Life Cycle Assessment of Selected Offshore Wind Foundations: Comparing Primary Design Structures from Development to Installation Phase

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Abstract ENG

Offshore wind energy is playing an increasingly important role due to the growing need to minimize climate change and its consequences. The urgency to mitigate climate change calls for a transition of fossil-based technologies to more ecologic sustainable technologies. To assess the ecological sustainability, the life cycle assessments (LCAs) of the primary design components of a XXXL monopile and a four-legged pin-pilled jacket foundations have been conducted evaluating their environmental impacts. The primary design components have been calculated for the same boundary conditions (a 15MW turbine, a water depth of -40m wtr LAT, a planned lifetime of around 25 years, manufacture in Europe and installation in the North Pacific/US). The LCA have been conducted using the software OpenLCA and the impact assessment method EF v.3.1 for the manufacture, transport and installation phases. Unlike most of the LCAs for offshore wind turbines which often use the energy production in kWh as the functional unit, this thesis's LCA refers to the unit of mass of required steel in t. The required steel mass has been assessed with the impact categories of global warming potential, abiotic depletion potential for fossil fuels (with energy payback time) and eutrophication. The assessment of the impact categories reveals that the primary design structures of the four-legged pin-pilled jacket foundation have a greater environmental impact and an overall larger footprint compared to XXXL monopile foundation. Therefore, the LCA concludes that the primary steel components of the four-legged pin-pilled jacket foundation are ecologically less sustainable (as they require more fossil energy for production and installation) than the structures of the XXXL monopile foundation.

Abstract GER

Die Offshore-Windenergie spielt eine immer wichtigere Rolle, da es immer wichtiger wird, die Auswirkungen des Klimawandels zu minimieren. Die Dringlichkeit, den Klimawandel einzudämmen, erfordert einen Wechsel von fossil-basierten Technologien zu ökologisch nachhaltigen Technologien. Um die ökologische Nachhaltigkeit bewerten zu können, wurden Ökobilanzen für die primären Designkomponenten eines XXXL-Monopiles und eines vierbeinigen, gepinnten Jacket Fundaments durchgeführt. Die primären Designstrukturen wurden für die gleichen Randbedingungen berechnet (eine 15-MW-Turbine, eine Wassertiefe von - 40m wtr LAT, eine geplante Lebensdauer von etwa 25 Jahren, Herstellung in Europa und Installation im Nordpazifik/USA). Die Ökobilanzen wurden mit der Software OpenLCA und der Folgenabschätzungsmethode EF v.3.1 für die Phasen Herstellung, Transport und Installation durchgeführt. Im Gegensatz zu den meisten Ökobilanzen für Offshore-Windkraftanlagen, die häufig die Energieerzeugung in kWh als funktionale Einheit verwenden, bezieht sich die Ökobilanz dieser Arbeit auf die Masseneinheit des benötigten Stahls in t. Die erforderliche Stahlmassen wurden mit den Einflusskategorien Treibhauspotenzial, abiotisches Erschöpfungspotenzial für fossile Brennstoffe (inkl. Energierücklaufzeit) und Eutrophierung bewertet. Die Bewertung der Einflusskategorien zeigt, dass die primären Designstrukturen des vierbeinigen, gepinnten Jacket Fundaments im Vergleich zum XXXL Monopile Fundaments eine größere Umweltbelastung und einen insgesamt größeren Fußabdruck aufweisen. Das Fazit der Ökobilanz ergibt, dass die primären Designstrukturen des vierbeinigen, gepinnten Jacket Fundamentes ökologisch weniger nachhaltig sind (da sie mehr fossile Energie für die Herstellung und Installation benötigen) als die Strukturen des XXXL Monopile Fundamentes.

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Electronic Attachement

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2) LCA report - LCI and LCIA results (PDF file)
3) Evaluation - LCIA results (Excel file)
4) Forecast – LCI and LCIA results for NOx reduction (Excel file)

Glossary

B	Boron
Bio-SNG	Bio-synthetic natural gas
DWT	Deadweight tonnage
EFf	Fuel-based emission factors
EFf)	Fuel-centric emission factor
EMi	Hourly emissions
ADPF	Abiotic depletion potential for fossil fuels
AoP	Area of protection
CH4	Methane
CO2	Carbon dioxide
CO	Carbon monoxide
Cr	Chromium

DRI	Direct reduction process
EAF	Electric arc furnaces
EDP	Environmental Product Declarations
EF	Environmental Footprint impact assessment method
EF_e	Energy-based emissions factors
EM_i	Fuel-based emissions
EN	European Norm
EoL	End of life
EPT	Energy payback time
EU	European Union
FCi	Hourly fuel consumption
FP	Fast Pyrolysis
FT	Fischer-Tropsch
GBS	Gravity based structure
GHG	Greenhouse gases
GWP	Global warming potential
HC	Hydrocarbon
HLV	Heavy lift vessel
HTL	Hydrothermal Liquefaction
IMO	International Maritime Organization
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment

LNG	Liquefied natural gas
MDO	Marine diesel oil
MGO	Marine gas oil
Mn	Manganese
MP	Monopile
n	Engine's rated speed
N2O	Nitrous oxide
NMVOC	Non-methane volatile organic compound
Nb	Niobium
NOx	Nitrogen oxide
NPC	Non-priced criteria
NSEC	North Sea Energy Cooperation
O&M	Operation and maintenance
OWT	Offshore wind turbines
OWF	Offshore wind farm
PM10	Particulate matter < 10 µm
PM2.5	Particulate matter < 2,5 µm
PRM	Revolutions Per Minute
RER	Europe
SEA	Strategic environmental assessment
SP	Scour protection
T&I	Transport and installation
TP	Transition pieces
$\dot{W}$	Electrical energy

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1 Introduction

With the growing imperative to mitigate climate change and ever-increasing global energy demand, the role of renewable energy. According to the insights from the Global Wind Energy Council (2023), wind energy emerges as a linchpin for building energy security, reducing electricity costs, and actively contributing to the decarbonization imperative. The urgency to mitigate climate change, as mandated by the Paris Agreement, necessitates a substantial reduction in global greenhouse gas (GHG) emissions by 2030. With less than six years remaining to overhaul high-emission technologies with zero or low-carbon alternatives, the offshore wind sector assumes a critical role in achieving these objectives (Global Wind Energy Council 2023).

As noted already by Haapala und Prempreeda (2014), wind turbines stand out as an environmentally friendly source of energy production, emitting virtually no pollutants during operation. However, the life cycle of wind turbines reveals environmental footprints across manufacturing, transport, installation, and decommissioning phases. Bonou et al. (2016) highlights the importance of recognizing the environmental implications, as contemporary literature and offshore wind farm projects underscore the pivotal role of strategic environmental assessment (SEA) in fostering sustainable wind energy planning (Bonou et al. 2016). The imperative for a comprehensive environmental assessment dovetail with the necessity for systemic management and planning strategies, a challenge that can be addressed through the application of life cycle assessment (LCA) (Bonou et al. 2016).

Spinergie (2023) defines non-priced criteria (NPC) in the offshore wind sector, comprising environmental, regulatory, technological, and societal aspects. NPC are crucial for the comprehensive feasibility of a successful wind project, which extends beyond economic factors and emphasizes balance and responsibility in the leasing process (Spinergie 2023). Recognizing the need to shift from prioritizing economic profit, Spinergie (2023) underlines the importance of NPC in developing sustainable offshore wind projects, which are crucial for aligning with Paris Agreement goals and achieving a balanced economic-environmental approach (Spinergie 2023).

The Global Wind Energy Council (2023) emphasizes the crucial role of environmental considerations in the alliance's tendering procedures. The report advocate for the adoption of a "bill of materials" linked to Environmental Product Declarations (EPD) and LCA as key criteria to incentivize suppliers adhering to specified guidelines (Global Wind Energy Council 2023). These guidelines encompass restrictions on certain raw materials, considerations for CO2, and water footprint. The alliance is dedicated to ensuring that 100% of newly produced or acquired equipment complies with certified EPD/LCA standards, with a transparent bill of materials targeted by the end of 2024, showcasing a strong commitment to environmental responsibility in equipment procurement (Global Wind Energy Council 2023).

This thesis examines an example project to generate a thorough LCA for the primary design components of XXXL monopile (MP) and four-legged pin-pilled jacket foundations. The objective is to assess and establish the ecological sustainability as defined by Kropp (2019) of the two chosen foundation types. Due to the complex supply chain involving many different suppliers from different countries for the secondary design, as emphasized in the report by Rystad Energy (2023), this work solely focuses on the primary design.

In order to provide a basis for the LCA, the theoretical principles of the different types of offshore wind FOU and their primary design construction, as well as the LCA method, project phases, and emission calculation are presented first. Based on the theoretical principles, the LCA according to the standards EN ISO 14040:2006 and EN ISO 14044:2006 is carried out on the example project. The LCA of XXXL MP and four-legged pin-pilled jacket foundation have been carried out from the development to installation phase. For the direct comparison, certain assumptions have been formulated based on data availability and literature review; these are elaborated upon in section 3.1.3. Among the EU recommended impact categories (European commission 2010b), three different categories are selected and analyzed phase by phase for both foundation types.

The LCAs of XXXL MP and four-legged pin-pilled jacket foundation have been conducted, evaluating their environmental impact based on a functional unit of 1 t of steel. The LCA software OpenLCA and the EF v.3.1 method (European commission 15.12.2021) has been used for this analysis, see Chapter 3.3. Employing an attributional life cycle model, see section 2.2.2, the study incorporated inventory data sourced from the integrated Ecoinvent 3.9 database as well as inventory data derived from assumptions, see section 3.1.3, and knowledge from experts at Ramboll. Additional numerical analysis required for the LCA have been carried out using Excel.

The LCA outcomes, see Chapter 3.3, of XXXL MP and four-legged pin-pilled jacket foundations have been elucidated and juxtaposed, then assessed. In the outlook, forthcoming tendencies and eco-friendly alternatives are delineated and their emissions are matched against computed values. Lastly, the findings of the life cycle impact assessment (LCIA) have been condensed, and the emissions of the main design elements of both foundation types kinds are weighed to facilitate an assessment and address the sustainability query.

2 Theoretical Background

The following chapter provides the necessary basics on the primary design structures of MP and jacket foundation, the life cycle stages considered in this work, the method LCA and the additionally required vessel's emission calculations.

2.1 Offshore Wind

The Global Wind Energy Council (2023) reports a significant increase in wind energy production over recent decade. Recognizing the urgency to mitigate climate change as mandated by the Paris Agreement, there is a pressing need for a substantial reduction in global greenhouse gas emissions by 2030, compelling the rapid adoption of offshore wind technologies (Global Wind Energy Council 2023). Nonetheless, as highlighted in the report by Spinergie (2023) the construction and operation of offshore wind farms (OWF) can impose significant environmental impacts. Therefore, it is imperative that this growth in renewable energy production does not result in significant environmental harm. New projects should align with goals for environmental and climate protection and conservation (Global Wind Energy Council 2023; Spinergie 2023). In this context, the selection of raw materials and design strategies carries notable importance (EDP standards). As Bonou et al. (2016) research indicates, offshore wind turbines exhibit heightened emissions relative to their onshore counterparts, primarily due to the substantial materials necessary to withstand sea-induced bending conditions. In particular, the foundation and tower stand out as more robust elements, as emphasized in Yildiz et al. (2021) investigation.

The following chapter explores the theoretical foundations of the subject covered in the latter section, with a specific focus on the primary structural designs for MP and jacket foundations.

2.1.1 Primary Design Structures

Understanding the relevance of primary design structures in offshore wind foundations provides the fundamental framework for further research. According to Bundesamt für Seeschifffahrt und Hydrographie (2021) and the fact sheet from Offshore Wind Scotland (n.D.) the designation "primary (design) structure" pertains to the supporting elements situated along the primary power flow path (Bundesamt für Seeschifffahrt und Hydrographie 2021; Offshore Wind Scotland n.D.). These include transition pieces (TP), pipes, flanges or the foundation itself, as illustrated in Figure 2-1 (Bundesamt für Seeschifffahrt und Hydrographie 2021; Offshore Wind Scotland n.D.).

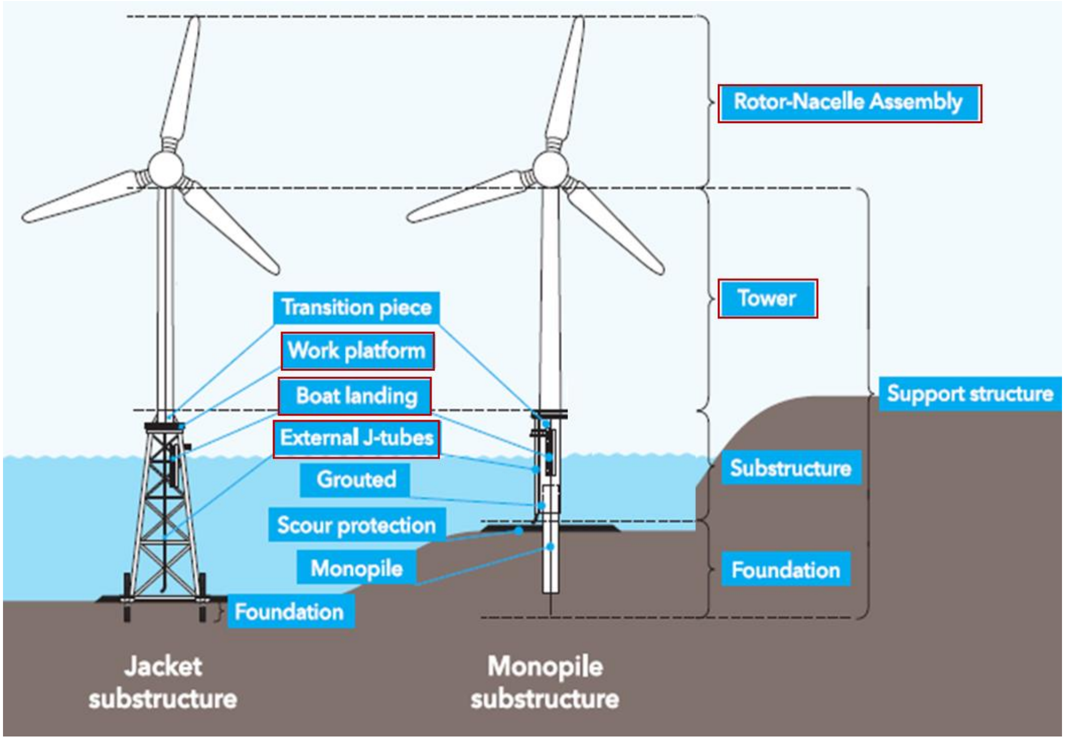

Figure 2-1: Primary and secondary components of an offshore wind turbine for jacket and monopile foundation adapted from DNV-ST-0054

After defining the primary design, it is important to address the sustainability and recyclability potential of its raw material - steel. Pagh Jensen (2019) emphasizes that steel can undergo recycling multiple times and stands out as the most frequently recycled metal, supported by an efficient secondary market (Pagh Jensen 2019). Nevertheless, steel is manufactured in numerous distinct alloy compositions, featuring diverse alloying elements like Cr, Mn, Nb, B, etc. (Pagh Jensen 2019).

Besides the primary design structures, there are also secondary design structure, red marked in *Figure 2-1*. Bundesamt für Seeschifffahrt und Hydrographie (2021) defines the secondary design structure as the built-on accessories, machine-mounted accessories and fixtures that are attached to the primary structure and located outside the main power flow (Bundesamt für Seeschifffahrt und Hydrographie 2021). Offshore Wind Scotland (n.D.) underline the wide range of secondary (steel) structure subcomponents (Offshore Wind Scotland n.D.). These subcomponents allow for essential access to the wind turbine for operation and maintenance (Offshore Wind Scotland n.D.). Unlike primary components, secondary design elements are not only made of steel, but also of aluminum, glass-fibre reinforced plastics, rubber, as well as paints and coatings (Offshore Wind Scotland n.D.).

