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Life cycle assesment of floating offshore wind farms	15 August 2022
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SUMMARY / SYNOPSIS

Currently, the energy sector is driven to renewable energy and especially to offshore wind energy. Floating wind turbines are developing to satisfy human's needs. In this study, it was evaluated the global warming potential of two floating wind farms. The one wind farm had a steel floater for its turbine and in the other one a concrete floater was examined. The farms had one 15 MW wind turbine. The LCA method was utilized. The data inputs were obtained from related studies, the Ecoinvent database and suppliers. The results showed that the concrete concept had lower environmental impact than steel concept. This is related with the manufacturing of the used materials. Finally, the examined systems are more environment-friendly than some non-renewable energy sources.

KEYWORDS
Floating wind turbine (concrete, steel)
LCA
Supply chain

Abstract

Life cycle assesment of floating offshore wind farms

Socio-economic conditions and environmental concerns induced the need of renewable energy. A continued growth of wind energy sector and specifically for offshore wind turbines is observed globally. For reasons of wind conditions and social acceptance, the turbines are placed further away from shore and different concepts are developing. In the current study, the global warming potential for the whole life cycle of two floating concepts was assessed. The one concept had a concrete support structure and the other one had a support structure made of steel. A wind farm with one 15 MW wind turbine was examined. In order to find the emissions from the two concepts and compare them, the LCA method was applied. Data were derived from related studies, from the Ecoinvent database and from suppliers. The emissions from the baseline scenarios were found to be 32.6 gCO2-eq/kWh for the steel concept and 24.3 gCO2-eq/kWh for the concrete concept. These values are lower than some non-renewable energy sources such as coal power. The main contributor in emissions is the first stage which is related with the manufacturing of the used materials.

Acknowledgment

I’m grateful for people who were by my side in this journey. I am particularly grateful to my supervisors Dimitrios Kraniotis from Oslo Metropolitan University and Eva Loukogeorgaki from Aristotle University of Thessaloniki, who, with their knowledge and their personalities, tought me how to work and how to learn.

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Chapter 1

Introduction

1.1 Energy sector

Energy sector has a dominant position on modern everyday life [1]. Most of people's activities, for instance doing experiments for research reasons (e.g. using a hydraulic press to generate the requisite compressive force to the concrete or the steel), using measures tools (accelerometers, tension monitors, moisture sensors etc.), transport by all the available means, cooking, need power to be conducted. New technologies need electricity to work (e.g. heating systems in the science sector as the ohmic heating or the infrared heating, new machines in the health sector etc.).

However, since 1973 [2], an energy crisis has started. Oil and Natural Gas reserves have entered in a decrease period. Environmental protection has started to being connected directly with the energy production and consumption [3]. This is social, political and scientific issue [4]. Many international conferences: "The United Nations Conference on Human Environment of 1972 in Stockholm, Sweden; International Environmental Education workshop of 1975 in Belgrade, Serbia (formally in Yugoslavia); Intergovernmental Conference on Environmental education of 1977 in Tbilisi, Georgia; Congress on Environmental Education and Training of 1987 in Moscow, Russia; United Nations Conference on Environment and development (UNCED) of 1992 in Rio de Janeiro, Brazil; World Summit on Sustainable Development of 2002 in Johannesburg, South Africa; United Nations conference on Sustainable Development (Rio+20) of 2012, in Rio de Janeiro, Brazil" [5], have conducted in the recent decades with environmental problems being the main concern. Obviously, there are changes, now, in the energy system worldwide [6]. In addition to environmental issues, economic challenges and impacts are here, even now, 50 years later [7]. Energy have become more expensive [2], [8]. The soaring inflation, have direct dependence from the oil market due to the reserves of oil. The fear of the future is large because of knowing the history of the decade of 1970s. Political instability (e.g. Russian's invasion of Ukraine, 23 February 2022), is a consequence that is obvious nowadays. After all these issues, industry and research led to "cleaner production" [9]. In 1991 the United Nations Environmental Program (UNEP), gave the definition of this phrase, which is: "The continuous application of an integrated environmental strategy to processes, products and services to increase efficiency and reduce risks to humans and the environment" [9]. Due to this attempt and the large range of the energy demand, world have been led in Renewable Energy [10], [11].

1.2 Renewable energy

Renewable energy has occupied the current global community, either the general society or the scientific community. A definition of Renewable Energy (RE) is: «Renewable energy (RE) refers to energy resources that are cyclic and naturally replenished within some time intervals»

[12]. Use of renewable resources is an attempt to protect the environment and to be independent from the ever-increasing cost of fossil-fuels. Is an effort to emit lower percentages of CO_2 emissions than conventional energy generators and contribute to put an end to climate change [13]. Although, not all of renewable resources can compete conventional energy generators like fossil-fuels [10] on the subject of the greenhouse gas (GHG) emissions. Another benefit of this energy is that regions can be undependable from fossil-fuels and, as a result, from energy imports [4], [14]. To achieve the targets, new technology, social and political issues are now under consideration. Governments change policy and structural conditions [4], [10] to conform in the new order of things. Despite the fact that due to pandemic, energy projects (mainly relate with Renewable Resources) have had retardation [15] research and development sector is still funded with several programs (National Renewable Energy Lab (NREL) Renewable Energy Project Finance, EU-funded SMILE, Renewable Energy Research and Development, Sustainable Energy Fund for Africa) to upgrade the technologies and investigate the renewable resources.

These resources include solar energy, hydropower, wave and tidal energy, biomass and geothermal energy and wind energy [4], [16]. Solar energy, can be used by photovoltaic panels [17]. Despite the fact that this kind of energy is renewable, there is a concern about cost and environmental issues. Cost for the production of the panels [17] and of recycling at the end-of-life [18] is under consideration at some researches. Also, emissions and waste in the whole life cycle of panels, have occupied investigators [18], [19]. On the other side, hydropower, wave and tidal energy, use the power of the natural flow of the water. Hydropower, is known as an energy with low rates of CO_2 emissions [16]. Hydropower, have the highest energy efficiency from the renewable resources [16]. On the other hand, the wave energy have not the same technology. Energy production depends direct from environmental conditions and even today the cost is high [20]. In contrast to wave energy, tides on the sea area, have the potential to produce, constantly [21], a large amount of energy [21], [22]. Common advantages is the simplicity in predictability [21], [23] and the mitigation of disturbance on aquatic ecosystem [21] under conditions [24]. However, in this form of electricity production, there is a concern about initial and maintenance cost [24] and geographical issues about the distance of the highest production areas till the regions with the energy demands [22], [24]. Also, biomass is connected with water. The used habitats can be the sea, fresh water resources and land [25]. This kind of energy is connected with combustion of "non-fossil biological materials" [25]. There is a concern about use of water and land resources [13], [25]. As a result, research supports that relevant technologies, need development [13]. The same consideration exists for technologies for geothermal energy [13]. The history of this energy starts many years ago [1], [26]. It is the heat that comes from the interior of the earth [1], [27], [28]. Cost of fossil-fuels energy, fully, competes the geothermal energy and that is an important reason that there is not a big development in this sector [26]. Although, a competitor of fossil-fuels energy, is the wind energy.

