is legislated via different laws. The primary legislation governing the EU ETS is the Directive 2003/87/EC. This directive was initially adopted in 2003 and has since been revised multiple times to strengthen and improve the functioning of the system, the last amendment being from June 2023. The directive, among other things, establishes monitoring, reporting, and verification requirements for installations. Participants in the system must monitor and report their greenhouse gas emissions annually, and these reports are subject to independent verification to ensure accuracy and compliance [25].

Annex IV of the directive addresses the principles for monitoring and reporting the greenhouse gas emissions.

However, this reporting section only covers the aviation sector and stationary installations. Since the maritime emissions are recently added as mandatory in the near future, in this annex maritime transport is not included. For the monitoring and reporting of emissions from maritime transport directive 2003/87/EC refers to regulation 2015/757. NB. For stationary installations the calculations of emissions should be performed using the formula: *Activity data x Emission factor x Oxidation factor*.

5.2. EU 2015/757

Regulation 2015/757 is mainly on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, with Annex I containing the measurement regulations. Part A is about the calculation of emissions and states ”For the purposes of calculating CO2 emissions companies shall apply the following formula: *”Fuel consumption × Emission factor”* ” , with default values for emission factors of various fuels on board being given [26].

Part B of Annex I is about various methods for determining the fuel consumption. The actual fuel consumption for each voyage shall be used and be calculated using one of the following four methods:

BDN and periodic stocktakes of fuel tanks

This method is based on the quantity and type of fuel as defined on the Bunker Fuel Delivery Note (BDN) combined with periodic stocktakes of fuel tanks based on tank readings. The fuel at the beginning of the period, plus deliveries, minus fuel available at the end of the period and de-bunkered fuel between the beginning of the period and the end of the period together constitute the fuel consumed over the period. Where the amount of fuel uplift or the amount of fuel remaining in the tanks is determined in units of volume, expressed in litres, the company shall convert that amount from volume to mass by using actual density values [kg/l]. The company shall determine the actual density by using one of the following: a.) on-board measurement systems; b.) the density measured by the fuel supplier at fuel uplift and recorded on the fuel invoice or BDN; c.) the density measured in a test analysis conducted in an accredited fuel test laboratory, where available [26].

Bunker fuel tank monitoring on board

This method is based on fuel tank readings for all fuel tanks on-board. The tank readings shall occur daily when the ship is at sea and each time the ship is bunkering or de-bunkering. The cumulative variations of the fuel tank level between two readings constitute the fuel consumed over the period. Fuel tank readings shall be carried out by appropriate methods such as automated systems, soundings and dip tapes. The method for tank sounding and uncertainty associated shall be specified in the monitoring plan. Also for this method the company shall convert the amount of volume to density if applicable, just like with the previous method[26].

Flow meters for applicable combustion processes

This method is based on measured fuel flows on-board. The data from all flow meters linked to relevant CO2 emission sources shall be combined to determine all fuel consumption for a specific period. Also for this method the company shall convert the amount of volume to density if applicable, just like with the previous methods[26].

Direct CO2 emissions measurements

The direct CO2 emissions measurements may be used for voyages and for CO2 emissions occurring in ports located in a Member State’s jurisdiction. CO2 emitted shall include CO2 emitted by main engines, auxiliary engines, gas turbines, boilers and inert gas generators. For ships for which reporting is based on this method, the fuel consumption shall be calculated using the measured CO2 emissions and the applicable emission factor of the relevant fuels. This method is based on the determination of CO2 emission flows in exhaust gas stacks (funnels) by multiplying the CO2 concentration of the exhaust gas with the exhaust gas flow[26].

The company shall define in the monitoring plan which monitoring method is to be used to calculate fuel consumption for each ship under its responsibility and ensure that once the method has been chosen, it is consistently applied. Any combination of these methods, once assessed by the verifier, may be used if it enhances the overall accuracy of the measurement[26].

5.3. EU 2013/34, 2014/95 & C/2019/4490

Directive 2013/34 is called ”on the annual financial statements, consolidated financial statements and related reports of certain types of undertakings”, but since later amendments resulting from Directive 2014/95 this directive also includes the disclosure of non-financial information such as sustainability reports [27]. After this change, the European Commission formed a document with guidelines on non-financial reporting. This communication (C/2019/4490) is useful and informative, but does not create new legal obligations. In this document the GHG protocol and ISO 14067 are recommended as common methods for the calculation of GHG emissions following a lifecycle approach [28]. This was also mentioned in Recommendation 2013/179, which is referred to, but was later replaced by Recommendation 2021/2279, which will be discussed in the next section. Because of later formed Directive 2022/2426 about corporate sustainability reporting, Directive 2013/34 was further amended and now also includes ’sustainability reporting standards’. This chapter however, is not comprehensive yet and it states that standards will be provided by June 2024 [29].

5.4. EU 2021/2279

This is the newest Recommendation on methods to measure and communicate the life cycle environmental performance of products and organisations, which makes the previous Recommendation 2013/179 being repealed. This new Recommendation promotes the use of the Environmental Footprint methods in relevant policies and schemes related to the measurement and/or communication of the life cycle environmental performance of all kinds of products, including both goods and services, and of organisations. The previously mentioned PEF method is recommended for products, in combination with the related Product Environmental Footprint Caregory Rule (PEFCR)s. If a PEFCR exists, this should be used for calculating the environmental footprint of a product belonging to that product category. As mentioned before, for many Product Categories, there is no PEFCR yet. In the Recommendation is also stated that companies should contribute to the review of public databases and populate these with high quality life cycle data in line with requirements on Environmental Footprint compliant datasets. Environmental Footprint secondary data sets version ’EF 2.0’ had a prolonged validity until 30 June 2023. Version ’EF 3.1’ is still valid until 31 December 2024 [4].

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