2.1.2 Foundation Types - Bottom-Fixed Offshore Wind Turbines (OWT)

This section describes the function of foundation and explains the structure of the MP and jacket foundation.

The foundation serves as the crucial link to a robust, load-bearing subsurface. As described by Bundesamt für Seeschifffahrt und Hydrographie (2021), its primary objective is to create a reliable connection that effectively manages and confines soil settling within acceptable thresholds. By accomplishing this, the foundation guarantees the long-term stability and structural integrity of the entire construction, as emphasized by the Bundesamt für Seeschifffahrt und Hydrographie. Concurrently, foundation elements, identified as vital design components by Piasecka et al. (2019), intricately contribute to the wind turbines functionality. These elements are instrumental in positioning and anchoring the support structure, onto or within the underlying subsoil. Their paramount responsibility lies in the meticulous distribution of ensuing forces. This intricate process is designed to occur with utmost safety, sustainability, and adherence to acceptable levels of displacements and deformations within the subsoil. As the linchpin of structural support, these foundation elements are meticulously integrated to ensure not only the immediate stability of the structure but also its sustained resilience against external forces and environmental conditions. In essence, they form the backbone of a foundation system that is both robust and adaptable, thereby contributing significantly to the overall success and longevity of the construction project (Bundesamt für Seeschifffahrt und Hydrographie 2021; Piasecka et al. 2019).

Jiang (2021) outlines that the dominant sector in the offshore wind energy market is primarily governed by fixed-bottom structures, such as MP, jackets, and gravity-based structure (GBS) offshore wind turbines (OWT).

Schaumann et al. (2021) delineates the MP as a large tube that is either driven or drilled into the ground, see Figure 2-2. Between the MP and steel tower a transption piece (TP) is commonly installeted to facilitate seamless integration, see Figure 2-2. This connection is established either through a grout connection using a pipe-in-pipe plug or a bolted ring flange connection. The TP serves a crucial role by providing access points for ladders, fenders, and platforms, enhancing both functionality and accessibility within the offshore structure, as noted by Schaumann et al. (2021).

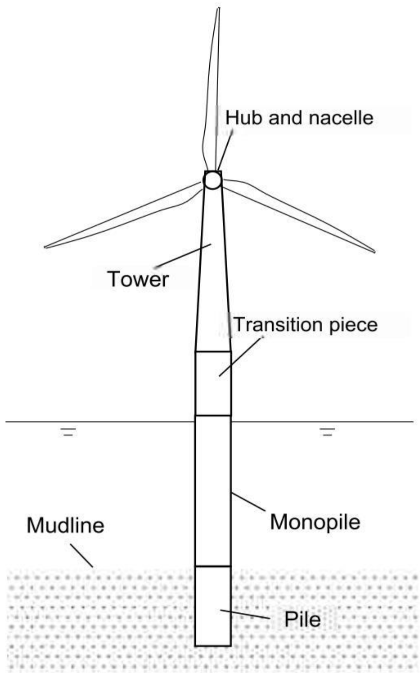

Figure 2-2: Schematic of monopile offshore wind turbine (Jiang 2021, S. 2)

MP foundation is currently the favored choice and is expected to remain so in the future, especially in Europe as per Rystad Energy (2023). Based on this trend, Rystad Energy’s (2023) target scenario for

2030 shows a rapid increase in demand for MP. The typical MP heavily depends on the lateral soil bearing capacity for effective bending moment transfer (Schaumann et al. 2021) and is frequently employed in seabed conditions described as hard to semi-hard, as described by Jiang (2021). The evolution of MP with larger diameters and extended lengths is currently in progress (Jiang 2021). Conventional MP OWT exhibit diameters ranging from three to eight meters, proving economically viable for water depths spanning 20 to 40 meters (Jiang 2021), typically reaching a height of 12 meters and weighing nearly 2500 tons (Schaumann et al. 2021). To achieve the, above mentioned, increasing capacity targets larger turbines sizes and the employment of these in higher water depths, thus higher wind forces, are required (Rystad Energy 2023). Consequently, there is a burgeoning need for lager MP foundations. To follow this trend, several suppliers have commenced scaling up their capacities to accommodate the demand for XXL and XXXL MP (Rystad Energy 2023). As defined by Rystad Energy (2023), XXL MP typically feature diameters ranging from 8 to 11 meters and support turbines ranging from 10 to 14 MW. Meanwhile, XXXL MP boast diameters exceeding 11 meters and are capable of supporting turbines exceeding 14 MW. Based on this description, the primary design structures for the MP foundation, applied in this thesis' LCA, correspond to size XXXL.

This widespread adoption of MP can be attributed to its economic advantages, boasting low construction costs and a streamlined construction process, as highlighted by Piasecka et al. (2019). Despite its considerable material requirement, advancements in automation have significantly streamlined the welding process, contributing to its popularity in the industry (Piasecka et al. 2019; Schaumann et al. 2021).

Schaumann et al. (2021) state that, in contrast to MP, jacket constructions exhibit significantly lighter characteristics (Schaumann et al. 2021). The jacket foundation is described as a three-dimensional truss construction characterized by three or more corner piles and a substantial footprint. These foundation piles, as illustrated in Figure 2-3, are driven through sleeves located at the lower corners, offering an alternative arrangement with suction bucket foundations at the corner piles. Alternatively, the foundation piles can be positioned before the assembly of the jacket structure, allowing for a flexible and adaptable foundation solution (Schaumann et al. 2021).

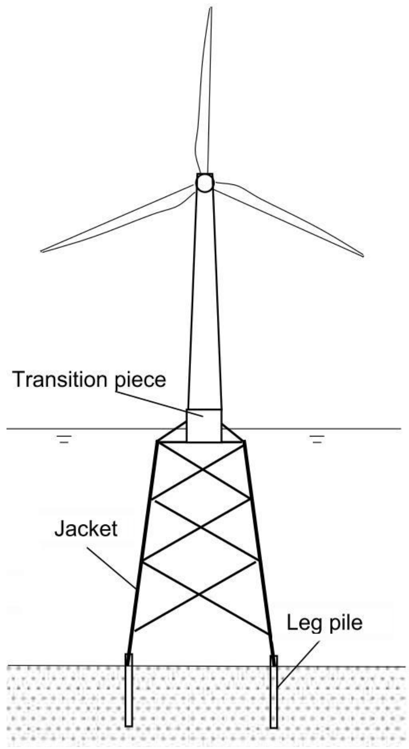

Figure 2-3: Schematic of jacket offshore wind turbine foundation (Jiang 2021, S. 2)

For the pin-pilled jacket the ground position of the foundation is secured through piles. They are renowned intermediate water depths (50m to 70m), as mentioned by Jiang (2021). Schaumann et al. (2021) additionally note that these structures are also suitable for difficult ground conditions, such as those frequently encountered on production platforms in the gas and oil industry. The individual components of the jacket consist of circular tubes, a design choice aimed at minimizing water drag. However, this construction approach introduces complexity to the fabrication process at the nodes, as highlighted by (Schaumann et al. 2021).

Beside the types monopile and jacket there is the third type of bottom-fixed foundations – the GBS, which is largely made of concrete. These will not be examined further, as they are not part of this thesis' LCA. The reason for this exclusion, especially for gravity-based design, is that the foundation type is not used at comparable water depths to monopile or jacket foundations.

2.1.3 Installation Specific

This section describes the details of the installation process, as well as the technical requirements for setting up the MP and jacket foundation.

The installation process commences with the placement of the foundation, as outlined by Asgarpour (2016). Prior to installing a MP, it is imperative to apply a layer of scour protection (SP) to prevent seabed erosion around the structure (Asgarpour 2016). This initial SP layer is created through rock dumping around the designated monopile position. In practice, the installation of SP after pile foundations is not seen as mandatory however it is a viable option dependent on a thorough assessment of site conditions, design specifications and timing considerations. Once the first layer of SP is established, the MP are lifted from the installation vessel and meticulously positioned on the seabed as described by Asgarpour (2016). Since the study exclusively focuses on the steel components and lacks data on the mass of the bricks, the aspect of sound protection was not considered in the LCA of this thesis.

The foundation installation processes for OWT, as discussed by both Asgarpour (2016) and Jiang (2021), involve crucial steps to ensure stability and secure connections. Typically, foundations are installed using either hydraulic hammer-driven pile installation or pile drilling, with jack-up barges providing stability during MP placement (Asgarpour 2016). For large diameter MP (as in this case), employing a hydraulic hammer is deemed infeasible, as underscored by Martinelli et al. (2023), owing to significant underwater noise emissions and the need for massive structures capable of enduring the considerable stresses induced by the procedure (Martinelli et al. 2023). Instead of jack-up barges, floating installation vessels, like heavy lift vessel (HLV) or semi-submersible crane vessels are employed, see Chapter 3 . Therefore, for these extra-large MP foundations, Martinelli et al. (2023) employes the process of vibro-piling. In this case, a hydraulic vibrator generates vertical vibrations that reduce the soil resistance around the pile, making it easier to insert into the ground. The difference in noise compared to traditional methods lies in its duration: vibro-piling produces continuous and not impulsive underwater noise. So far, noise regulations have primarily focused on impulsive underwater noise. However, as more research is conducted on the effects of continuous noise emissions on the environment, vibro-piling methods may soon be subject to stringent norms as well (Martinelli et al. 2023).

Jiang (2021) emphasizes the very high noise emissions caused by the pile-driving work, which can significantly disturb and harm marine mammals such as dolphins and harbor porpoises. This problem can be minimized by temporarily deterring the animals and taking noise protection measures. MP foundations cannot be built on rocky seabed, Jiang's (2021) highlights the importance of maintaining the MP’s upright position on the seabed through friction on its sides (Jiang 2021). This is achieved by deploying a substantial hydraulic hammer throughout the pile-driving operation. Gripper devices are employed to securely grasp and align the MP vertically. Following that, specialized grouting equipment or bolted connections applied to amalgamate the MP and TP, ensuring a robust and stable foundation (Jiang 2021). Afterword, a transition piece is positioned atop the MP, and the interstitial space between these components, also referred to as "anulus", is grouted to establish a secure connection between the foundation and the tower (Asgarpour 2016; Jiang 2021).

Typical pin-pilled jacket foundation is characterized by its lightweight lattice structure, featuring three or four legs with structural elements snugly inserted into the corner tubes (see chapter 2.1.2). According to Jiang (2021) most jackets foundation are supported by anchor piles, strategically placed at each corner of the foundations. Won et al. (2024) distinguish between post- and pre-pilling method. The post-piling method employs a complete substructure. The piles are installed by ramming and trenching, inserting them following the assembly of the substructure (Won et al. 2024). This is an efficient method that requires no specialized equipment, but this process take approximately up to 48 days for the installation of one foundation (Won et al. 2024). The pre-piling method utilizes a template serving as a support tool (Won et al. 2024). Piles are installed on the seabed, and the structures are inserted, mounted, and combined. The template acts as a guiding framework for pile assembly (see Figure 2-4), facilitating the installation of piles while the template is in motion. This method has an overall faster installation time than the post-piling method. However, it requires additional materials for the template and special machinery (Won et al. 2024). Won et al. (2024) recommends the pre-piling procedure for the construction of offshore wind farms with a capacity of 300 MW or higher (Won et al. 2024). The pre-pilling method is used for the installation of the jacket structure described in the application, see Chapter 3 .

Jian (2021) explains that tugboats (support vessels) are used a.o. to provide navigation support and aiding in anchor deployment. The Heavy Lift Vessel (HLV) is utilized to deploy the jacket structure. It is gently hoisted using the vessel's crane and precisely aligned with the pre-installed piles—a visual representation of this process is provided in Figure 2-4 (Jiang 2021).

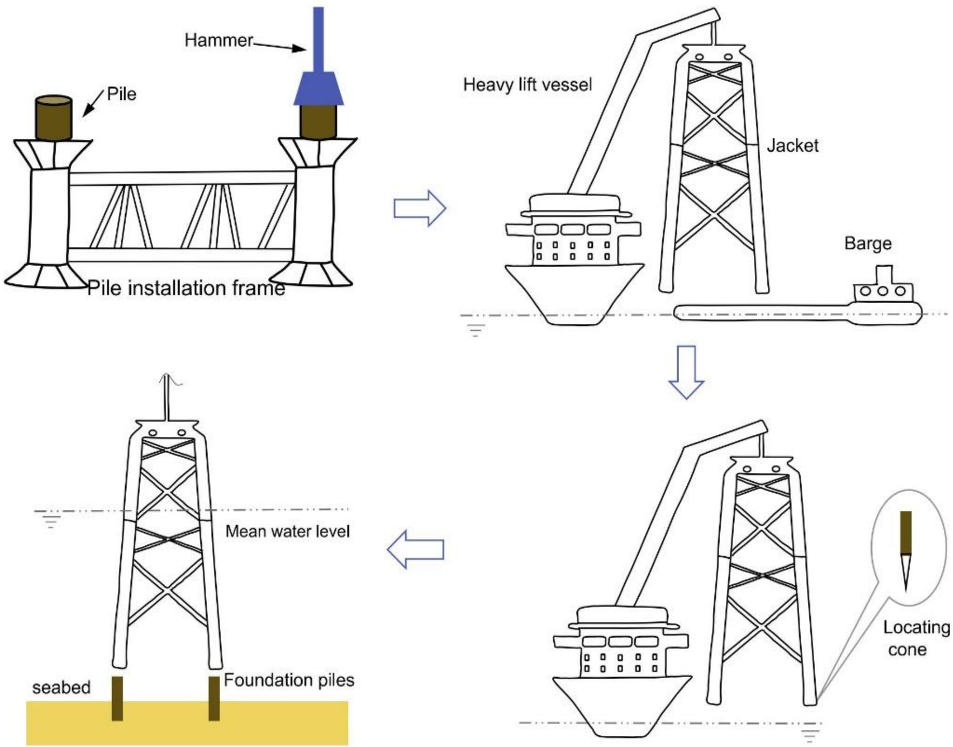

Figure 2-4: Installation: jacket foundation - key steps (Jiang 2021, S. 8)

The installation phase of both foundations requires the deployment of HLV. According to Bai und Bai (2018) a HLV, often referred to as a floating vessel, is equipped with a specialized crane boasting an impressive lifting capacity that can extend into the thousands of tons. This robust lifting capability becomes especially crucial when dealing with substantial subsea structures such as templates, making the deployment of HLVs essential for efficient lifting operations (Bai und Bai 2018).

In contrast to the relatively straightforward installation of MP, the jacket installation entails a more intricate sequence of steps and extends over a prolonged duration, as underscored by Jiang’s (2021) observations.

2.2 Life Cycle Assessment

The chapter defines the LCA method and describes the life cycle stages of an OWT. Furthermore, the implementation of the LCA and the methods, as well as the selection of the appropriate impact assessment categories are discussed in more detail. Subsequently, the basics of data preparation for the LCA is presented.

As per the definition outlined in EN ISO 14040:2006 a LCA equips companies with a robust framework for making sustainable decisions in product design and development. This method is applicable across diverse products or systems, encompassing renewable energy sources such as wind power (EN ISO 14040:2006).

The foundation of LCA rests upon internationally recognized standards EN ISO 14040:2006 and EN ISO 14044:2006. These standards form the essential framework for the comprehensive assessment of environmental aspects and potential impacts throughout the entire life cycle of a product. Starting with choice of an appropriate selection of raw materials to production, transport, installation, use, and eventual end-of-life treatment (including recycling and final disposal), LCA provides a holistic perspective on the environmental footprint of a product (EN ISO 14040:2006; EN ISO 14044:2006). LCA, at its core, is a systematic approach for scrutinizing the environmental dimensions and potential risks associated with a product across its entire life cycle. Spinergie (2023) argues that this theoretical understanding is not only instrumental for practitioners in the field but also for researchers, policymakers, and academics aiming to delve deeper into the theoretical foundations shaping environmental decision-making.

EN ISO 14044:2006 outlines four phases in the LCA study: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation of results. The individual phases are explained in more detail in section 2.2.2.