1.3 Wind energy

Wind energy systems convert the energy of wind flow to electricity. The earth provides a great amount of wind energy capacity. Approximately 10 TW is constantly available [14] to the air. This capacity can be used in a relatively acceptable percentage and compete fossil-fuels under specific conditions [14]. In the recent decades, wind turbines technologies are continuously improving [14], [29]. Mainly there is an effort to minimize the cost and environmental impacts. These issues is connected not only with mechanisms and construction, but, also with locations, predictions of wind intensity and the interaction with the environment (e.g. with fauna and flora) and constructions (e.g. dynamic interaction among different turbines). As a result more and more studies have been conducted to improve technology and investigate environmental and cost issues [3], [13], [14], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43]. That can be more understandable with the depicted numbers of annual publications at the Figure below (*Figure 1*), referring to renewable energy. It is clear that renewable energy have the major position on research. Companies like Vestas, General Electric, Siemens Gamessa, Stiesdal develop systems and fund research to improve design. They don't focus only to reduce the cost. They aim to decrease environmental impacts (e.g. GHG emissions, water and air pollution, effects of deriving the energy from a habitat) and, also, to being acceptable from the society. With better designs, industry achieves access to certifications from organizations such as "DNV (Det Norsk Veritas)" [44] and "ISO" [45] and better conditions in the marketplace. Generally, wind systems seem to be a multifactorial and a constantly improving subject that needs continuous research.

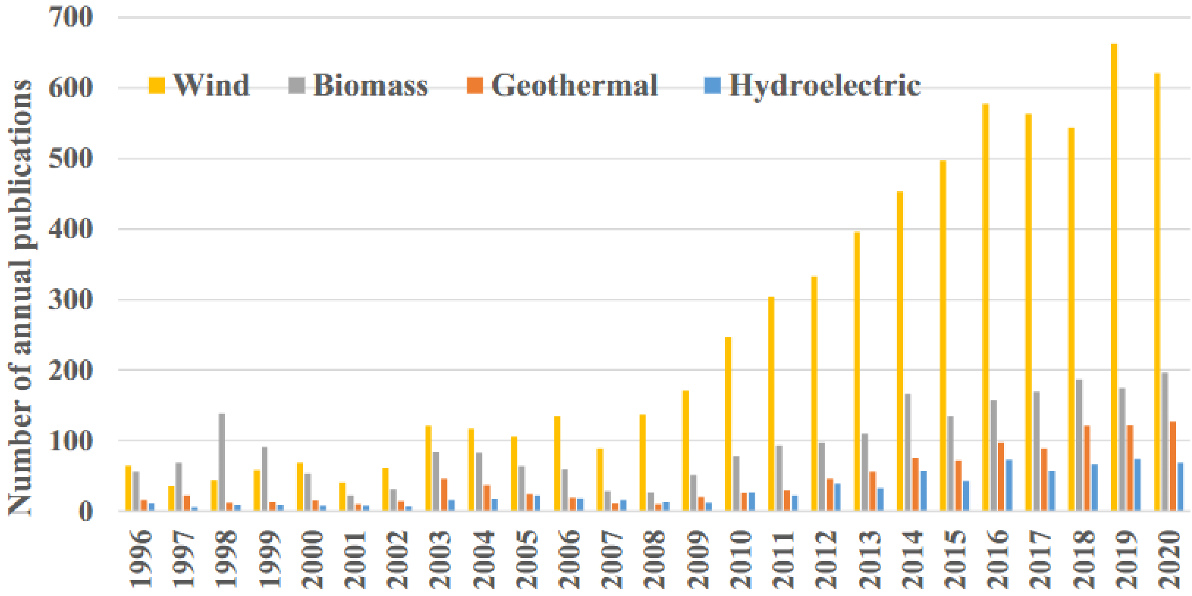

Figure 1.1: *Publications concerning different renewable energies over the period 1996–2020 number of annual publications [13]*

Wind power can be obtained from onshore and offshore wind farms. As it can be concluded from the figure below (***Figure 1.2***), onshore was the first installed type and there is more installed capacity recent years. At first, there was no need to go to the marine environment. The main concern was (and still is) to replace hydrocarbons. But, during last decade we encounter the climate change effects. In addition, governments and EU try to be energy independent. These reasons and the advantages of offshore wind, led to the development of offshore wind. This development boosted by the mature technology (since 1990s) of offshore hydrocarbons.

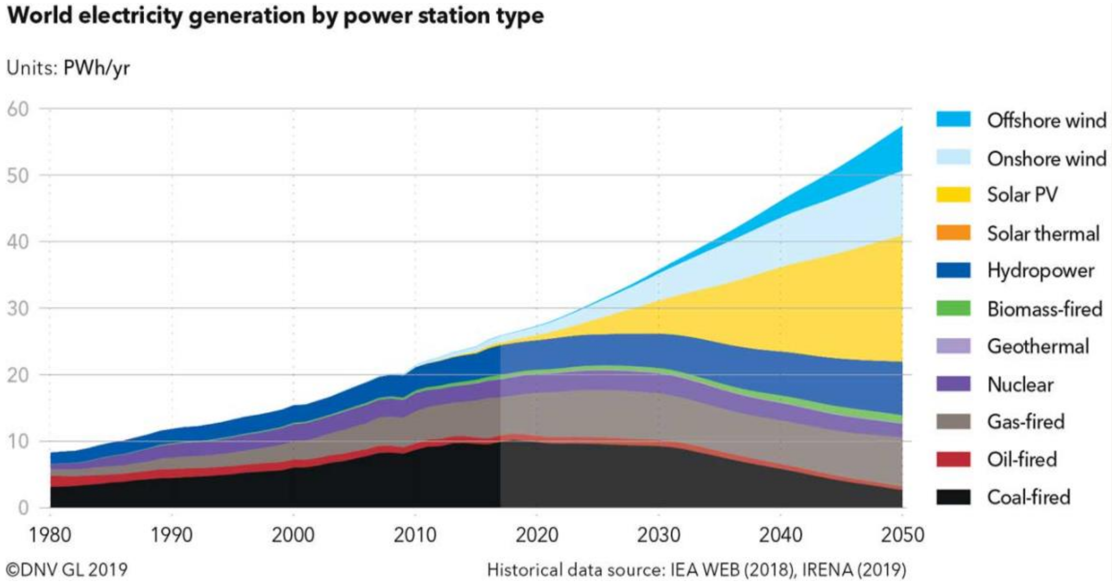

Figure 1.2: *World electricity generation by power station type. From 1980 with a forecast to 2050 [44]*

1.4 Offshore wind energy

Offshore wind energy has some unique characteristics [46]: i) on the sea, there are high energy amounts, ii) winds have better quality and iii) there is more intensity (is increased with the distance of coast) and constancy (not irregular surface) on the offshore winds. Moreover, wind can be combined with wave energy and give high energy performance with greater nominal power, 10 MW [11]. There are, also, hybrid systems with wind energy and hydropower [47] and Norway is able to use them [48]. Also, the 71 % of the Earth's surface is water-covered, so there is space to manage and ease the land. Social acceptance is coming, also, with the decrease of land use. That is to say, that noise and visual pollution with the turbines next to towns and villages, will be decreased. Although, it can’t be overlooked that offshore wind technology as a modern technology has also disadvantages. The cost still remains higher than onshore [49]. It takes time to implement the offshore projects and the access to the site it should be taken into account. Furthermore, there is a concern about the environmental burdens and ref. [30] - [43] analyze them. As it can been seen from these investigations the burdens depend from the type of the turbine [30].