2.2.1 Life Cycle Stages

Central to the theoretical framework of LCA is the concept of life cycle thinking. The definition of system boundaries in LCA is a theoretical cornerstone. It involves delineating the extent of the product system under assessment. Theoretical considerations guide practitioners in making informed choices about including or excluding specific stages, processes, or inputs within the life cycle.

Each product undergoes distinct stages throughout its life cycle. In accordance with EN ISO 14040:2006, the life cycle is defined as the “consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal” (EN ISO 14040:2006). Based on that definition, Figure 2-5 illustrates the life cycle of a wind turbine system, emphasizing and highlighted in blue the phases considered within this study.

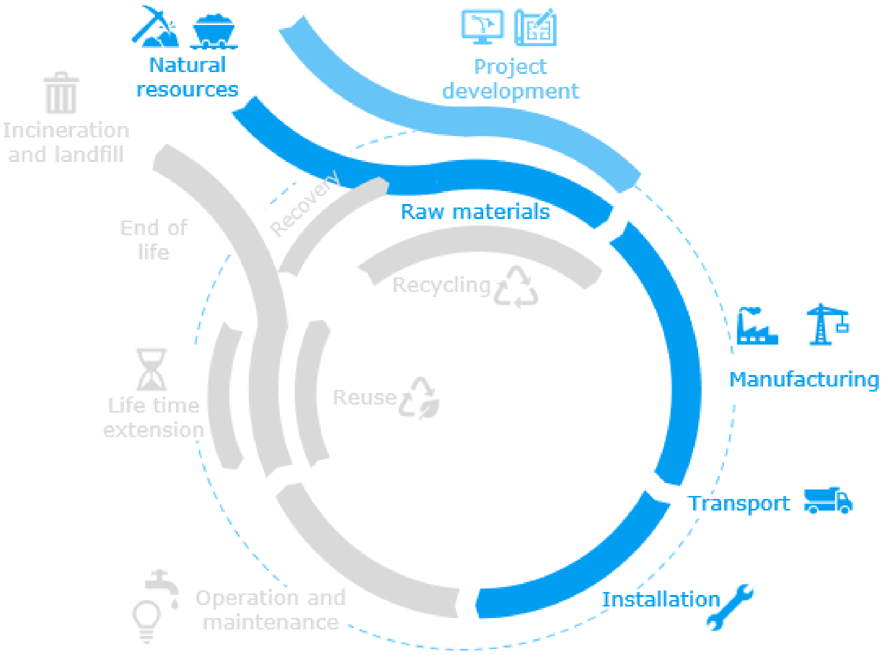

Figure 2-5: Life cycle stages; based on (EN ISO 14040:2006)EN ISO 14040:2006

The life cycle begins with the procurement of raw materials, which is part of the project development phase. According to Bundesamt für Seeschifffahrt und Hydrographie (2021), this phase marks a foundational juncture in the life of an offshore wind farm (OWF), wherein crucial procedures and decision-making processes shape both the design and the selection of raw materials. To provide a robust basis for material and design choices, various reports are generated, including the geotechnical report and the environmental impact report (Bundesamt für Seeschifffahrt und Hydrographie 2021). Furthermore, the installation and operation manual and a decommissioning concept should be developed (Bundesamt für Seeschifffahrt und Hydrographie 2021). During the development phase, the design principles and basic construction models as well as the primary and secondary design structures are to be finalized. Only the primary design of foundations is considered in the thesis (section 2.1.1). Due to the extent of the deployment stage, this phase plays a crucial role in determining the final product and its associated emissions and environmental impacts (Bundesamt für Seeschifffahrt und Hydrographie 2021).

The manufacturing phase, constituting the second stage, involves the production and assembly of all components into larger parts, such as the foundation or tower as outlined by the Bundesamt für Seeschifffahrt und Hydrographie (2021). According to the report from Rystad Energy (2023) in most cases, the production of individual parts and their assembly into larger components takes place at different locations. Furthermore, it may occur that there are not just one but multiple suppliers, causing the individual parts to travel several kilometers to be assembled (Rystad Energy 2023). This makes the supply chain difficult to track and causes additional emissions within the manufacturing stage.

All components of an OWF must undergo transportation from the manufacturing facility to the construction location. Asgarpour (2016) elucidates that this logistical operation relies on a variety of semi-submersible HLV or heavy load carriers, which transport the foundation structures (MP and jackets) as single-piece construction. The deck's dimensions determine the quantity of foundation structures, pipes, and transition pieces that can be efficiently transported in each shipment. Asgarpour (2016) emphasizes the staged delivery of wind farm components to mitigate storage challenges and ensure efficient deployment. Depending on the location of the manufacturer and of the wind farm sometimes the components will not be directly delivered to the target location. They can be transported on land via trucks to the onshore assembly site at the harbor and then be loaded on the installation vessels to be further transported to the target location (Asgarpour 2016).

Upon arrival, the components are methodically installed, commencing with the foundation. As per Jiang (2021), offshore installations deviate from standard operations due to their intricate complexities. The distinctive demands for offshore installation within each OWF hinge on factors such as rotor dimensions, foundation types, technological advancements and site-specific conditions. The installation of an OWT entails the assembly and eventual connection of various turbine components to the grid. Given its offshore location, this endeavor qualifies as a marine operation. Thus encounters challenges the limited availability of installation equipment in the market, dependence on optimal weather windows, and inherent safety risks associated with lifting operations (Jiang 2021). Once the installation process is successfully completed, the wind farm is ready to be operational (Bundesamt für Seeschifffahrt und Hydrographie 2021).

It's important to note that the operation and maintenance phase and the end-of-life phase (highlighted in gray in Figure 2-5) will not be extensively discussed in the following work, as they not fit in the scope of this work’s LCA. The exclusion of these phases from the study is due to archival data from Ramboll indicating that the first offshore wind parks were constructed in the early 2000s. These facilities are slated for decommissioning no earlier than 2025, resulting in a lack of practical recycling rate values for the company. Additionally, the initial installations featured small turbines and were situated in shallow waters, which are no longer representative of current industry standards, rendering comparisons with newer installations unfeasible.

According to Pagh Jensen (2019) the end of life (EoL) is the life cycle stage least covered in wind power LCAs and is associated with several uncertainties. For example temporal uncertainties arise due to the long lifetime of the plants and the difficulty in predicting future markets and corresponding treatment technologies (Pagh Jensen 2019).

2.2.2 Methodologies in LCA

The standards EN ISO 14040:2006 and EN ISO 14044:2006 outline the following steps for the LCA: Firstly, the scope and goal, which includes determining the system boundaries and level of detail of the study are defined. When defining the system boundary, the process units to be included in the system are determined. The theoretical concept of the functional unit establishes the reference point for LCA studies. It involves defining the unit by which the environmental performance of different systems (or products) is measured. In developing the model for the product system, it is crucial to ensure that only elementary flows constitute the inputs and outputs at its boundary. During this phase, the rationale for conducting the study is established, the target audience is identified, and the application is specified. The scope and depth of a LCA can vary significantly depending on specific objectives. This initial phase serves not only to establish the reasons for undertaking the study but also to identify the target audience and specify the application context (EN ISO 14040:2006; EN ISO 14044:2006).

The subsequent phase outlined by EN ISO 14040:2006 entails the life cycle inventory (LCI), wherein data is gathered and computed to quantify pertinent inputs (resources) and output (emissions) data for the analyzed system. This process involves gathering the necessary data to achieve the predefined study objectives. EN ISO 14044:2006 emphasizes the necessity of collecting qualitative and quantitative data for each unit process within the system boundary to effectively quantify both inputs and outputs (EN ISO 14044:2006). Additionally, a description of each unit process should be recorded to mitigate the risk of misunderstandings, such as double counting during data validation or reuse (EN ISO 14044:2006). Transparently presenting each source is essential since the data may originate from various references.

The European commission (2010a) defines two main ways of modelling principles for an LCI – the attributional and the consequential. The attributional life cycle model illustrates the current or expected supply chain, usage, and end-of-life value chain within a static Technosphere (European commission 2010a). Contrastingly, the consequential life cycle model depicts the impact of decisions on supply chains and markets within a dynamic environment (European commission 2010a).

Aligned with EN ISO 14040:2006, the LCIA introduces an additional layer of insight, providing supplementary information to assess the outcomes of the LCI. EN ISO 14044:2006 outlines that LCIA evaluates the sufficient LCI data and results ensuring the comprehensiveness of system boundaries and data cut-off decisions. Furthermore, LCIA examines potential reductions in environmental relevance resulting from functional unit calculation and data manipulation techniques (EN ISO 14044:2006). For conducting LCIA essential elements should include the selection of impact categories, category indicators, and characterization models (EN ISO 14044:2006). The European commission (2010a, 2010b) emphasizes thorough alignment of impact categories, encompassing all pertinent environmental factors associated with the system under review, such as the product in question. However, due to the diverse units of LCIA results across impact categories, direct comparison or summation is not possible.

In the concluding phase, as defined by EN ISO 14044:2006, the culmination of the LCA process involves summarizing and discussing the results of both LCI and LCIA. The analysis progresses through three tasks: recognizing noteworthy concerns, assessing these matters concerning their impact or importance on the comprehensive outcomes of the LCA, and drawing conclusions derived from the assessment. The interconnection of these phases ensures a holistic and informed approach to access the environmental impacts of the studied system (EN ISO 14044:2006).

2.2.3 Impact Assessment Categories

To carry out the LCIA, suitable categories must be selected. EN ISO 14044:2006 provides comprehensive guidance on the selection of impact categories in LCA. This process involves careful consideration of several key factors. Firstly, the selection of impact categories is justified and aligned with the specific goals and scope of the LCA study. Secondly, the chosen impact categories should effectively cover a wide range of environmental issues relevant to the product system under investigation, ensuring that all pertinent aspects are addressed in line with the LCA objectives. Moreover, it is important to identify other relevant LCI results, such as land use, and establish their relationship to corresponding category indicators. The flexibility to select category indicators along the environmental mechanism between LCI results and category endpoints allows for a tailored approach to suit the specific characteristics of the studied system. Finally, environmental relevance is assessed qualitatively, considering the degree of linkage between category indicator results and category endpoints, which are categorized as high, moderate, or low linkage (EN ISO 14044:2006).

European commission (2010b) complements the guidance described by EN ISO 14044:2006 by emphasizing the importance of assessing different characterization models against a set of criteria. These criteria, encompassing both scientific rigor and stakeholder acceptance, serve as fundamental requirements for LCIA methods across all impact categories within associated areas of protection (AoP). The criteria include completeness of scope, environmental relevance, scientific robustness and certainty, documentation transparency and reproducibility, and applicability. Additionally, the stakeholder acceptance criterion considers the degree of acceptance and suitability of the chosen characterization models for communication in various contexts, such as business and policy settings (European commission 2010b). The European commission (2010b) classifies the AoP into three core spheres: safeguarding human health, preserving the natural environment, and managing natural resources. These fundamental pillars further branch into eleven essential categories, spanning human health, environmental integrity, and resource sustainability. These encompass human health, natural environment, natural resources, climate change, ozone depletion, human toxicity, respiratory inorganics/particulate matter, ionizing radiation, photochemical ozone formation, acidification, eutrophication, ecotoxicity, land use, and resource depletion (European commission 2010b).

2.3 Data Preparation LCA

Adequate data for constructing the manufacturing process in OpenLCA can be sourced from Ecoinvent 3.9, obviating the need for pre-calculation during the phases transport and installation (T&I).

Given the absence of data on transportation and installation stages in Ecoinvent 3.9, pre-calculations of emissions for each phase and vessel type have been carried out with OpenLCA. These emissions will serve as output flows for modeling the transportation and installation phases, with the list of vessel types for each foundation and phase provided in the subsequent Chapter 3 . The pre-calculation process is conducted in Excel, and the file is available in the electronic attachment, Data preparation LCA – steel weights and emissions. The International Maritime Organization (2020) study categorizes the hourly emissions for each system (main engine, auxiliary engine, and boiler) in two groups: fuel-based and energy-based.

For fuel-based calculations, pollutants has been determined by the quantity of pollutant in the fuel and the engine type, with fuel-based emissions (EM_i) obtained through the product of the hourly fuel consumption (FC_i) and the fuel-centric emission factor (EF_f) in g pollutant/g fuel, see Equation (2-1). The computation has been performed for marine gas oil (MGO), as it is the fuel used by all vessels in the given scenario, see Chapter 3 .

$$\mathrm{EM_i} = \mathrm{FC_i} \cdot \mathrm{EF_f} \qquad (2\text{-}1)$$

$$[g] = [\mathrm{g\,MGO}] \cdot \left[\frac{g\ pollutant}{g\ MGO}\right]$$

The fuel-based emission factors (EF_f) for MGO, provided in Table *2-1*, are taken from International Maritime Organization (2020).

Table 2-1: Fuel-based emission factors (International Maritime Organization 2020)

Emission indicator	Emission factors (EF_f) [kg/mt]
CO_2	3206.00
SO_x	2.150
CH_4	0.045
NMVOC	2.285
CO	2.465
PM10	0.945

For energy-based groups, the pollutants has been determined based on the power output of the engine, utilizing an energy-based emission factor (EF_e) in g pollutant/kWh, see Equation (2-2) (International Maritime Organization 2020). The computation for hourly emissions (EM_i) follows this approach:

$$\mathrm{EM_i} = \mathrm{EF_e} \cdot \dot{\mathrm{W}}_\mathrm{i} \qquad (2\text{-}2)$$

$$[\mathrm{g}] = \left[\frac{\mathrm{g}}{\mathrm{kWh}}\right] \cdot [\mathrm{kWh}]$$

For the calculation of the nitrogen oxides (NO_x) emissions ($\mathrm{EM_e, NO_X}$) the data from the follow Table 2-2 has been used.

Table 2-2: Energy-Based Emission Factors (EF_e) for NO_x depending on the Engine tier differentiation (International Maritime Organization 2020)

Tier	Construction Date	$\mathbf{EF_e, NO_X\ (\frac{g}{kWh})}$ n = RPM (engine's rated speed)		
		n < 130	**130 <= n < 2000**	**n >= 2000**
I	2000 – 2010	17.00	$45 \cdot n^{-0.2}$	9.80
II	2011 – 2015	14.40	$44 \cdot n^{-0.23}$	7.70
III	From 2016	3.40	$9 \cdot n^{-0.2}$	2.00

To calculate the emissions based on the energy-based emission factors (EF_e), the engine's rated speed (n) for each vessel must be known and the electrical energy ($\dot{W}$) in kWh of the used engine:

$$EM_e = \dot{W}_l \cdot n \quad (2\text{-}3)$$

The following example refers to a vessel that has been used for the transportation of four-legged pin-pilled jacket foundation. Example: Heavy lift vessel (HLV) type Tier I with n = 82.5 PRM and P = 2000 kW over $\Delta t = 173.84$ h

$$n = 82.5\ \text{PRM} > 130\ \ \text{means}\ EF_e, NO_X = 17.00\ \text{g/kWh}$$

The data yields the following electrical work:

$$\dot{W} = 2000\ \text{kW}\ \cdot 173.84\ \text{h}$$

$$\dot{W} = \ 347676.45\ \text{kWh}$$

Insert $\dot{W}$ in Equation (2-3):

$$EM_eNO_x = 347676.45\ \text{kWh}\ \cdot \left(\frac{17.00\,\frac{g}{kWh}}{1000}\right)$$

$$EM_eNO_x = 5910.50\ \text{kg}\ NO_X \approx 6.00\ \text{t}\ NO_X$$

During the entire transportation (both ways), the vessels emit round 6 thousand kg NOx or 6.00 t NO_X.

The International Maritime Organization (2020) recommends sourcing emission factors for methane (CH4), carbon monoxide (CO) and particulate matter (PM2.5 and PM10, where PM2.5 is assumed to be constitued by 92% of PM10) from the Third IMO GHG Study 2014 (International Maritime Organization 2020). Furthermore, the study recommends acquiring nitrous oxide (N2O) and non-methane volatile organic compounds (NMVOC) emission values from the Office of Transportation Air Quality, average values are employed in Table 2-1 (International Maritime Organization 2020). The specified emission factor (EF_eN2O) is 0.03 g N2O/kWh for all diesel-cycle engines (International

Maritime Organization 2020). To compute these emissions, Equation (2-3) has been used for the EFeN2O:

$$\mathrm{EM_e} = \dot{\mathrm{W}}_\mathrm{i} \cdot \mathrm{EF_e N2O} \tag{2-4}$$

The subsequent computation of energy based N2O emission value pertains to the earlier example involving a transportation vessel utilized for the jacket foundation. Inserting the above given data for the transportation vessel into equation (2-4) results in the following N2O emissions:

$$\mathrm{EM_e N2O} = \left(\frac{0.03\ \mathrm{g} \frac{\mathrm{N2O}}{\mathrm{kWh}}}{1000} \right) \cdot 347676.45\ \mathrm{kWh}$$

$$\mathrm{EM_e N2O} = 10.43\ \mathrm{kg\ N2O}$$

During the entire transportation (both ways), the vessel emits around 10.43 kg N2O.

For non-methane volatile organic compounds (NMVOC), the average value of 2.29 kg NMVOC/t MGO has been used (see Table 2-1).

The transport emissions have been calculated using the consumption for the transported distance, which the components have to travel from the supplier to the wind farm site, over the transported weight (the mass of the components). The emissions during the installation are the sum of the emissions for the distance between the harbor and wind farm site and the emissions during installation process of the foundation.

3 Application of LCA on Primary Design Components for XXXL MP and Four-Legged Pin-Pilled Jacket Foundation

As alluded to in the introduction (p.1), there has been a rapid expansion in the demand for offshore wind installations due to the prevailing pressure to reduce greenhouse gas (GHG) emissions (Environmental Protection Agency 2016; Rystad Energy 2023). However, in striving to minimize its environmental impact and enhance independence from fossil fuels, the industry has been increasingly focusing on methods such as LCA (Global Wind Energy Council 2023; Bonou et al. 2016).

The LCA methodology and the results (see Chapter 4) are structured based on the sequence of the four phases: goal and scope definition, LCI, LCIA and interpretation of the results. Aims to deepen our theoretical understanding of LCA and its broader implications in the realm of environmental analysis.

The input data is based on the company's empirical knowledge. Therefore, certain data is confidential and cannot be included in the thesis.

3.1 Goal and Scope

3.1.1 System Boundaries

The methodology employed in this study is EF v.3.1 (Environmental Footprint package version 3.1) and utilizes the Ecoinvent 3.9 database in OpenLCA.

The system boundary illustrated in Figure 3-1, encompasses the life cycle of the primary design structures of XXXL MP and four-legged pin-pilled jacket foundations, spanning from development to installation phase. The inputs are the required amount of steel and its production (the exact production process is not known, hence it will not be further discussed), as well as fuel consumption and the resulting emissions (EN ISO 14040:2006; EN ISO 14044:2006). In Figure 3-1, the transport phase has been visualized within the development and manufacturing phase, as it is necessary to deliver the components from the supplier to the installation site. To simplify the illustration, the outputs has been labelled as life cycle impacts, as there are different emissions (outputs) for the two processes. The outputs have been analyzed in detail in Chapter 3.3.

The LCA has been carried out for primary design structures of two different bottom-fixed foundation types – XXXL MP and four-legged pin-piled jacket. To ensure uniform quality, the steel grade remains consistent across all components. The detailed list of the XXXL MP and four-legged pin-pilled jacket foundation’s components can be found in section 3.2.1.

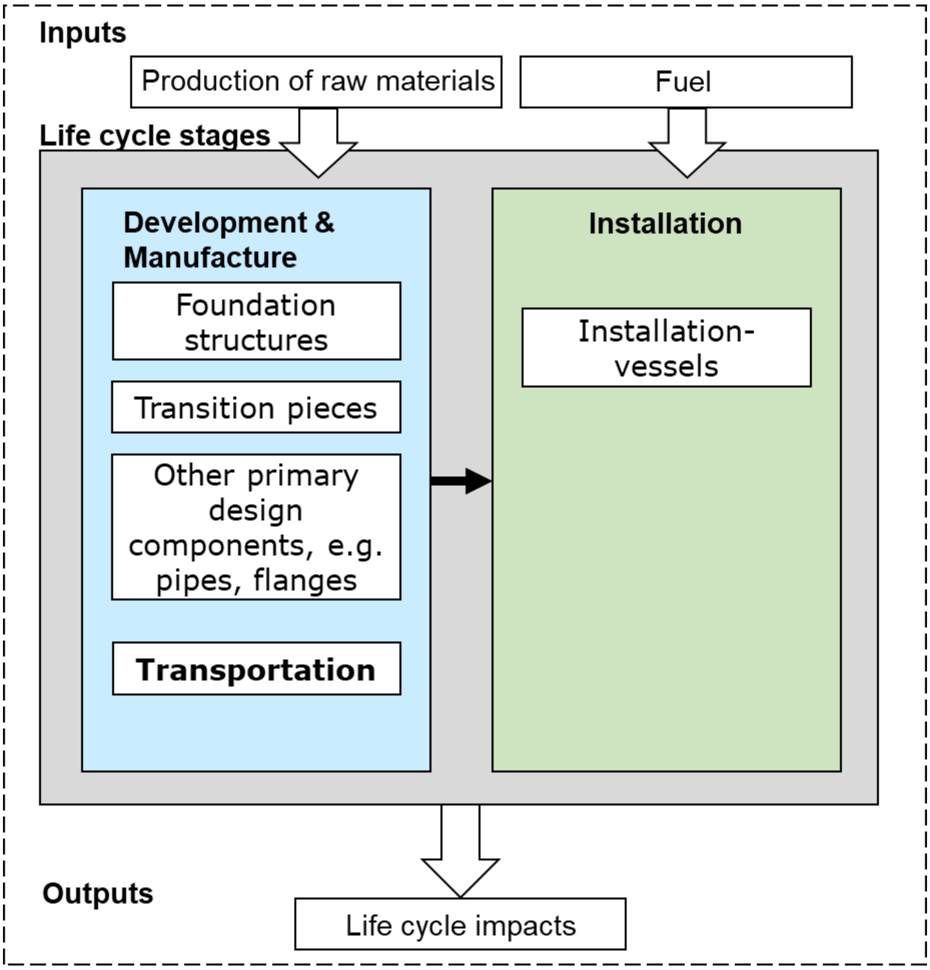

Figure 3-1: System boundaries for the LCA assessment of the primary design for offshore wind, based on Garcia-Teruel et al. (2022)

In both cases, the components are manufactured in Europe and transported for the installation phase to the North Atlantic. The distances for transport and installation are identical for both foundation types. Both types of foundations were simplistically dimensioned for a turbine size of 15 MW and an average water depth of -40m wtr LAT. The input data for each phase will be shown and described in the following sections.

3.1.2 Functional Unit

For this work, the mass of steel needed for primary design components of XXXL MP and four-legged pin-pilled jacket foundations in t have been selected as a functional unit. The calculation of input resources and associated emissions across the life cycles of offshore wind power systems have been conducted using this functional unit.

3.1.3 Assumptions

By performing the LCA for the primary design of offshore wind foundations, the following assumptions have been maintained:

- To streamline and ensure data confidentiality, the example presupposes the integration of the Vestas 15MW turbine in both designs, with an annual energy production of 80GWh and an operational lifetime of 25 years (Vestas n.D.).
- The steel grade is the same, however the exact composition and manufacturing process is unknown; the Ecoinvent 3.9 data set "steel production, converter, low-alloyed (RER)" (ecoQuery 2024) has been used to analyze the manufacturing process. According to ecoQuery (2024) this steel is used for the production of "offshore and onshore structural engineering plates" (ecoQuery 2024).
- The original data (indications of mass concerning the water depth) has been converted, relying on a highly simplified (linearized) conversion of the steel requirements for the respective primary design of the foundation. These have yielded the mass fractions shown in Table *3-1*.
- The same fuel is considered for all vessels: marine gas oil (MGO) is a distillate fuel with typically low sulfur content (International Maritime Organization 2020).
- For modeling the T&I vessels, only the air emissions criteria outlined by the International Maritime Organization (2020) are considered, see Table 3-3 and Table 3-5 as Ecoinvent 3.9 data base does not include data on cargo or installation vessels that could be used for the T&I of an offshore wind farm.

3.2 Life Cycle Inventory (LCI)

This chapter presents and describes the required steel weight per component and vessel's technical specifications (background data), and the steel weight of each foundation type per transportation's distance (input data) for each phase of the life cycle. In addition, the calculated emissions of the vessels (output data) are presented.

LCI of primary design of offshore wind foundation drew on the expertise and insights of Ramboll experts (Ramboll, 2023). Moreover, data for the installation and transportation phases were enriched with information gleaned from International Maritime Organization (2020). Steel quantities, vessel numbers and construction-phase time have been adjusted to facilitate meaningful comparisons (see section 3.1.3). Further elucidation on inventory data across manufacture, transportation and installation phases will be provided in subsequent sections.

3.2.1 Manufacture Stage

This thesis delves into the primary design of offshore wind turbines for XXXL MP and four-legged pin-pilled jacket foundation. The primary design components were fabricated using the same raw material (steel). The steel quantities utilized were computed for a standardized turbine model (approximately 15MW), uniform water depth (-40m wtr LAT) at the designated site. The components were manufactured in Europe and deployed to North Atlantic, USA. The required steel amount percentage for each component, as well as the total mass of both foundations are presented in Table 3-1.

Table 3-1: Manufacture (weight) inventory data for both foundation types

XXXL MP		Four-legged pin-pilled jacket	
Components	**Average mass [%]**	**Components**	**Average mass [%]**
MP structure	82.57	Jacket structure	48.78
Transition piece (TP)	19.76	Transition piece (TP)	14.18
Flanges (4x)	2.94	Piles (3x)	37.04
Support Ring	0.26		
Total mass [t]	2062	**Total mass [t]**	2821

Table 3-1 presents only the total amount of steel used for each foundation in tons as the calculations for the manufacture stage, as well as for the T&I has been made per foundation and not per component. To emphasize the mass proportions and consequently the effect of the individual components on the total weight, the individual weights are shown as percentages.

3.2.2 Transport Stage

This section examines technical details of the transportation vessels and their engines, which is needed to calculate the vessels emissions. Additionally, the vessel's emissions for each foundation type are presented. To facilitate the transportation of primary design components from Europe to the wind farm site in the USA, vessels have been categorized as "general cargo" have been deployed, in accordance with data extracted from the International Maritime Organization (2020) report.

For the transportation of the XXXL MP foundation, a sole Tier II vessel boasting a deadweight tonnage (DWT) of approximately 25,000 tons was enlisted (PAN Ocean n.D.). For the transportation of four-legged pin-pilled jacket foundation components, a combination of two Tier I vessels, each equipped with an approximate DWT of 65,000 tons (Seaway 7 2022), alongside one Tier II vessel with a DWT of around 25,000 tons (PAN Ocean n.D.), was utilized. It has been presumed that all vessels uniformly utilized the same fuel type – marine gas oil (MGO). The technical specifications of the transport vessels and the installed engines are outlined in Table 3-2.

Table 3-2: Technical specifications of the transport vessels

Foundation type	Vessel type	Description	Technical data
XXXL MP and four-legged pin-pilled jacket	HLV	Deadweight tonnage (DWT)	24,629 t
		IMO Tier	II
		Revolutions Per Minute (PRM)	735 PRM
		Power	4000 kW
Four-legged pin-pilled jacket	Semi-submersible vessel / HLV	Deadweight tonnage (DWT)	64,900 t
		IMO Tier	I
		Revolutions Per Minute (PRM)	82.5 RPM
		Power	2000 kW

The above presented transportation vessel types (HLV and semi-submersible vessel / HLV) have been modeled with the OpenLCA program. The transportation vessel´s emissions have been calculated in accordance with the theoretical specifications and formulas described in Chapter 2.3 Data Preparation LCA. The emissions presented for the transportation of the four-legged pin-pilled jacket foundation components represent the combined emissions of HLV and semi-submersible vessel / HLV. For the transportation of the XXXL MP foundation components only one vessel is needed. Detailed calculations available in the electronic appendix, Data preparation LCA – steel weights and emissions.

Table 3-3 displays the inventory data for the transport phase of primary design structures for both foundation types, including: average speed, consumption and calculated emission factors.

Table 3-3: Transportation inventory data for both foundation types

Description		XXXL MP	Four-legged pin-pilled jacket
Cruising speed [kn]	av	13	
Consumption [mt MGO/day]		10	
Emissions: Foundation round trip [kg]	CO2	157677.13	232218.90
	SOX	105.99	155.73
	CH4	2.21	3.26
	NMVOC	112.38	128.45
	CO	121.23	138.57
	PM10	46.48	68.45
	PM2.5	42.76	62.97
	NOX	4552.85	13236.74
	N2O	14.16	31.29

Table 3-3 presents emissions arising for vessel operations throughout the transportation route, alongside the mass to be transported, has been meticulously calculated based on their consumption rates and leveraging insights provided by the International Maritime Organization (2020) report. Detailed calculations are available in the electronic appendix, Data preparation LCA – steel weights and emissions.

3.2.3 Installation Stage

This section examines technical details of the installation vessels and their engines, which are needed to calculate the vessel's emissions. Additionally, the installation vessel's emissions for each foundation type are presented. For the installation of primary design components from Europe to the wind farm site in the USA, vessels classified as “general cargo “ and "work vessel- offshore" have been utilized, based on data provided in the International Maritime Organization (2020) report.

For the installation of XXXL MP foundation, a Tier 3 category vessel (HLV) has been employed. While for the installation of four-legged pin-pilled jacket foundation components, one Tier I vessel (support vessel) and two Tier III vessels (HLV) have been utilized. Similarly, to the transportation phase, it was assumed that all vessels consumed the same type of fuel. The technical specifications of the installation vessels and the installed engines are outlined in Table 3-4.

Table 3-4: Technical specifications of the installation vessels

Foundation type	Vessel type	Description	Technical data
XXXL MP and four-legged pin-pilled jacket	Floating HLV	Deadweight tonnage (DWT)	30,000 t
		Crane capacity	main 5,000 t aux 1,500 t
		Tier IMO	III
		Revolutions Per Minute (PRM)	1100 RPM 600 RPM
		Power	44190 kW
Four-legged pin pilled jacket	Support Vessel	Deadweight tonnage (DWT)	4,800 t
		Tier IMO	I
		Power	20485.87 kW

The above presented installation vessels (floating HLV and support vessel) have been simulated with the OpenLCA program. The installation vessel´s emissions have been computed following the theoretical specifications and formulas outlined in Chapter 2.3 Data Preparation LCA. The emissions attributed to the installation of the jacket foundation components reflect the aggregate emissions of floating HLV and support vessel. Elaborate computations are accessible in the electronic appendix, Data preparation LCA – steel weights and emissions. The calculated emissions for the primary design for both foundation types (inventory data for the installation phase), is presented in Table 3-5.

Table 3-5: Installation inventory data for both foundation types

Description		XXXL MP	Four-legged pin-pilled jacket
Cruising speed [kn]	av	11	
Consumption [mt MGO/day]	av	45	
Operational time per one foundation [d]	av	3.46	9.74
Emissions: Installation plus round trip [kg]	CO2	2684542.28	8742714.02
	SOX	1804.49	5863.02
	CH4	37.68	122.71
	NMVOC	1913.34	6231.16
	CO	2064.07	6722.02
	PM10	791.30	2601.54
	PM2.5	727.99	2393.42
	NOX	9519.46	31877278.92
	N2O	109.97	620.04

Table 3-5 presented emissions for the installation vessels along the travelled route, relative to the weight being transported from the manufacture to the offshore wind farm site, have been calculated based on their consumption rates, drawing from information in the International Maritime Organization (2020) report. Additionally, the operational duration of the vessels (installation duration) was also taken into consideration. Detailed calculations available in the electronic appendix, Data preparation LCA – steel weights and emissions.