The main difference between onshore and offshore structures is the support structures and not the turbine parts [31]. Offshore wind turbines can be separated in two categories with point of reference the type of support structure. Offshore wind turbines can be bottom fixed or floating. Bottom fixed turbines are for depths less than 50 m [50], [51]. Floating support structures create the opportunity to go in deeper water. Deeper water means more wind and more space. Notwithstanding that the first offshore wind farm had installed in Denmark [50], equinor created the ‘’Hywind Scotland’’ wind farm which corresponds to the first floating wind farm worldwide [52]. The farm had a great Capacity Factor (CF) and lower cost than “Hywind Demo”, i.e. a test turbine installed at Karmøy, Norway.

On the other side, the transportation to the site of the offshore wind projects and the problems caused by the depths is a new challenge. Technologies need to be improved [11] and that is achieved with continues research and technology development [53]. The evolution of this technology generates new data that should be taken under consideration in new studies. As the energy production from these turbines is constantly grows, environment have to confront different impact. Research related to cost, e.g. determination of LCOE indicator, and mechanics, e.g. investigate issues related to stability of the wind structures, improving the mechanisms and participating machines, has to be followed by environmental studies.

1.5 LCA method

To calculate environmental burdens Life Cycle Assessment (LCA) method can be used. LCA is a method to quantify environmental indicators of a specific system. It was first appeared on 1969 by Harry E. TEASLEY [54], [55]. At first, only waste, energy consumption and simple environmental impacts were under consideration. Gradually, it is now used to assess different and significant aspects of environmental consequences. Depending on the type of technology and the current needs, to quantify these consequences researchers consider various impact categories. Namely, the twelve most common impact categories are: Acidification, Biodiversity, Climate change (or Global Warming Potential-GWP), Ecotoxicity, Eutrophication, Human toxicity, Ionizing radiation, Land use or land occupation, Ozone depletion, Particulate matter, Photochemical ozone formation (or photo-oxidant formation), Resource depletion [56]. This evolution is due to improving the method from the experience results and standardization the steps.

According to ISO 14040, the method has the following steps [31], [32], [34], [57]: (a) goal and scope definition, (b) inventory analysis, (c) impact assessment and (d) results interpretation. At the first step, goal and scope definition, the basis of the study is defined. The goal determination includes, as the ISO standard requires, the analyzed subject, its contribution to the global and the limitations of the analysis. The recipients of the results and the manner of how the results will be comprehensible for the audience, e.g. with comparisons with familiar, to them, data or with using a intelligible LCA framework, are also defined. The scope definition includes, inter alia, the system boundaries, which summarizes the life cycle stages of the system, the required inputs for the analysis and the so-called examined mid-point impact categories. The mid-point categories express indicators of the final (endpoint) impacts in ecosystem and human health. Moreover, details of the examined system and methodology are described. An integral part of the scope is the functional unit (FU) which is described in more detail below. At the next phase of the method, inventory analysis, the data are collected and analyzed. The data analysis leads to results relating with resource use and environmental emissions and the process to express them as impacts is the impact assessment. The impact assessment is followed by the results interpretation. The points of importance and the accuracy and correctness of results are thoroughly investigated in this step. In this phase, the results could also be visualized and compared with relevance and common data to be disclosed to the public. To make comparisons, a common unit is presupposed to exist, and this is the aforementioned functional unit. The functional unit makes the inputs and results from different concepts comparable [32]. Depending on the type of the study and the examined system, FU shall have specific characteristics: (a) quantity, (b) quality and (c) duration. The inventory data are normalized by referring to this unit. FU examples are: (a) the "kg" and "ton" that are used to LCA for food products and express masses units [58], (b) "m^3" is used to liquid analysis, expressing volume, (c) "ha" is an area unit, equal to 10000 "m^2", (d) "kJ", "MWh", "kWh" are energy units which may refer to the generated electricity amount of a power plant. Is useful for most of LCA studies, which are in similar scientific fields, to work with the same functional unit if this is possible. Investigations in regard with energy sector, can use energy units, e.g. 1 kWh, and quantify impacts for 1 electricity unit that the power plant generates in its lifetime. The FU can't change during the LCA method due to the need of cohesion in all the steps.

The basic steps of the LCA method are under discussion during the assessment because of new data in the process. Is a complex and multilayer process that needs reliable data for all lifetime stages [54]. Stages of a wind farm concept can be the: "Extraction of raw materials", "Production/Fabrication", "Transportation", "Installation", "Operation/Maintenance" and "Disposal". A simple and comprehensive example is shown at ***Figure 1.3***. The consideration of the life cycle stages depends on the type of the considered system. Between a conventional building and an offshore wind farm the life stages can differ. At the offshore wind, may be considered one more transport stage and one more related stage to manufacturing/fabrication. For an offshore wind project there is the potential of the use of a fabrication yard in addition to the production site. In the fabrication yard (the yard is located to coast) materials can take their last shape and after can be transported to the harbor near to the considered site of the farm. In the harbor the assembly can be conducted and follows the loading to vessels. For floating turbines, the assembly should be conducted to the harbor but for bottom fixed is not always necessary. After the loading, the assembled components (turbines, support structures etc.) of the wind farm are transported to the site (load out process) and the installation is the next phase. Is worth noting that on an innovative floating offshore technology, SATH technology, by the Saitec firm [59], the fabrication yard and its added transportation phase can be overlooked (as in ***Figure 1.3***). That is due to the material of the turbine's platform (concrete) that can be formed at the harbor (as a construction site of a building). As it can be seen, LCA requires data and calculations from the entire life cycle for a product, activity or process and the results of an LCA study can be used for decision making when they are combined with economic and social reality.