3.3 Life Cycle Impact Assessment (LCIA)

This Chapter describes the chosen impact assessment method (EF 3.1) and the impact categories for the LCIA. The selected impact assessment method for conducting this LCA is the Environmental Footprint (EF) 3.1 method, which has been endorsed by the European commission (15.12.2021) as a common mean of measuring environmental performance. This impact assessment method, recognized as EU-recommended LCA approach, is specifically designed to quantify the environmental impacts of goods, services and organizations. EF 3.1 offers a robust framework for comprehensively evaluating environmental footprints throughout various stages of a product's or organization's life cycle, thereby facilitating informed decision-making and promoting environmental sustainability (European commission 2024).

The selection of all impact categories is grounded in the conditions outlined in section 2.2.3, aligning with the objective of the thesis's LCA focusing on the assessment of ecological sustainability. The sustainability definition refers to the World Commission on Environment and Development (1978), framework, with a specific emphasis on the ecological dimension, which is described by Kropp (2019).

Embedded within the guidelines laid out by the European commission (2010b), the EF 3.1 method meticulously dissects inventory findings across 25 diverse impact categories, enabling a thorough and comprehensive assessment. In the subsequent section, particular attention will be directed towards the following three chosen categories: Global warming potential (GWP 100) in t CO2-Eq., energy payback time (EPT) in months based on abiotic depletion potential for fossil fuels (ADPF) in MJ and eutrophication in t N-eq. The first and the second impact categories (GWP 100 and ADPF, along with the resulting EDP) have been determined based on customer requirements and their direct applicability in the project scenarios. This strategic decision has been substantiated by relevant examples such as Gkantou et al. (2020), Haapala und Prempreeda (2014), Huang et al. (2017) and Yildiz et al. (2021). The third impact category (eutrophication: marine - fraction of nutrients reaching marine end compartment) has been selected to investigate influences on environmental quality, as for example in Piasecka et al. (2019).

The first impact category (GWP 100) serves as a metric to compare the warming effects of different greenhouse gases (GHGs) relative to carbon dioxide (CO2) over a specific timeframe, typically 100 years as outlined by Environmental Protection Agency (2016). The GWP pertains to the impact of the process on climate change, essentially quantifying how a specific amount of GHG contributes to global warming. It operates on a relative scale, comparing the gas in question to an equivalent mass of carbon dioxide. (Environmental Protection Agency 2016). The primary GHGs include CO2, methane (CH4), and nitrous oxide (N2O). It's measured in CO2 equivalents (CO2-Eq.) per kilowatt-hour (kWh), factoring in the combined impact of GHGs based on their individual GWP (Environmental Protection Agency 2016). CO2 is used as the reference with a GWP of 1 CO2-Eq., reflecting its long atmospheric lifespan lasting thousands of years. CH4 has a GWP of 27-30 CO2-Eq. over 100 years due to its shorter atmospheric lifespan compared to CO2 but higher energy absorption. N2O has a GWP of 273 times that of CO2, remaining in the atmosphere for over 100 years (Environmental Protection Agency 2016).

The second impact category (ADPF), delves into the ramifications of diminishing availability of non-renewable resources, driven by their consumption outpacing the natural rate of replenishment, as defined by the European commission (2010b). This depletion extends beyond mere exhaustion; it pertains to the curtailment of the total reserve of potential functions of these resources (European commission 2010b). Minerals and fossil fuels exemplify non-renewable resources within this category (European commission 2010b). Furthermore, this impact factor belongs to the environmental footprint method and is characterized by its time independence, as described by OEKOBAU.DAT (2017). ADPF assessment operates on a depletion model based on the use-to-availability ratio, assuming full substitution among fossil energy carriers (OEKOBAU.DAT 2017). The ADPF values can be used to determinate the EPT. EPT is characterized by Bonou et al. (2016) as the duration required for a system to generate an energy output equivalent to the primary energy consumed throughout its lifespan. This definition provides insight into the equilibrium between energy input and output over the system's lifecycle (Bonou et al. 2016). Umweltbundesamt (2021) underscores the significant impact of system-specific and site-specific factors on the calculated EPT, particularly observable in wind energy systems. This highlights the importance of considering diverse influencing factors for precise EPT assessments, essential for informed decision-making in energy planning and implementation.

The third impact category (eutrophication, also known as nutrient accumulation) delves into the impacts of nitrogen and phosphorus in bioavailable states on both aquatic and terrestrial ecosystems, see European commission (2010b). The (excessive) supply of nutrients in aquatic systems triggers excessive algal blooms, which causes light filtering and degradation in relation to the water layers below. The high algae concentration and lack of light is followed by a decrease in oxygen near the seabed, which is exacerbated by the emission of biological material (European commission 2010b). The overgrowth of algae in aquatic systems is often limited by the one of the macronutrients (European commission 2010b). In general, phosphorus is the limiting nutrient in freshwater systems, while nitrogen is limiting in marine ecosystems. The function of the ecosystem and biodiversity are affected by the nutrient accumulation (European commission 2010b). Over-nutrition of terrestrial systems can also change the biodiversity of natural vegetation so that only species which benefit from higher nutrient levels survive. Consequently, plant communities change from nutrient-poor to nutrient-rich environments. Terrestrial eutrophication is primarily caused by air emissions of nitrogen compounds from combustion processes and ammonia from agriculture (European commission 2010b).

4 Results and Discussion

In this chapter, the outcomes of the LCIA are presented and summarized. Subsequently, the impact categories selected in the preceding chapter are interpreted. Table 4-1 provides a comprehensive overview of the results derived from the LCIA concerning the primary design structures of both foundations (XXXL MP and four-legged pin-pilled jacket) throughout each phase of the assessment and for all chosen impact categories. The table provided offers a generalized overview, serving as an initial point of reference. For a more comprehensive insight, detailed explanations and graphical representations of individual influx factors and their values will be provided in the subsequent chapters.

Table 4-1: LCIA results per stage for the chosen impact categories (global warming potential (GWP), Eutrophication, abiotic depletion potential (ADP) and Energy payback time).

Foundation types	Impact categories	Manufacture	Transport	Installation
MP	**GWP 100 [t CO2-Eq]**	4291.37	139.72	2685.67
	Eutrophication [t N-Eq]	4.04	1.57	3.70
	ADP [MJ, net calorific value]	44732785.25	-	-
	EPT [m]	1.86	-	-
Four-legged pin-pilled jacket	**GWP 100 [t CO2-Eq]**	5871.02	232.32	8746.37
	Eutrophication [t N-Eq]	5.52	5.15	33.25
	ADP [MJ, net calorific value]	61198816.89	-	-
	EPT [m]	2.55	-	-

4.1 Global Warming Potential (GWP 100)

The chapter describes the LCIA results (presented in the upper table) for the GWP 100 for XXXL MP and four-legged pin-pilled jacket foundation. Table 4-1 reveals evident disparities between the GWP 100 values of the primary design for XXXL MP and four-legged pin-pilled jacket foundation. The cumulative CO2 emissions from production to deployment are depicted in Figure 4-1.

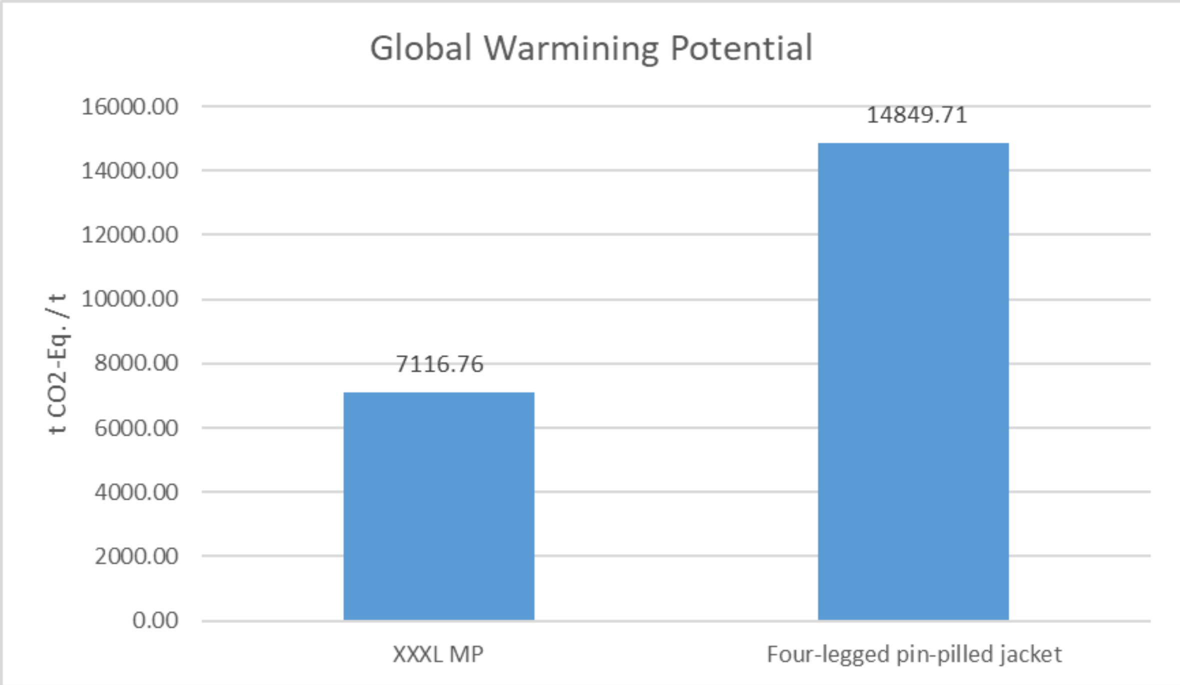

Figure 4-1: Global warming potential - total CO2 emissions of both foundation types

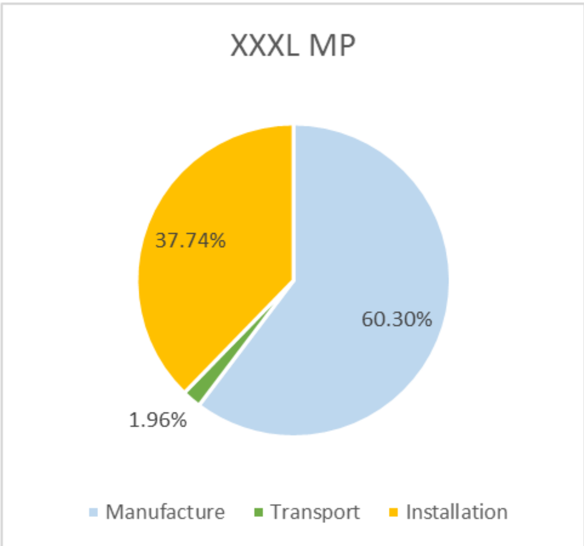

Figure 4-2: GWP - percentages of the individual phases for XXXL MP

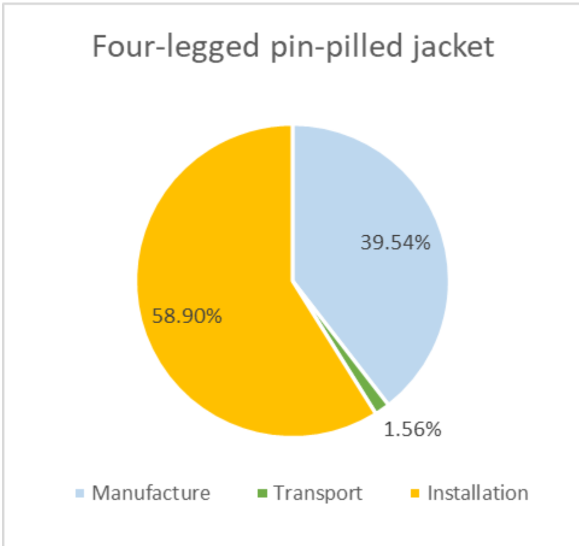

Figure 4-3: GWP - percentages of the individual phases for four-legged pin-pilled jacket

Figure 4-1 shows the total CO2 emissions for MP and jacket foundation in t CO2-Eq per 1 t steel. The primary design structures of the four-legged pin-pilled jacket foundation yield CO2 emission levels of 14849.71 t CO2-Eq./t. The primary design structures of the XXXL MP foundation yield CO2 emission levels of 71116.76 t CO2-Eq./t, approximately 7732.95 t CO2-Eq./t steel lower than for the four-legged pin-pilled jacket foundation. Figure 4-2 and Figure 4-3 present the percentage breakdown of the manufacture, transport and installation phases for both types of foundations as a pie chart. The combination of all three figures is used to describe the GWP per phase and to identify the highest influences of the respective phases for each foundation.

In the manufacturing phase, the XXXL MP and four-legged pin-pilled jacket foundation show a notable discrepancy of 1579.64 tons of CO_2 although the total mass of primary design components for the jacket foundation surpasses that of the XXXL MP foundation by approximately 759 tons (as indicated in Table 3-1). This translates to a production emission rate of 2 tons of CO_2 per ton of steel, see electronic appendix, Evaluation - LCIA results. These emission levels align closely with the data provided by Dillinger (2023) for conventional steel production using the Blast Furnace Converter method, one of the most widely adopted techniques in the steel manufacturing industry.

Both foundation types place the transport stage as having the least impact on GWP, accounting for 1.96% for XXXL MP and 1.56% for four-legged pin-pilled jackets (refer to Figure 4-2 and Figure 4-3). Numerically, XXXL MP account for 139.72 t CO_2-Eq./t, while four-legged pin-pilled jackets' primary design components contribute to 232.32 t CO_2-Eq./t, representing a substantial difference. This discrepancy may stem from calculating only air emissions for transportation, potentially leading to inaccuracies. Nonetheless, the positioning of transport at the bottom of the GWP ranking aligns with literature findings, such as those presented by Yildiz et al. (2021).

The installation phase of the four-legged pin-pilled jacket foundation accounts for over half (58.90%) of the total CO_2 emissions (see *Figure 2-1*), amounting to over 8.5 thousand tons of CO_2, as delineated in Table 4-1. This is primarily attributed to the extended duration of the installation phase of the primary steel components, which spans nearly 10 days for the jacket foundation (in contrast to approximately 5 days for the XXXL MP, as indicated in the appendix, App.Table 1). Thus, this elongated installation phase results in increased vessel operation time. Furthermore, the number of vessels deployed for installation, totaling three, alongside the distances they must traverse and their daily fuel consumption, also contribute to this trend. While the installation process accounts for the majority of emissions for the four-legged pin-pilled jacket foundation, totaling approximately 60.30%, manufacturing processes take precedence for the XXXL MP foundation, comprising a similar percentage of the total CO_2 emissions, which amount to 4281.37 t CO_2-Eq./t Notably, for the MP foundation, the installation process ranks second, contributing with 37.74%. This contrasts with the ranking for four-legged pin-pilled jacket foundations, suggesting factors such as reduced vessel deployment (only one vessel), shorter operational duration, and the simplicity of installation for XXXL MP as detailed in section 2.1.3.

Furthermore, the importance of the pre-manufacturing phase, particularly the deployment stage, has been highlighted in both graphs. Up to this point, this phase has solely been discussed within the theoretical background (section 2.2.1). However, it significantly influences manufacturing choices, impacting the selection of raw materials and design approaches. It becomes increasingly evident how crucial this phase is in mitigating CO_2 emissions and, consequently, lowering the global warming potential of offshore wind foundations.

4.2 Abiotic Depletion Potential for Fossil Fuels (ADPF) and Energy Payback Time (EPT)

Due to data limitations, the calculations of ADPF for the transportation and installation stages were unfeasible. Both phases exclusively relied on air emissions data from the Fourth Greenhouse Gas Study by the International Maritime Organization (2020). Consequently, the subsequent section will solely focus on the manufacturing phase.

To enhance clarity and facilitate comparison, the ADPF values depicted in the preceding Table 4-1 have been transformed into gigawatt-hours (GWh) and are illustrated in the subsequent Figure 4-4.