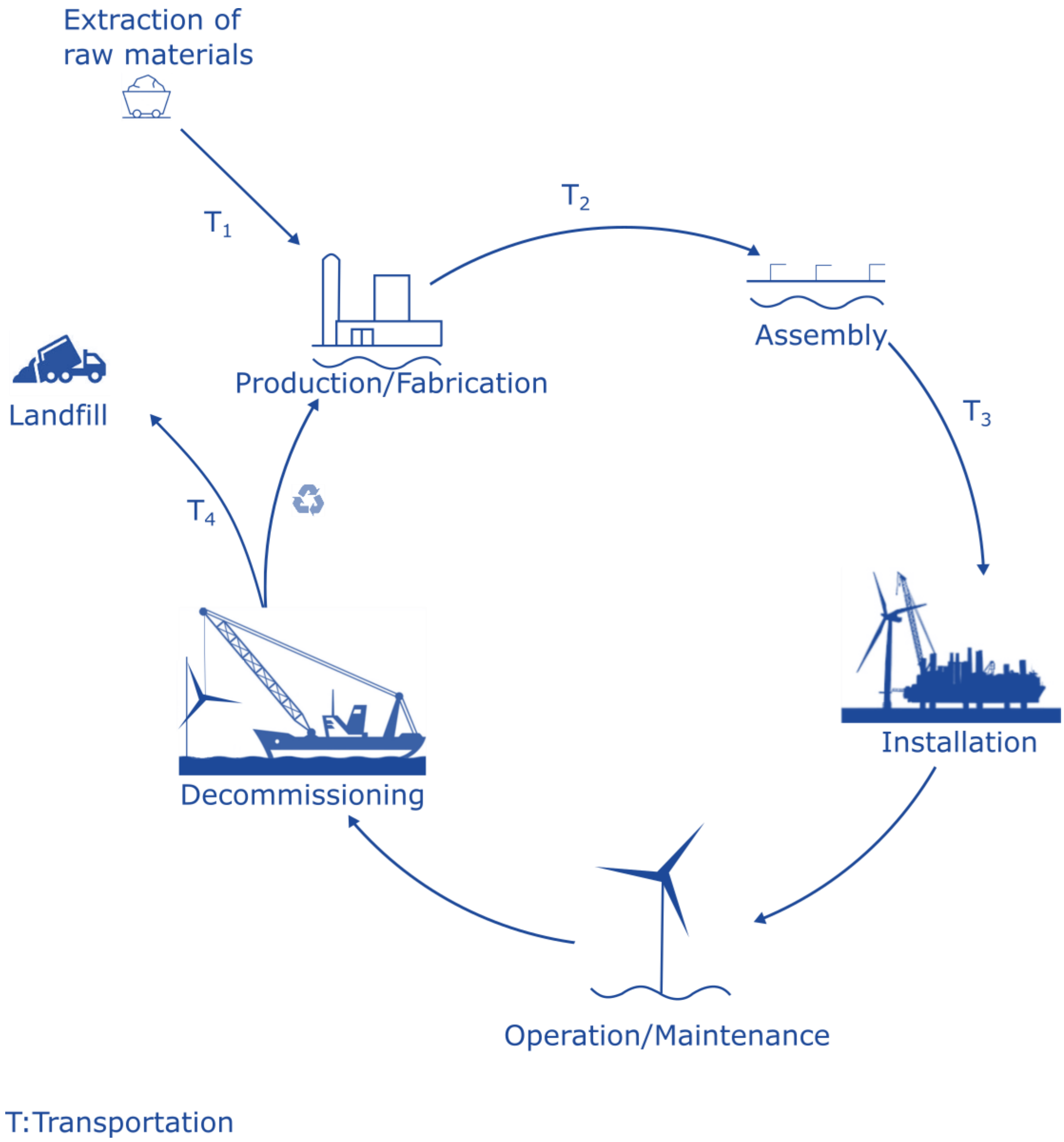

Figure 1.3: *Life cycle stages of floating offshore wind farm*

Nowadays, due to the development and standardization of the method (ISO 14040:2006 [60] and ISO 14044:2006 [61]) there is the opportunity to assess a wide range of new technologies and embodied emissions of the products. There are also other methods to present the environmental burdens. Most popular are the "ERM: environmental risk mapping", "EIA: environmental impact assessment", "MAS: multi-agent system", "LP: linear programming", "AEI: agro-environmental indicators" [62]. Some of them, also concern about economic field. However, in order to consider in a holistic way the environmental impacts, only LCA and EIA can be used [62]. Beyond the EIA, LCA can give a clear description of the life **cycle** of a product, a construction, services etc. (***Figure 1.3***). It takes into account the **embodied** emissions of materials and activities. Also, an advantage of LCA approach is the **quantification** of the environmental impacts. The latter is achieved by using data from inventories (Life Cycle

Inventories-LCI) that are results from reports, called “Environmental Product Declaration-EPD”. This situation led, not only public institutes, but also private organizations and companies to use the method. With the increase of environmental-conscious consumers, enterprises need to prove that their processes and their targets are environmentally friendly.

Data inventories included in databases e.g. ecoinvent3 and IPCC Emissions Factor Database 3.0 (11.9.18) [35], tools e.g. SimaPro, Eco-Indicator, GaBi, Open LCA and methods e.g. EDIP, CML 2001, TRACI have been improved and allow the research to take into account different parameters at the LCA analysis. The internet have opened a large scale of sources and information is available in every side of the world. The digital communications have been improved and data from companies and design teams of specific projects can easier be obtained in comparison with the past decade. As a novel, under development technology, the assessment of environmental impacts of floating wind turbines requires the consideration of new data and parameters. Moreover, due to the small lifetime, i.e. 20-25 years, of wind turbines, phases such as the operation and maintenance are significant to the impacts quantification and differ from a conventional building with 50 years lifetime.

Based to all aforementioned, it is decided that LCA method fits to this research work. There are different types of LCAs studies that can be used. For instance, an LCA can be prospective, process-based or comparative. The prospective LCA is when the novel technology studied is at an early age (e.g. pilot turbines), but the technology is future-oriented (e.g. wind farms that product energy for use) [63]. The process-based type, contain in detail the processes of the input and output products/services to a specific life-cycle phase of a system [64], [65]. The comparative analysis is equally important with prospective and process-based analysis. This type is when the study compares products and technologies according to specific environmental indicators (e.g. GHG of offshore and onshore wind turbine). The choice of the LCA type depends on the needs and the examined technology.

Chapter 2

LCA investigations for wind energy – State-of-art

2.1 Overall image

According to Garcia-Teruel et al. [34] when their research was conducted, there were 32 LCA investigations concerns offshore wind systems and only 6 investigations for floating offshore wind energy were in existence. Today, there are in existence more than 32 LCA research works about offshore wind systems and 6 of them deal exclusively with floating offshore wind systems. The first research work that concerns floating wind turbines, had started before the first floating turbine installation. The article [33] that use the LCA method and consider a type of a floating wind farm (Sway Company's project, ***Figure 2.1***) was available online since 2008. However, the first floating installed turbine (Hywind, ***Figure 2.2***), that the type of the construction was distinctly separated, was installed in Norwegian Sea in 2009. It is important to pay attention to the dates that investigations were conducted due to the rapidly development of floating wind technology and the changes that this development cause to the LCA framework. For upcoming research works reliable and real data may be chosen to be examined.

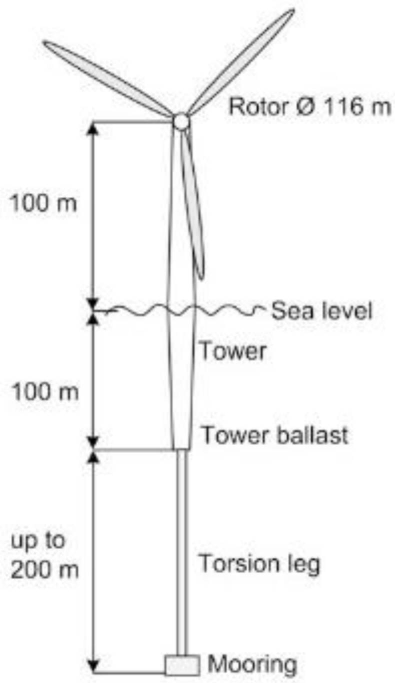

Figure 2.1: *Wind turbine concept [33]*

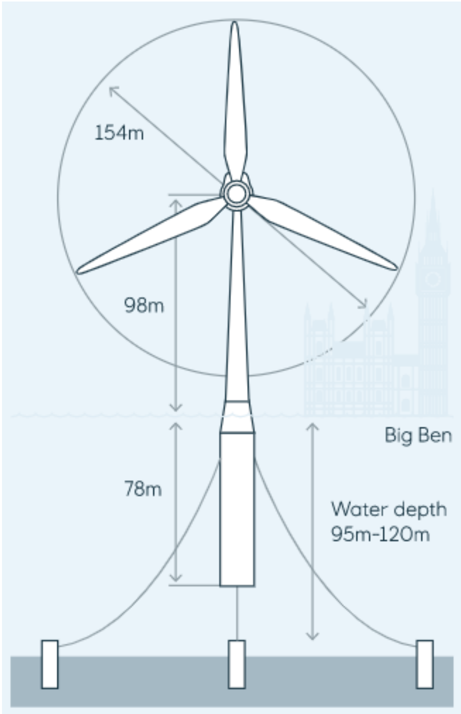

Figure 2.2: *Hywind turbine by equinor [52]*

2.2 LCA for onshore wind energy

Unlike the lack in relative literature with floating offshore wind energy [32], there are investigations concerns onshore wind energy, where useful data and methodologies (e.g. System boundaries, Inventory Datasets etc.) can be obtained. One of them **compares** an onshore **wind farm** with a coal-fired power plan [36]. The farm consists of **33** wind turbines with nominal power **1.5 MW** and **20 years** lifetime. The distance from equipment supplier to wind farm is **630 km** and the wind farm and transmission grid have distance **25 km**. The **stages** that are under consideration at the LCA framework are: "Production and manufacturing", "Transport", "Construction", "Operation and maintenance", "Recycling and disposal". The **environmental emissions** that the paper examine are:

1. CO_2
2. SO_2
3. NO_x
4. CO
5. PM (Particulate Matter)

Focus is given in CO_2 emissions which is found to be the main environmental impact contributor of the two energy generators. For these environmental gasses, data about energy losses and storage system was not considered as it is hard to be obtained. An, also, important information of the paper is that Hui Li et al. (the authors) say that the quantitative studies of wind power are limited in indicating the differences in environmental impacts as compared with coal-fired power. The relative results show that wind power has much lower contribution to the total environmental impact than coal-fired power.

Qiangfeng Li et al. [37], also, indicate that wind power has better environmental performance than other electricity generators. According to their research, from a **GHG** emissions perspective, onshore wind power seems to have less than thermal and biomass power gCO_2-eq/kWh and competes the performance of photovoltaic power. However, the GHG emissions from nuclear power and hydropower remain to be less than the examined wind power system. The findings rely on a process-based LCA. The onshore **wind farm** consists of **20 wind turbines** with nominal power in **2 MW**. For the analysis, six scenarios are formed and assessed with different lifetime years and percentages of metal recycling. The stages of the life span that are considered are in accordance with ISO 1440 and ISO 14044. These are five stages: “Materials and Manufacturing”, “Transport”, “Construction & Installation”, “Operation” and “End of Life”. For the second phase (“Transport”) it is assumed **500 km** distance and about the last phase (“End of Life”) it is assumed **10 km** from landfill. As shown the results, the biggest GHG emissions is located at the Phase 1 (“Materials and Manufacturing”) and specifically at the manufacturing of wind turbines components.

“Manufacturing” phase of wind turbines components is also the main source of pollutant at the repowering process with the “Installation” phase [38]. Repowering a wind farm is an important process recent years. More and more turbines and farms arrive at the end of 15-25 years lifetime [66] and there is a need of research to decide what will be the end-of-life scenario for a farm. An investigation [38] deals with the **repowering** process of an onshore **wind farm**. The new farm consists of **17** wind turbines with nominal power **2 MW**. Specifically, the aforementioned numbers reflect a 41.7 % increase of the power on the original farm. The two farms (the original and the repowered) were assessed. About the **stages** the two farms are considered separately for the first four stages. The first four stages are “Manufacturing of Components”, “Manufacturing and Installation of Foundation, Tower, Nacelle and Rotor”, “Operational and Maintenance phase” and “Decommissioning phase”. Also, the materials and energy were assessed for the “Medium Voltage Network”, “Substation” and “Medium Voltage Network and Substation Modifications”. The definition of the boundaries doesn’t take into account the systems and cables beyond the transformer substation, i.e. the system boundaries include all the facilities above the “limits” of the wind farm. The **impact categories** that are assessed are:

1. Abiotic depletion
2. Global warming
3. Ozone layer depletion
4. Human toxicity
5. Fresh water aquatic ecotoxicity
6. Marine aquatic ecotoxicity
7. Terrestrial ecotoxicity
8. Photochemical oxidation
9. Acidification
10. Eutrophication

The total impact/benefit of repowering is calculated. This is done considering a lifetime of **7 years** for the original facility and a useful lifetime of **20 years** for the repowered wind farm. There is no analysis about the capacity of the grid at the connection point. Repowering process is a scenario at the end-of-life of the turbine and ref. [66] pointed out that the literature about extension, repowering or refurbishment is limited.

2.3 LCA for offshore and onshore wind energy

Useful data can be obtained from investigations that, in addition to onshore, consider offshore wind farms as the ref. [39]. Wang et al. [39], conduct a process-based LCA study. There are two concepts: (a) onshore, (b) offshore. At these concepts only the **wind turbines** (***Figure 2.3***) are under consideration. The nominal power of turbines is **2 MW** and the turbines have **20 years** lifetime. The offshore turbine has a **floating** platform fixed in sea (with a torsion leg being connected with the mooring) and is close to the shore (is assumed that the transport and installation of the concepts are equivalent). The determinates values are refer to distance from wind turbine factory to installation location (1500 km) and from the wind farm site to recycling and landfill locations (100 km and plus 30 km for the offshore case). The functional unit for the 2 concepts is **1 MJ**. The **stages** that authors assume, are: "Manufacturing", "Transport and installation", "Operation and maintenance", "Dismantling and disposal" (***Figure 2.4***). The examined **impact category** is the GWP and the indicator that is in use is the GHG emissions. It is inferred that, in contrast with ref. [37] and others, the transport and installation phase of the two concepts present the highest percentage (~ 90 %) of GHG emissions. The phase with lower emissions (< 1 %) is the operation and maintenance.