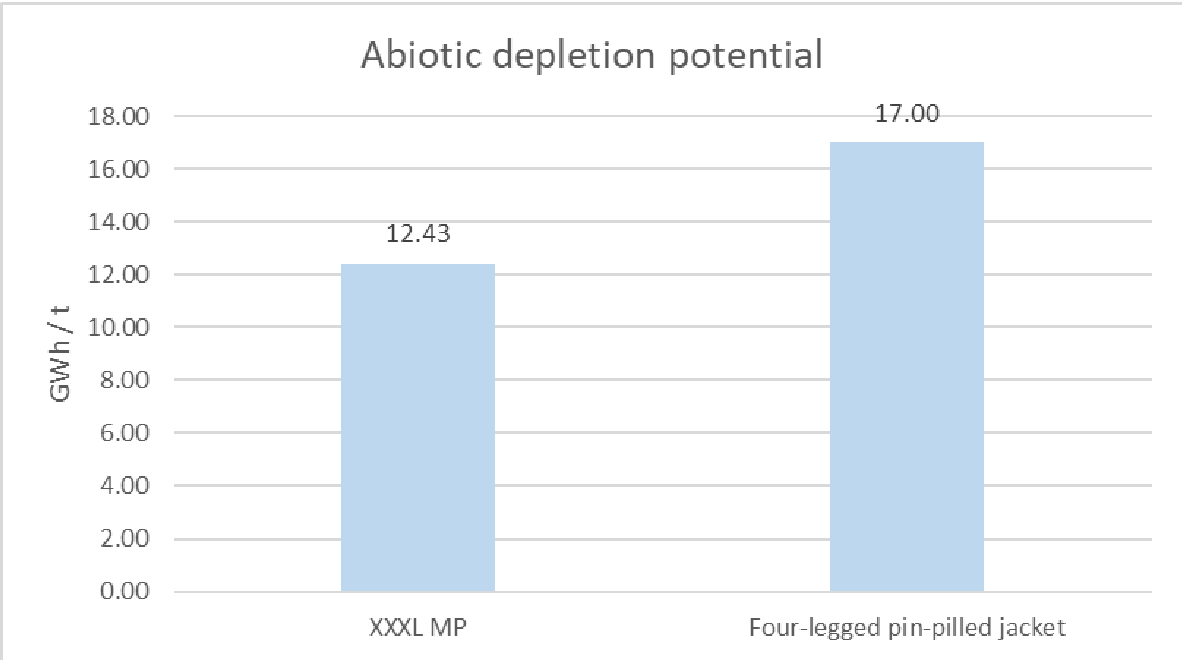

Figure 4-4: ADPF of both foundation types for the manufacturing phase

Figure 4-4 displays the ADPF in GWh per 1 ton of steel for XXXL MP and four-legged pin-pilled jacket foundation. The ADPF during the manufacturing of primary design components for a XXXL MP foundation is observed to be approximately 4.57 GWh/t lower than that of the four-legged pin-pilled jacket foundation. This suggests a reduced reliance on fossil energy in the production of XXXL MP components. Notably, this disparity can be attributed to the variations in steel quantities discussed in the preceding chapter.

Following the method outlined by Weinzettel et al. (2009), as described by Haapala und Prempreeda (2014), the EPT (P) is computed using E_k to represent the energy required for each life cycle stage (k), and E_{annual} representing the annual electricity generated by the wind turbine (see following Equation).

$$P = \sum_{k=1}^{n} \frac{E_k}{E_{annual}} \tag{4-1}$$

Both the initial (k) and final (n) values are set at 1 (number of analyzed phases), given that only one phase is being calculated. The E_{annual} value can be sourced from the turbine's datasheet (see Assumptions), which is indicated as E_{annual} = 80 GWh. E_k corresponds to the values of the ADPF presented in Table 4-1 and illustrated in the Figure 4-4. Inserting these values into Equation (4-1) gives the EPT, for exact calculation see electronic appendix, Evaluation - LCIA results. For thoroughness, the EPT for the primary design structures of both foundation types were also logged in Table 4-1 and are visually represented in Figure 4-5.

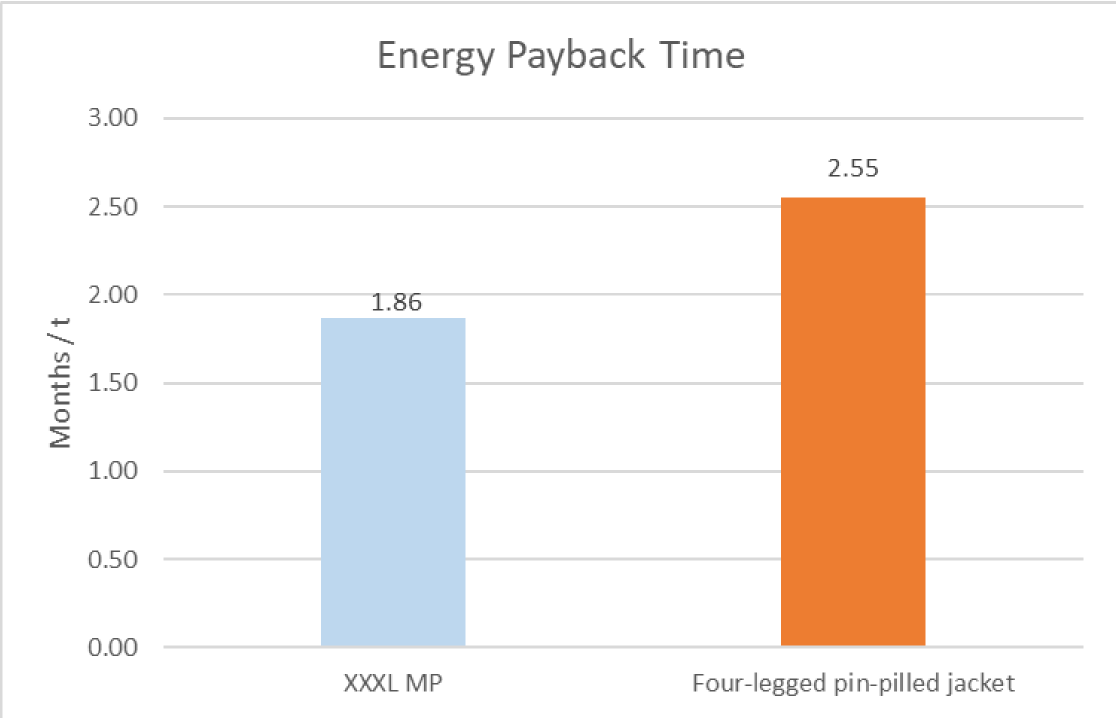

Figure 4-5: Energy payback time of both foundation types for the manufacturing phase

Figure 4-5 presents the EPT in months per 1 ton of steel for primary design components of XXXL MP and four-legged pin-pilled jacket foundation, with the months/t steel plotted on the x-axis and the two foundation types next to each other on the y-axis. The primary design structures of the four-legged pin-piled jacket foundation require an extended duration of over half a month (0.69 months/t) compared to the XXXL MP foundation components, in order to balance out the fossil energy expended during the manufacturing process. The discrepancy in EPT can be attributed to the differences in the amount of fossil energy required (Figure 4-4) and the amount of steel required for the respective foundations (Table 3-1).

4.3 Eutrophication: Marine - Fraction of Nutrients Reaching Marine End Compartment (Nitrogen)

The chapter describes the LCIA results (presented in Table 4-1) for the primary design of eutrophication for XXXL MP and four-legged pin-pilled jacket foundation. The eutrophication values in t N-Eq. for the primary design structures of XXXL MP and four-legged pin-pilled jacket plotted over the different phases, illustrated in Figure 4-6. In order to facilitate the analysis of the percentage weighting of individual phases for the primary design structures of both foundation types, Figure *4-7* and Figure 4-8 illustrate these phases accordingly.

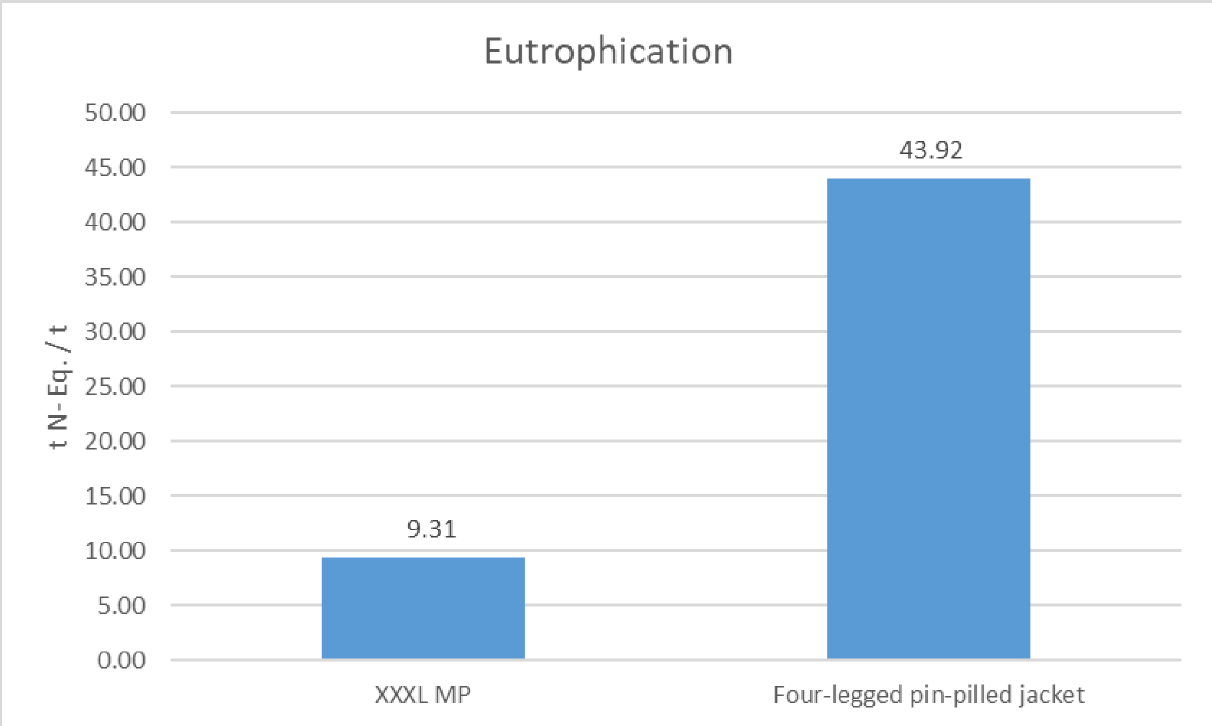

Figure 4-6: Eutrophication in t N-eq of both foundation types covering all considered phases

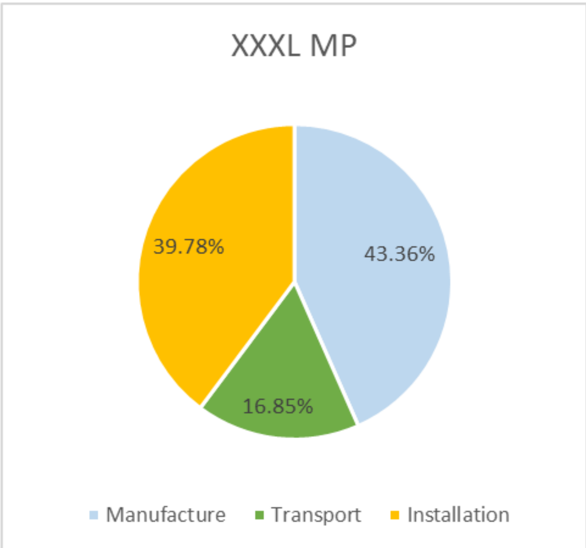

Figure 4-7: Eutrophication - percentages of the individual phases for XXXL MP

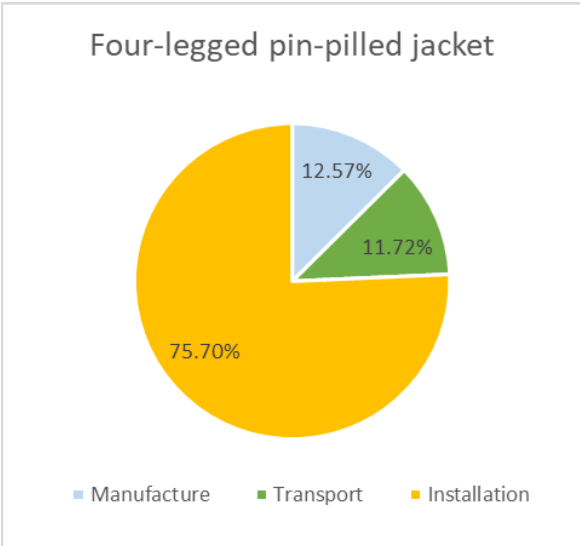

Figure 4-8: Eutrophication - percentages of the individual phases for four-legged pin-pilled jacket

Figure 4-6 shows the total accumulation of N-Eq. per 1t steel required for XXXL MP and four-legged pin-pilled jacket foundation. The primary design structures of the jacket foundation yield nitrogen accumulation levels of 43.92 t N-Eq./t. The primary design structures of the XXXL MP foundation provide nitrogen accumulation levels of 9.31 t N-Eq./t, approximately 34.61 t N-Eq./ t steel lower than for the jacket foundation. Figure *4-7* and Figure *4-8* present the nitrogen accumulation's percentage breakdown of the manufacture, transport and installation phases for both types of foundations as pie charts. Comparing *Figure 4-6* with Figure *4-7* and Figure *4-8*, notable distinctions arise. In the case of the XXXL MP foundation, the percentages for manufacturing (39.78%) and installation (43.36%) are closely aligned, allowing for nearly equal weighting. Transport contributes the smallest share (16.85%), exerting the least influence on eutrophication of the primary design components of the XXXL MP foundation. In the case of four-legged pin-pilled jacket foundation, the shares of manufacturing (12.56%) and transport (11.72%) for the four-legged pin-pilled jacket foundation are similar. The installation phase is responsible for well over half (75.70%) of the nitrogen loads and has therefore the greatest influence on the eutrophication. To understand the significant accumulation of N-Eq. during the installation phase of four-legged pin-pilled jacket structures, it is essential to delve into the installation process (section 2.1.3), the method for the emission calculation (described in Chapter 2.3) and thoroughly scrutinize the data outlined in section 3.1.3.

The high proportion of manufacture phase in the case of the XXXL MP can be explained by the fact that the nitrogen emissions for the manufacture of the required primary design components quantity of 2062.23 tons are higher than during the transport and installation phase. The manufacture of the primary design components for four-legged pin-pilled jacket foundation, despite higher total steel mass (2821.33t), has around 30.78% smaller contribution to the total N-emissions than in the case of the MP foundation. The manufacture process is for both foundation types the same, see section 3.2.1. However, the technical requirements within the T&I phases of the two foundations differ (see sections 3.2.2 and 3.2.3) with the jacket foundation requiring greater vessel deployment than the XXXL MP foundation. Therefore, the percentage of manufacture in relation to the total nitrogen emissions for the four-legged pin-pilled jacket foundation is less relevant then for the XXXL MP foundation.

By employing the more time-efficient pre-piling method, as described in section 2.1.3 Installation Specific, the installation of primary design structures for a four-legged pin-pilled jacket foundation requires the use of both a support vessel and a HLV, essential for deploying pin-piles and installing jacket structures. Upon scrutinizing the assumptions (section 3.1.3) and data from the life cycle inventory (Chapter 3.2), it becomes evident that the installation of the jacket foundation was estimated to require three vessels (one support vessel and two HLVs), while only one HLV is necessary for assembly of the MP foundation. Additionally, upon examining the calculation table (electronic appendix, Evaluation - LCIA results), it becomes apparent that during the installation of the jacket foundation, a Tier 1 vessel (support vessel) is utilized, which energy-based emission factor (EF_e) NOx is over four times higher than the of the HLV. The duration of vessel deployment also plays an important role. The installation process of the calculated jacket foundation spans about 10 days. However, as two vessels are deployed for half of this duration (approximately 5.5 days), the total vessel operational time is calculated at 15 days. In contrast, for the installation process of the XXXL MP foundation, only one vessel is utilized for approximately 3.5 days per foundation. Therefore, the installation duration of the XXXL MP foundation aligns with the vessel operational time. The vessels consume energy even during apparent "standstill phases" in which no locomotion takes place, which leads to fuel consumption. The NOx and N2O emissions resulting from the installation process has been presented in Table 3-5.