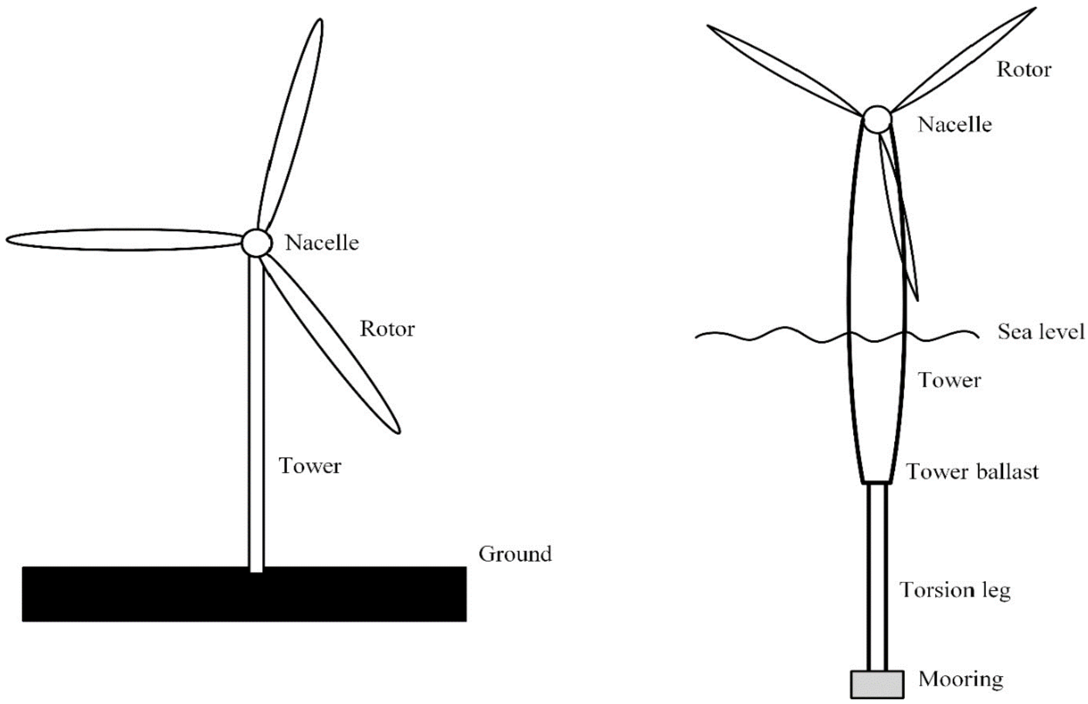

Figure 2.3: *The two examined concepts [39]*

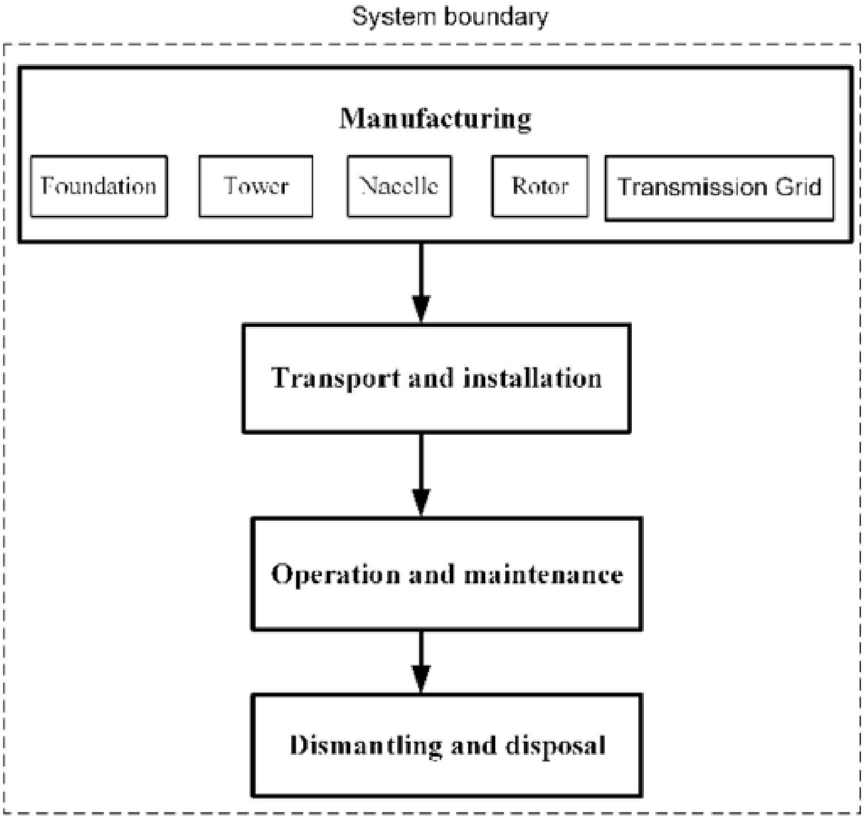

Figure 2.4: *Stages/System boundary of the study [39]*

There are also research works that are based on the literature and draw conclusions by combining other research works. There is a study that the conclusions apply to vary systems of wind energy [32] by take into account different parameters. Firstly, three basic cases are examined: **(a) Onshore single turbine, (b) Onshore wind farm, (c) Offshore wind farm**. Author examines different parameters as the hub height, the rotor diameter, the CF, the nominal power of the turbine and the AEY (Annual Energy Yield). The offshore wind concept, include turbines with nominal power **0.5-6 MW**. Author mentions that limited studies exist for farm instead of single turbines and especially for offshore wind farms. The **stages** that are considered summarized in: “Wind plant components manufacturing”, “Construction”, “Operation” and “End of Life”. Each stage include more specific “parts”. The first stage “Wind plant components manufacturing”, consists of “Resources extraction”, “Raw material Processing”, “Components manufacturing”. “Construction” stage constists of “Installation”, “Commissioning”, “Transportation”. The third stage “Operation” have the parts: “Maintenance”, “Replacement”, “Plant operation”. The end-of-life scenario doesn’t include repowering and consists of “Decommissioning”, “Disposal”, “Recycling”. It can be seen that comparison with the aforementioned investigations, there is more detailed description of the stages on this study. The environmental **impact** that the study concerns about, is the GWP by using the GHG emissions indicator. Authors state that by increasing the dimensions of wind turbines, a reduction of CO_2 emmissions is appeared. In this investigation, the functional unit is **1 kWh** electricity production. As it can be seen, the “Recycling” stage is seperated from the other stages. That can be justified from the fact that recycling of components is a separate subject in other investigations [66].

The "Recycling" stage can also be replaced by the "Reuse" of equipment. At ref. [40] **reusing** at the EoL of **onshore and offshore wind farm** is discussed. ***Figure 2.5*** illustrates the main stages of a floating wind farm that are considered in this study. Reuse make the system cyclic by creating an extra ideal "arrow" from the "End of service" till "Manufacturing" in ***Figure 2.5***. Therefore, the need of using the LCA approach is clear, given that the method emphasis to the circularity feature of a system (***Figure 1.3***). The study, focus on $\mathbf{CO_2}$ emissions but also is referred to energy consumption and other environmental impacts. An important statement is that "the equipment **manufacturing and decommissioning**, have different and significant contributions in terms of inputs and energy consumption, but also gases emissions and environmental impacts". Author mention that reuse and recycle may show decrease in energy consumption and CO_2 emissions at the decommissioning phase.

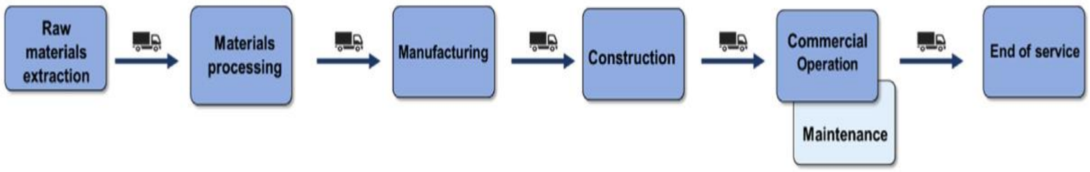

Figure 2.5: *Main stages of wind farms life cycle [40]*

As the variety of choices that follow the end-of-life of wind farms and the variety of manufacturing and construction technologies, the existing literature is chiefly differ on the "upstream" and "downstream" processes [41]. In the research work [41] "Upstream" refer to "manufacturing" and "construction" phase and "downstream" to "dismantling" phase. This literature review has as a target to update the data of LCA studies about electricity generated from **onshore and offshore wind turbines**. Different capacities are under consideration. Onshore turbines have nominal power from 0.001 MW up to 5MW and offshore have from **0.5 MW up to 8 MW**. The **impact categories** are the four below:

1. Acidification Potential (AP)
2. Eutrophication Potential (EP)
3. Global Warming Potential (GWP)
4. Cumulative Energy Demand (CED)

The system boundaries (**stages**) were considered with different way from the above-mentioned investigations. There are three substantial stages: upstream (raw material extraction, manufacturing, wind turbine construction), operational (power generation, operation and maintenance) and downstream (decommissioning and end of life scenarios). It can be overlooked a mention from author: "Further works should focus on: i) inclusion of **other environmental indicators**, ii) improving prediction of LCA models by **considering innovative technologies**, iii) development of a simplified LCA model for an entire wind farm, which can be performed by investigating on the correlation between the farm size and the additional material consumptions, and, finally, iv) further harmonization of the results focusing on the background process modeling and methodological choices.”.

2.4 LCA for offshore wind energy

At the study [33], an innovative technology is examined. the examined technology it wasn’t even at the marketplace, so a prospective LCA analysis was conducted. A **floating wind farm,** not only the wind turbines, is under consideration. Components of wind farm as the one substation and the cables to deliver the electricity to the coast are in the examined system. The wind farm consists of **40** floating wind **turbines**, which have the same floating platform with the considered platform in the research of Wang et al. [39] (***Figure 2.1***). The lifetime is **20 years** and nominal power **5 MW**. The farm is **50 km** far away from the shore and the water depth is **100-300 m**. The functional unit that Weinzettel et al. use is **1 MJ** (=0.278kWh). This functional unit is used, not only for comparison reasons but also for the interpretation of the results i.e. the Cumulative Energy Demand is calculated to be 0.054 MJ_{eq}/1 $MJ_{electricity}$. Authors separates the stages of the life of the wind power turbine and the rest components of the wind farm (as below mentioned). The **stages** of the parts of the plant correspond to “Production”, “Transport to assembly”, “Assembly”, “Transport to final location”, “Maintanance”, “Transport to harbor” and “End of life scenario (EoL)”. There are two options about end-of-life scenarios. The one assumes high amount of materials recycling and specific distances to transport waste pieces. The other is to skip the EoL and use secondary materials as Ecoinvent processes. The rest components of the examined system correspond to “moorings”, “cables” and “transition station”. Moorings and cables, have the “production” phase and the EoL (the moorings will be left at the bottom of the sea). However, due to the different nature of these two components, moorings are taken into account into the “transport” phase, while, the cables in the installation phase. The **impact categories** being examine are:

1. Human Toxicity
2. Abiotic Depletion
3. Global Warming (or Global Warming Potential in further literature GWP)
4. Eutrophication
5. Photochemical Oxidation
6. Acidification
7. Fresh Water Aquatic Ecotoxicity
8. Terrestrial Ecotoxicity
9. Cumulative Energy Demand (CED)

In contrast with Martínez et al. [38], Weinzettel et al. [33] couldn’t examine the “Marine Ecotoxicity” due to the lack of gathered data and suitable calculation methods. Instead of this, a closer look was made to the three first categories, Human toxicity, Abiotic depletion, Global warming, are examined in more extend. This examination shows that the alloy steel has the largest contribution in GWP and Abiotic Depletion and copper is related to the Human Toxicity. Additionally the End-of-life and the production stages contribute to a large extend to the total environmental impact. In this investigation exists a comparison of the examined floating wind farm with the Ecoinvent offshore (non-floating/bottom fixed) wind power plant 2 MW and electricity from a natural gas combined cycle plant. This comparison indicates that the only category that floating concept seems to have less impact than the offshore concept is the Global Warming. Also, natural gas combined cycle power plant has significantly higher impacts than the two other concepts. An interesting part of the paper is that Energy Payback Time (EPT) is calculated to be about one year. This indicator shows the time period that the wind farm can produce the amount of electricity that is equal to the energy consumed over its lifetime [67]. This study can be considered as a base to understand the LCA method and the relevance between LCA and the sector of the floating wind energy.

One another indicator that is used for the energy performance is the Energy Payback Ratio (EPR). This indicator is the amount of electricity that the wind farm can produce divided by the energy consumption during its lifetime. A few years ago (2014), was published a LCA study [30] that besides the EPT, examines, also, the EPR. The researchers here, consider not only one, but 6 different offshore concepts. Every concept corresponds to an **offshore wind farm** consisting of **100 5 MW** wind turbines with **20 years** lifetime and CF 46 %. As the authors mention, the 5 MW nominal power is not under examination in many LCA studies when this study were conducted and useful information can be obtained from the results of the present investigation. For this nominal power, a specific type of Rotor-Nacelle-Assembly (RNA) is used. The considered distance from shore is **200km**. For the floating concepts the water depth is **200 m** and for the bottom-fixed **50 m**. The functional unit is **1 kWh**. The 500 MVA substation is calculated by using data from another study with a 220MVA offshore substation. The difference between the six concepts lies on the type of the support structure. In five concepts a specific type of **floating** support structure is taken into account corresponding to SWAY, U-Maine Semi-S, U-Maine Spar, U-Maine TLP, MIT TLB, while in the sixth concept a **bottom-fixed** support structure (OC4 Jacket) is taken into account. The examined **impact categories** are:

1. Global Warming Potential (GWP)
2. Energy performance

For the two aforementioned categories, the indicators that are in use are GHG emissions for the first and for the second there are two indicators: i) Energy Payback Ratio (EPR) and ii) Energy Payback Time (EPT) as is aforementioned. As the authors say more impact categories need to be under examination, as the "land use, visual aspects, biodiversity and noise", specifically when comparing onshore and offshore power. The related with GHG emissions LCA **stages** are: "Installation", "Turbine materials", "Platform materials", "Maintenance (fuel)", "Maintenance (infrastructure/reinvestment)", "Maintenance (others)" and "Decommissioning (fuel)". In the "Turbine materials" and "Platform materials" most of the life cycle phases for turbine and platform, respectively, are under consideration. That is to say that extraction of raw materials, production, fabrication, assembly, transport and disposal are assumed to be in the same stage. The "Maintenance" stage is divided to three subcategories. At the first is considered the fuel consumption for the transportation from coast to the farm site for the maintenance. The second, named "Maintenance (infrastructure/reinvestment)", includes stages from the extraction of raw materials and fuels to the transportation (except the transportation from shore to the site) of the required materials for the maintenance. The last, “Maintenance (others)”, includes stages from extraction of raw support materials to the transportation of these materials and waste treatment. It is noted that at Decommissioning stage only the fuel is considered for the calculations. That is because the waste creation, despite its environmental burdens, does not release GHG emissions. After the end-of-life there are assumptions about percentages of recycling and landfill materials. The recycling credits are not included to the calculations to be in accordance with The International EPD System [68]. Although, the landfill materials percentages are required for the calculations is the Decommissioning stage. At the end, Raadal et al. [30] **compare** their results with relevant results from offshore and onshore research from literature. It is inferred that the six concepts have more GHG emissions and a lower Energy Payback Ratio (EPR) than the concepts from the existing literature, whether it is for offshore or onshore cases. An explanation of these results is the different assumed steel masses in the analysis. The required steel masses are highly vary within offshore bottom-fixed, offshore floating and onshore support structures. Furthermore, the accuracy and completeness of the data collection in relevance with steel masses for the platform, anchor and mooring cables, in this study, end-up differences even with similar offshore concepts. The discrepancy with the literature data, may also be connected with i) assumptions relating production and installation energy demands, ii) the type of the LCA analysis iii) the type of the wind farm (onshore or offshore), and iv) variations in operation and maintenance activities. Despite this discrepancy, authors confirm the lack of standardizing energy performance methods which have been substantiated by other studies [69], [70]. In accordance to this confirmation is the fact that the EPT here (1.6-2.7 years), have more than double value than in the other investigation above [33] (0.4-1.1 years). On the other hand, the results for the GHG emissions have also similarities with the literature results. The numbers shows that GHG emissions from wind power can completely compete the low GHG emission electricity technologies (e.g. hydropower, nuclear and photovoltaic power) and fossil electricity generation technologies. This is in accordance with the conclusions of Weinzettel et al. who have drawn the same inference about a natural gas combined cycle plant. Furthermore, GHG emissions seems to have a reduction by increasing the nominal power and the CF and this is also in line with literature [71]. Besides the nominal power and CF, it is concluded that parameters like lifetime of the turbines, wind conditions, distance to shore, and installation and decommissioning activities have principal contributions in GHG emissions.