The percentage of nitrogen emission for the transport phase turned out to be the lowest for both foundation types. The rationale behind transport taking third position becomes apparent upon reviewing the consumption quantities, see Table 4-2 and the emission volumes outlined in section 3.2.2, Table 3-3.

Table 4-2: Fuel consumption for installation and transportation for both foundation types, a cut-off App.Table 2 in the Appendix

Phase	**Unit**	**XXXL MP**	**Four-legged pin-pilled jacket**
Transport	t MGO	43.56	72.43
Installation		340.91	1022.73

The fuel consumption during transportation is notably lower compared to that during installation, with an eightfold difference for the XXXL MP and roughly a fourteenfold difference for the four-legged pin-pilled jacket foundation. Higher consumption leads to higher emissions, for the applied fuel (MGO) also in terms of nitrogen accumulation.

5 Outlook

This chapter identifies ways to reduce emissions based on the impact categories described in the previous section. In addition, environmentally friendly alternatives are considered in relation to the primary design structures of the two foundations at all stages from development to installation.

Green steel is currently a prominent topic across all sectors reliant on steel constructions, as well as for steel producers themselves. For offshore wind, green steel emerges as a potential remedy for diminishing CO2 emissions during the manufacturing phase, constitute a significant percentage of the total CO2 emissions (see Life Cycle Impact Assessment (LCIA) results). A feasible approach to mitigate these emissions involves the adoption of "greener" manufacturing processes and the integration of environmentally sustainable materials such as “green” steel.

As per Dillinger (2023), one of the prominent steel manufacturers in Germany, the traditional production method of steel (utilizing the blast furnace converter route) generates approximately 2 tons of CO2 emissions per ton of steel (Dillinger 2023). In response to the imperative to curb CO2 emissions across industries, Dillinger (2023) have devised a strategic plan to revamp their production process, enabling the utilization of green hydrogen (Dillinger 2023). This transformative approach involves the adoption of the direct reduction process (DRI) facilitated by two electric arc furnaces (EAF) to yield green steel. Projections indicate that this innovative pathway is poised to reduce emissions drastically, emitting only 339 kg of CO2 per ton of steel—a nearly six-fold decrease (Dillinger 2023). Based on this information and the GWP values calculated for conventional steel within the scope of this study, a comparison has been drawn for the manufacturing phase of both foundation types and visualized in Figure 5-1.

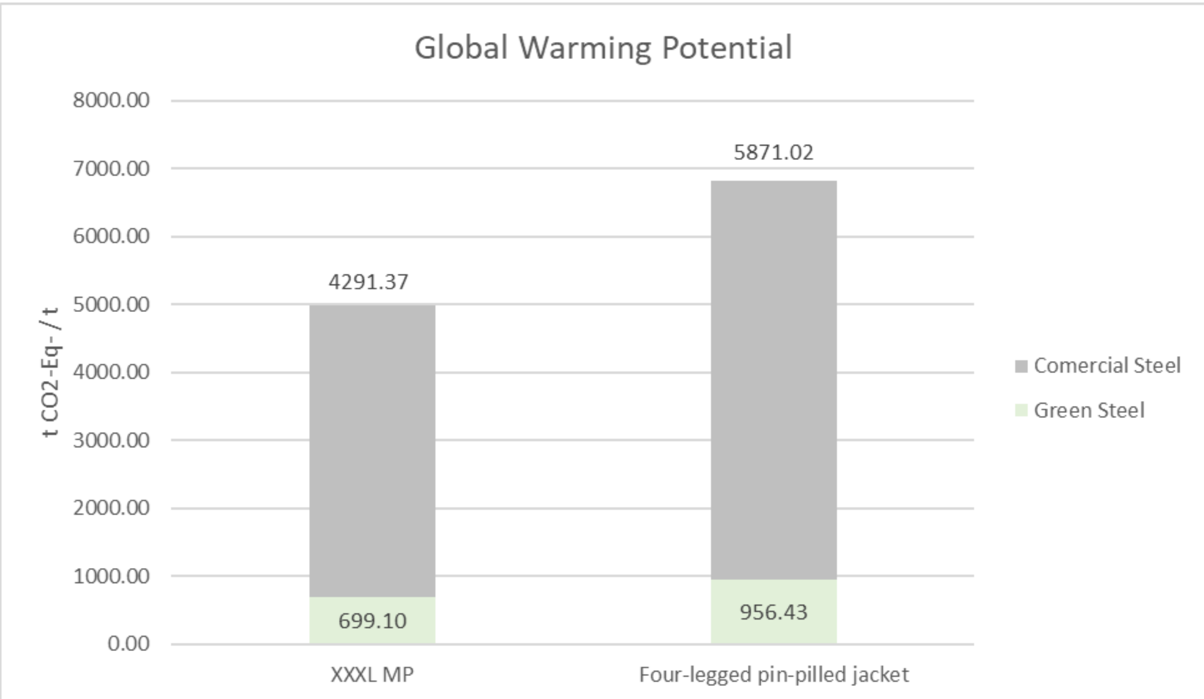

Figure 5-1: Comparison GWP for green steel (Dillinger 2023), and commercial steel (results of the LCIA)

Figure 5-1 presents the GWP 100 for the manufacturing of primary design structures for XXXL MP and four-legged pin-pilled jacket foundation in t CO_2-Eq. per one ton of steel. To visualize the difference between the CO_2 emissions of green and conventional steel required for XXXL MP and four-legged pin-pilled jacket foundation, the staked column chart has been applied. The emissions from manufacturing the primary design components of both foundations are below 1000 tons of CO_2-Eq./t when using green steel. The resultant reduction precipitates a decline in the manufacturing contribution within the comparative percentage analysis of the two foundational types, plummeting below the 20% threshold. Consequently, this drives down the overall GWP 100 for both foundation types. Notably, the new total CO_2 emissions for XXXL MP stand at approximately 3.5 thousand tons of CO_2-Eq./t, one thousand tons less than the emissions solely from component manufacturing, see App. Figure 1, App. Figure 2 and App. Figure 3 in the Appendix or elaborated further in the electrical attachment, Evaluation - LCIA results. The four-legged pin-pilled jacket foundation's total emissions, with the adoption of green steel, linger below 10 thousand tons of CO_2, albeit relatively high. This anomaly is elucidated by the subsidiary impact of manufacturing on the overall CO_2 emissions, as depicted earlier in Figure *4-3*. However, the shift from conventional to green steel remains incomplete, contingent upon various factors including substantial government support, adequate financial resources for restructuring and advancements in green hydrogen research as outlined by (Dillinger 2023). The European Green Deal (European Union n.D.) offers an opportunity to provide financial support for the decarbonization of the steel industry. Nonetheless, successfully implementing the CO_2 reduction targets set by Dillinger (2023) in steel production would mark a significant leap forward in the decarbonization of offshore wind energy.

To further reduce the overall emissions, it is important to take a closer look at the (second) biggest polluter – the installation phase. Finding environmentally friendlier alternatives is paramount. This is where the deployment phase comes into play again: optimizing the design (in relation to the jacket) with a view to simpler installation could reduce both the duration and the number of required ships. This measure could lead to a decrease in overall emissions. Nevertheless, this remains a theoretical assumption based on these thesis's LCIA findings. Looking beyond the development phase, there is potential to optimize the installation vessels or their fuel consumption. The "Martime Forecast to 2050" report by DNV (2023) refers among others the use of liquefied natural gas (LNG) or biofuels as a possible solution for the GHG reduction (DNV 2023).

In the study by Livaniou et al. (2022), an examination of sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) emissions was conducted, comparing the two fuels: liquefied natural gas (LNG) and marine diesel oil (MDO) (Livaniou et al. 2022). The research delved into both the aggregate emissions of ships within the surveyed port and their breakdown across various vessel types. Livaniou et al. (2022) states that the use of LNG can reduce CO_2 by 20.70%, NO_x by 83.66%, PM by 98.14% and SO_2 by 99.48% emissions and thus would minimize the overall emissions by 21.24% (Livaniou et al. 2022). However, the emissions of CO, HC, or CH_4 are higher for LNG than for MDO (Livaniou et al. 2022). For the "general cargo" vessel type (which is also used in this thesis LCA, see Chapter 3.2), there is a reduction of approximately 24% in total emissions when using LNG. Overall, the introduction of LNG fuel led to a 76% reduction (across all types of vessels) in total emissions, which represents a significant environmental achievement (Livaniou et al. 2022). Applied to the foundation types analyzed in the thesis, this reduction would signify that the combined CO_2

emissions for both types of foundations remain below 10 thousand tons. To elaborate, MP foundations would emit roughly 6 thousand tons of CO2-Eq, while jacket foundations would emit approximately 10 thousand tons of CO2-Eq. These specifics are illustrated in *Figure 5-2* or elaborated further in the electrical attachment, Evaluation - LCIA results. A reduction of the NOx emissions by almost 84% could have a positive effect on the amounts of nitrogen equivalent accumulation and ultimately reduce the eutrophication potential. The results of the NOx emission reduction can be seen in Appendix, *App. Figure 4* Performing the LCIA with the reduced NOx values reveals that in both cases, the accumulation of nitrogen does not exceed 12 t N-eq. This calculation is provided in the electronic annex, Forecast – LCI and LCIA results for NOx reduction. The eutrophication potential has been reduced by approximately 33 tons for jacket foundation and by roughly half for MP of the values for MGO.

Watanabe et al. (2022) explores the potential of marine biofuels, particularly bio-synthetic natural gas (Bio-SNG), Fischer-Tropsch (FT), hydrothermal liquefaction (HTL) and fast pyrolysis (FP). The analysis highlights the lack of ecological sustainability analysis for marine biofuels, especially those considering future changes in the energy system. It reveals that marine biofuels hold promise in addressing climate change when compared to traditional fossil fuel counterparts. Across FP, HTL and FT pathways the emissions are between 11 and 14 g CO2 eq/MJ. The FT pathway's capacity is capable to reduce the CO2 emissions up to 89 % compared to conventional marine diesel (Watanabe et al. 2022). In practical terms for the chosen application, this reduction of the CO2 emissions translates to a scenario where the cumulative CO2 emissions for both types of foundations remain below 10 thousand tons. Specifically, XXXL MP foundations would emit around 5 thousand tons of CO2-Eq., while four-legged pin-pilled jacket foundations would release approximately 7.4 thousand tons of CO2 eq, as illustrated in Figure 5-2 or calculated in detail in the electrical attachment, Evaluation - LCIA results).

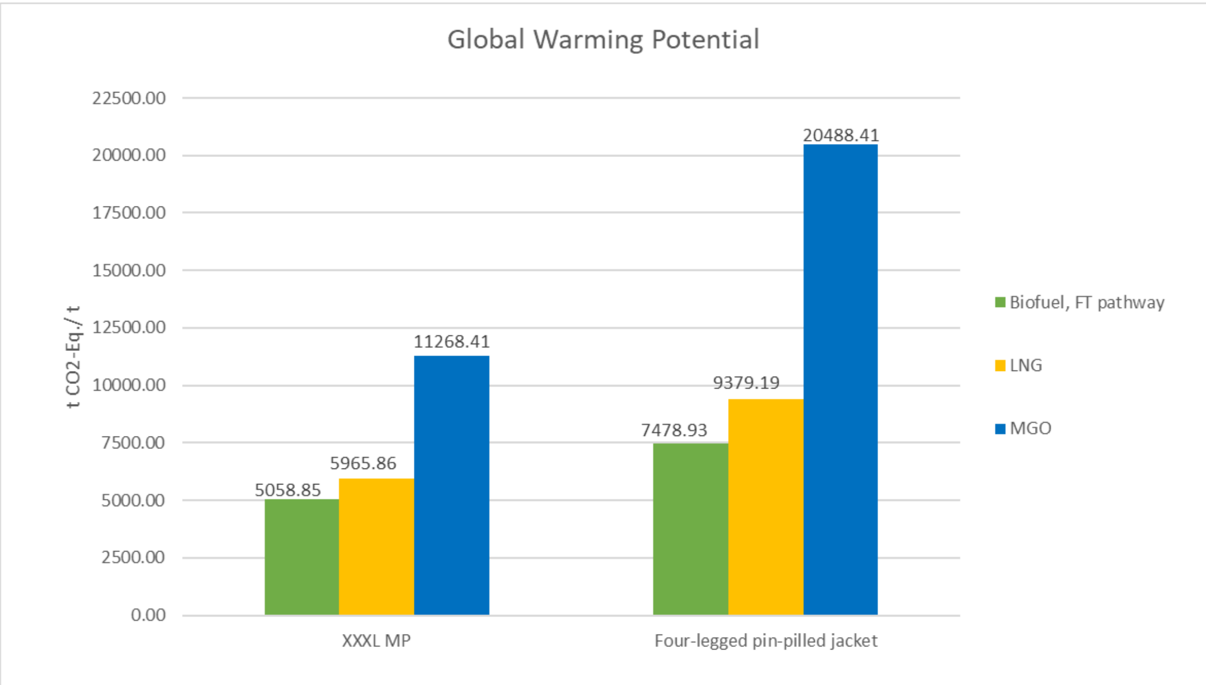

Figure 5-2: Comparison GWP for alternative fuels (Livaniou et al. 2022; Watanabe et al. 2022) and marine gas oil (MGO) (results of the LCIA)

Figure 5-2 presents the total GWP 100 from deployment to installation for XXXL MP and four-legged pin-pilled jacket foundation when using biofuels (FT pathway), LNG and MGO, measured in t CO2-Eq. per 1 t steel. The total XXXL MP's CO2 emissions (11268.41 t CO2-Eq./t) could be reduced by half using biofuels (5965.86 t CO2-Eq./t) and LNG (5965.86 t CO2-Eq./t). The total four-legged pin-pilled jacket's CO2 emissions have been reduced to around 10 thousand t CO2-Eq./t from the previous 20 thousand t CO2-Eq./t by using LNG. The application of biofuels during the T&I phase leads to a total reduction of CO2 emissions to around 7.5 thousand tons of CO2. Therefore, the potential of alternative marine biofuels or LNG compared to fossil fuels in terms of decarbonizing becomes clear, see *Figure 5-2*. However, the disadvantages of producing alternative marine fuels should not be overlooked at this point. Wachsmuth et al. (2019) examines the climate friendliness of LNG. Liquefied natural gas can be delivered anywhere without pipelines and the associated risks. Wachsmuth et al. (2019) writes that EU import LNG among others from the USA, Qatar, Algeria and Australia. LNG from the USA and Australia is often fracked gas, which is more harmful to the climate than conventional fossil gas due to leaks. The long transportation routes (in the case of Australia, USA or Qatar) result in additional CO2 emissions. Overall, the upstream chain CO2 emissions for LNG imported into the EU are up to seven times higher than those of the pipeline gas supply (Wachsmuth et al. 2019). Nonetheless, Wachsmuth et al. (2019) does not consider the full definition of sustainability which includes three dimensions – ecological, economic and social, see sustainability definition by Kropp (2019). The economic and social situation of the supplying countries or the supply chain (along with all its associated factors) should therefore be taken into account and put into perspective.

Due to increasing water depths, floating foundations will play an increasingly significant role in the future. The Global Wind Energy Council (2023) present in their report that wind-generated energy is experiencing a global increase. With the rise of offshore wind and pioneering technologies like floating foundations, there is a pledge to yield substantial wind energy volumes in locales where deployment would have been deemed implausible until very recently (Global Wind Energy Council 2023). The 2023 Targets Scenario encompasses countries with stated offshore wind aspirations and predominantly water depths (deep waters over 70m) conducive to buoyant wind solutions, as delineated in the in the report by Spinergie (2023). Unfortunately, the development of the production of floating foundations is not yet at an advanced stage. The forecast from Spinergie (2023) predicts high demand towards the end of the 2020s, which will exert pressure on the supply chain to expand, resulting in a bottleneck from 2025. To prevent this, the current manufacturing levels and capacities must amplify five to six times by 2030 (Spinergie 2023). Not only should the current manufacturing process be optimized, Garcia-Teruel et al. (2022) highlight in their study the importance of mitigating the hotspots of increased environmental impact identified among others for the operation and maintenance (O&M) vessels or the amount of steel used for the turbine and floating substations. The adjustment of O&M tactics with the aim of minimizing the number of trips should be made furthermore vessels with higher efficiency should be selected. The streamlined designs for the turbine tower and floating substructure (part of the development phase) should be further developed as it has significant potential to improve the environmental impact of floating offshore wind technologies (Garcia-Teruel et al. 2022).

Considering all the possible alternatives presented above and the development prognosis of the offshore wind sector, there is a great requirement for further improvement of environmental alternatives and methods.

6 Conclusion

A LCA of primary design structures of XXXL MP and four-legged pin-piled jacket offshore wind foundations have been conducted for the phases from development to installation using the Ecoinvent 3.9 database and the EF v.3.1 impact assessment method as recommended by the European Commission. Both primary structure designs have been calculated for the water depth of - 40m wtr. LAT and the location in North Atlantic. For the energy comparison, it has been assumed that the Vestas 15MW turbine will be used for both types of foundations. The LCA considers the following categories GWP, Eutrophication, ADPF and EPT. Unlike most of the LCAs for offshore wind turbines, which often use the energy production in kWh as the functional unit, this thesis's LCA refers to the unit of mass of required steel in t.

In terms of GWP, the primary design components of XXXL MP foundation emit around 7 thousand tons CO2- Eq. The primary design components of four-legged pin-pilled jacket foundations emit nearly 15 thousand tons of CO2-Eq., thus more than double of the XXXL MP's emissions. The manufacture's phase is with 60.30% the largest percentage share of the total GWP emissions for the XXXL MP foundation. The installation's phase is with 58.90% the largest percentage share of the total GWP emissions for the four-legged pin-pilled jacket foundation. Therefore, those both phases (manufacture and installation respectively) have the greatest influence on the total CO2 emissions.

The marine eutrophication fraction, measured in tons of N-Eq., reveals distinct patterns between the primary design components of XXXL MP and jacket foundations. XXXL MP components accumulate nearly 10 tons of N-Eq./t, while jacket components amass almost 44 tons N-Eq./t, marking a significant 4.5-fold increase. In the case of XXXL MP components, the manufacturing and installation phases contribute nearly equal proportions, suggesting a balanced impact on nitrogen values. Meanwhile, for four-legged pin-pilled jacket structures, fabrication shares a similar percentage to transportation (under 20%), whereas the assembly phase dominates, constituting nearly 76% of the accumulated nitrogen tonnage for the four-legged pin-pilled jacket foundation.

The ADPF and the EPT calculations were limited to the manufacturing phase due to data availability for the transport and installation (T&I) phase. The ADPF related to the primary components of the XXXL MP foundations is approximately 4.57 GWh/t lower than fossil fuels related to the components of the four-legged pin-pilled jacket designs. Hence the EPT for four-legged pin-pilled jacket components is over half a month longer (about 2.55 months/t), compared to the 1.86 months/t that the primary structures of an XXXL MP foundation need to compensate the fossil energy input.

The LCA of the primary design structures for XXXL MP foundation illustrates the high impact of the manufacturing phase among all impact categories, which is consistent with the results of the reviewed studies and highlights the relevance of the development phase and the decision-making process regarding the raw materials and the design. Meanwhile, the primary structure design for four-legged pin-pilled jacket foundation displays particularly high values for the installation phase, caused by the service period of the installation vessels and the number of these.

Comparing the environmental impact of both foundation types, the four-legged pin-pilled jacket foundation performs worse than the XXXL MP. This is partly because, although the monopile structure itself is heavier compared to jackets, its other components are lighter (as presented in Table 3-1), which is why the overall steel demand for the primary steel components is lower for XXXL MP than for four-legged pin-pilled jackets. Secondly, the installation of the primary design structures for an XXXL MP is simpler to install than the four-legged pin-pilled jackets, requiring not only less time but also a smaller number of vessels.

The great need to achieve the goals of the Paris Agreement requires a significant reduction in global greenhouse gas emissions by the year 2030, with less than six years left to replace high-emitting technologies with low-carbon alternatives. The time pressure of less than six years to replace high-emission technologies with low-carbon alternatives is driving the rapid development of offshore wind energy. Although wind turbines are renewable and therefore sustainable energy source, emitting almost no pollutants during operation, it is important not to forget the emissions produced across the rest of lifetime of a wind power plant. These emissions should be minimalized as far as possible. The GWP as well as the ADPF and EPT could be decreased by the choosing alternatives materials like the (described in Chapter 5) green steel, other possibility could be the usage of recycled steel. However, these alternatives still require further research and thus financial support, which could be provided, for example, by the European Green Deal (European Union n.D.). With the application of alternative fuels such as LNG, a reduction in NOx values has been achieved, ensuring that the eutrophication potential related to nitrogen accumulation does not exceed 12 t N- Eq./t. This information is detailed in the appendix, App. Figure 4 and electronic annex, Forecast – LCI and LCIA results for NOx reduction.

Further possibilities would be the implementation of ships with higher efficiency or the minimization of installation time by modifying the design. Both options lead to focus on reducing environmental impacts during the development phase. This includes recognizing the importance of the design approach and the selection of the raw materials. Poorly selected resources results in subpar environmental performance and inflict harm upon the environment and all organisms. At this point, the significance of adapting the Non-Priced Categories (NPC) proposed by Spinergie (2023) and the "Bill of Materials" suggested by Global Wind Energy Council (2023) coupled with EPDs, during the development phase becomes evident. These categories, in combination with EPD certification, could influence the needed improvement in offshore wind energy by enhancing environmental responsibility in equipment procurement.

It is important to highlight that the LCA is limited by the defined scope (the system boundaries) and the availability of data, which is why it does not provide a complete overview of the primary design structures for both foundations. Furthermore, only the environmental dimension of sustainability is covered. It is possible to carry out an additional cost analysis, but due to information accessibility and confidentiality this is not included in this thesis. Social factors are not covered by the LCA method; hence this dimension of sustainability cannot be considered either.

To sum up, considering the XXXL MP and the four-legged pin-pilled jacket foundation with the same boundary conditions (water depth, turbine size, planned lifetime, manufacture and installation location) but different design and therefore diverse steel requirements and installation processes, it is evident that the primary design structures of the four-legged pin-pilled jacket foundation have a greater environmental impact and an overall larger footprint compared to XXXL MP. Therefore, it can be concluded that in terms of environmental sustainability, the primary steel components of the four-legged pin-pilled jacket foundation are less sustainable (as they require more fossil energy for production and installation) than the structures of the XXXL MP foundation.

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Eidesstattliche Erklärung

Ich versichere, dass ich die vorliegende Arbeit ohne fremde Hilfe selbstständig verfasst habe und nur die angegebenen Quellen und Hilfsmittel benutzt habe. Wörtlich oder dem Sinn nach aus anderen Werken entnommenen Stellen sind unter Angabe der Quelle kenntlich gemacht.

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Ort, Datum	Unterschrift

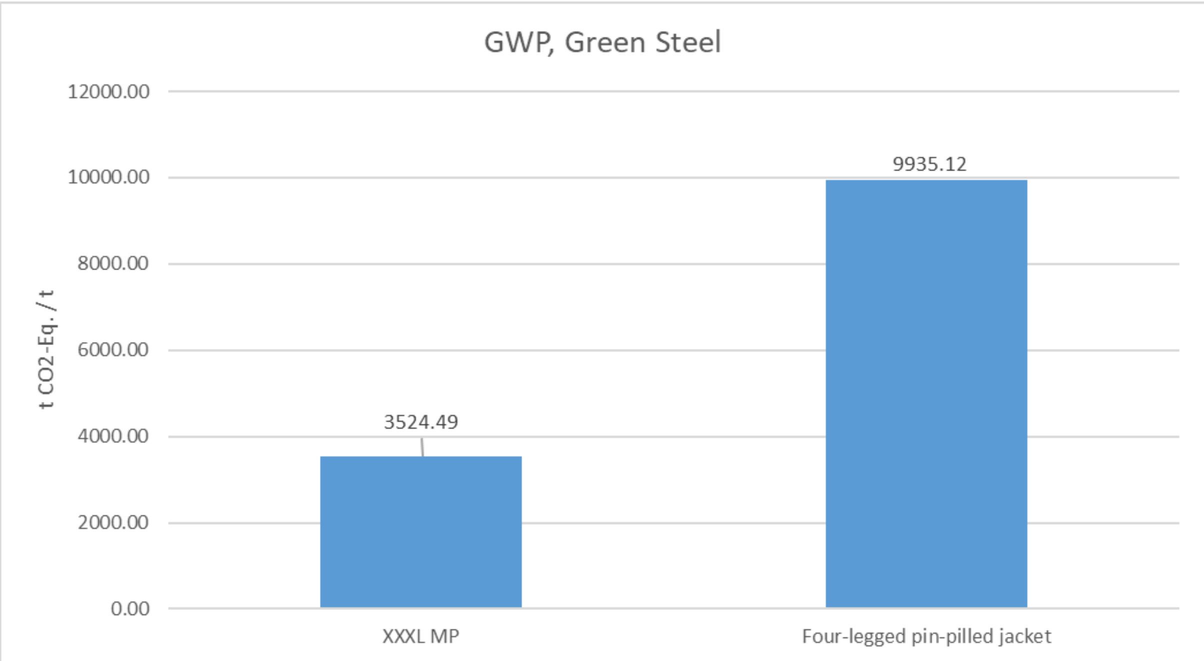
Appendix

App.Table 1: Results of the emission calculation (data preparation for LCA)

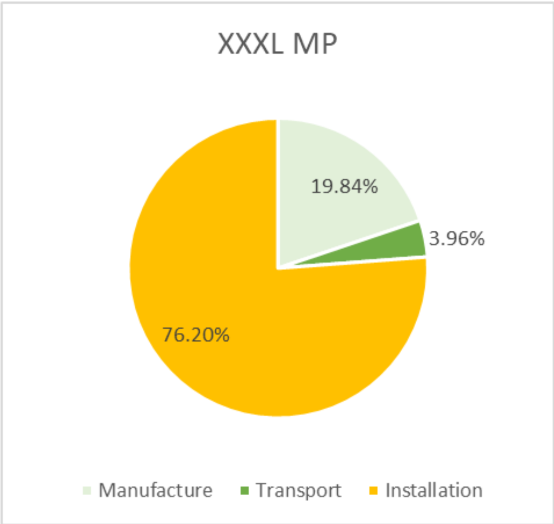
			XXXL MP	**Four-legged pin-pilled jacket**
Transportation	**Emissions: 1x foundation both ways [kg]**	**CO2**	139664.08	232218.90
		SOx	93.88	155.73
		CH4	1.96	3.26
		NMVOC	99.54	128.45
		CO	107.38	138.57
		PM10	41.17	68.45
		PM2.5	37.87	62.97
		Nox	4032.73	13236.74
		N2O	12.55	31.29
Installation	**Emissions: 1xfoundation both way [kg]**	**SOx**	2684542.28	8742714.02
		CH4	1804.49	5863.02
		NMVOC	37.68	122.71
		CO	1913.34	6231.16
		PM10	2064.07	6722.02
		PM2.5	791.30	2601.54
		Nox	727.99	2393.42
		N2O	9519.46	85471.52

App.Table 2: Additional information for T&I

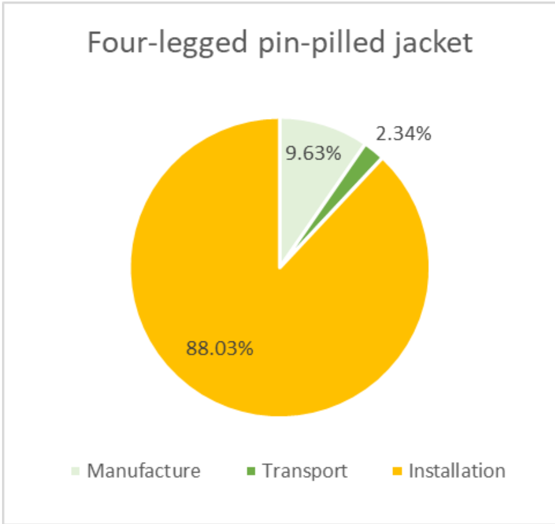
Phase		XXXL MP	Four-legged pin-pilled jacket
Transport	Average cruising speed [kn]	13	13
	Number of vessels	1	2
	No of routes	33	28
	Average consumption round trip [mt MGO]	49,18	72,43
Installation	Average cruising speed [kn]	11	11
	Number of vessels	1	3
	Average consumption round trip [mt MGO]	340.91	1022.73
	Average vessel's operational time per one foundation [d]	3.46	15.15



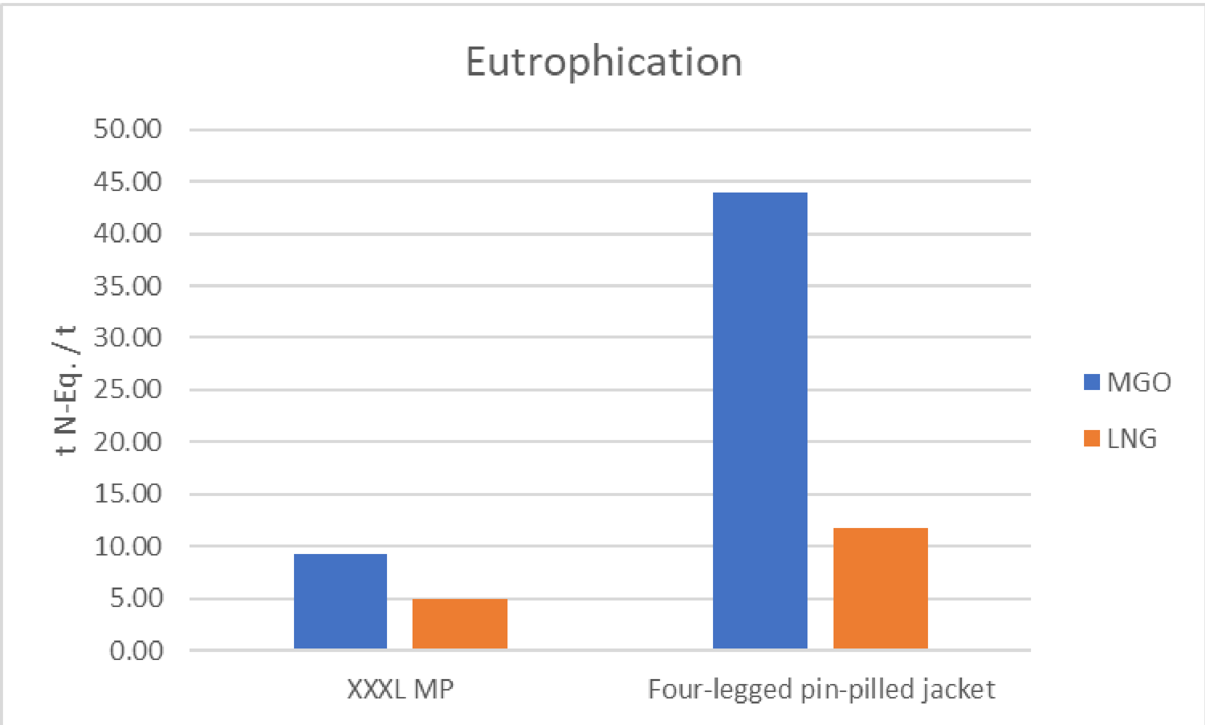
App. Figure 1: GWP for green steel - total CO2 emissions of both foundation types



App. Figure 2: GWP for green steel - percentages of the individual phases for XXXL MP



App. Figure 3: GWP for green steel - percentages of the individual phases for four-legged pin-pilled jacket



App. Figure 4 Forecast NOx reduction in t N-eq of both foundation types covering all considered phases