In 2016, another investigation, also considers 100 wind turbines in the examined system [42]. This investigation is a process-based LCA investigation for **offshore wind farms** concepts. In this research, there are in total 20 different offshore wind farms (OWF), which include 8 **floating** wind farms. The considered farms, consists of **100** wind turbines with **3 MW** nominal power and **20 years** lifetime. Also, one transformer station and the collection and transmission cables (including both submarine cables and land-based cable) are in the examined system. The scenarios are located in four different areas in the U.S. It is important to say that authors haven’t conducted this investigation for EU input data. However, the investigation is performed based on U.S. data and only a few European data have been taken into account. The main difference between these areas is the electricity mix, which include more fossil-based energy at the United States. For each U.S. location, there are examinations about five different distances from shore

(**5, 10, 15, 20 and 30 km**). The 20 scenarios has their own support structure (foundation), transmission, installation and operational systems. The **impact categories** that are under consideration are three:

1. Cumulative (fossil) energy demand (CED)
2. Global Warming Potential (GWP)
3. Acidification potential (AP)

The results for the examined environmental impacts show that water depth, distance from coast and distance to power grid have significant effects to the environment. By increasing these three parameters, the impacts are becoming larger per the used functional unit. It is noted that the FU is the **1 kWh** electricity production, so the optimization of the wind conditions and increasing the energy production by go deeper and faraway from coast, doesn't face the environmental burdens. The main reason of this result is the used type of support structure and not the over-land (land-based) cables. In deep waters, more than 60 meters [72], turbines can't be founded with monopile and there is a need of floating support structures which is followed by worse environmental performance. In relation with this fact, is that by increasing the distance from shore or the distance to power grid in calculations, usually, lead to the increase of the water depth. Distance from shore, also, contribute to impacts related to transportation. Tsai et al. (the authors) clarify that the scenario with the minimum environmental impacts at Oceana County, had small distance from shore (5 km), water depth (25 m) and a monopile support structure. Besides the three above-mentioned important parameters, each concept has characteristics that contribute to his environmental performance. All the concepts is assumed to have the same **stages**: "Manufacturing and Assembly", "Installation", "O&M", and "Decommissioning". The "Manufacturing" stage is proven to be the most significant energy "consumer". At this stage, support structure, tower and a considered category with small various parts of the turbine, plays decisive role at the CED. Meanwhile, at the last stage, "Decommissioning", two different EoL cases are compared. One of the two cases, takes into account recycling amounts. It is clear that in this way, environment is disburdened. On the other hand, according to this paper and other investigations [34], [73], processes at the "O&M" stage, have a direct and principal effects to GWP.

Garcia-Teruel et al. [34], examine thoroughly the "O&M" stage. They analyze different types of vessels which are in use, spare components etc. Authors mention that most of studies obtain data, for this stage, from onshore wind investigations due to the lack of reliable data and difficulties in modelling. The selected **stages** for the needs of the LCA analysis in this paper are: "Materials and Manufacturing", "Installation" (starting with the transportation to the assembly port), "Operation and maintenance" (O&M), "Decommissioning & Disposal". The environmental impacts of two different **floating offshore wind farms** were assessed. Authors had inspired from two already installed and operated farms at Scotland. Is worth noting that these farms have not an offshore substation, however a substation may be necessary for forthcoming research work as the capacity is increasing to every forthcoming floating offshore wind project. At the first case (Hywind), the farm consists of **5** wind turbines with **6 MW** nominal power. Platforms have **spar-type** floater ("spar-type foundation" [34]). The distance from the shore (Peterhead) is **25 km** and the depth vary from **95 m to 129 m**. At the second case (Kincardine), the farm consists of **5** wind turbines with **9.5 MW** nominal power (one 2 MW wind turbine is on the real farm but is not at the examined system) **semi-submersible** platforms. The distance from the shore (Aberdeen) is **15 km** and the depth vary from **60 m to 80 m**. For the two cases, **25 years** lifetime is considered. To achieve comparability with other LCA studies and between the two cases, the considered functional unit is **1 kWh**. This paper examine the most **impact categories** in comparison with other papers. These categories are:

1. Fine particulate matter formation (FPM)
2. Fossil resource scarcity (FRS)
3. Freshwater ecotoxicity (F Etox)
4. Freshwater eutrophication (F Eut)
5. Global warming (GW)
6. Human carcinogenic toxicity (HT-C)
7. Human non-carcinogenic toxicity (HT-nonC)
8. Ionising radiation (IR)
9. Land use (LU)
10. Marine ecotoxicity (M Etox)
11. Marine eutrophication (M Eut)
12. Mineral resource scarcity (MRS)
13. Ozone formation, Human health (OF-HH)
14. Ozone formation, Terrestrial ecosystems (OF-TE)
15. Stratospheric ozone depletion (SOD)
16. Terrestrial acidification (TA)
17. Terrestrial ecotoxicity (T Etox)
18. Cumulative energy demand (CED)
19. Water consumption (WC)

For the category WC, the results aren't described due to their high value of uncertainty of background data. In contrast with the ref. [33] in this study, "Marine Ecotoxicity" category is taken into account. A special mention is made about the GW, due to its popular use in other LCA researches. Regarding to the relatively low uncertainty of the results in this category, its conclusions could be important and can be compared with the literature results. Spar case seems to contribute more to GW than the Semi-sub. It is also important that in both cases, the first stage, "Materials and Manufacturing", is the substancial source of GHG emissions followed by the O&M. In a more detailed level, the vessels for the O&M, possess principal amount of GHG emissions, followed by turbine or substructure manufacturing. O&M vessels, possess, also, a significant position to categories related with Ozone and to TA. It is underlined that the power transmission (export and inter-array cables) contribute to a large scale to F Etox, F Eut, HT-nonC, M Etox, T Etox, without taken into account the over-land cables as Tsai et al. [42]. Another interesting aspect of this investigation are the results in relation with energy production and consumption. In contrast with Weinzettel et al. [33] where the Energy Payback Time is calculated to be 0.4 to 1.1 years, Garcia-Teruel et al. found that EPT is about 2.8 to 3.7 years, which is closer to Raadal et al. results, 1.6 to 2.7 years. Moreover, the reduction of the "Annual

Energy Production (AEP)" lead to a decrease in all impact categories since kWh is the FU. With indirectly way, in ref. [41], there is the same observation. Namely, the findings are showing that by decreasing the CF and the lifetime, the impacts appear to be lower.

The positive effect of increasing the energy production to environmental impacts is, also, observed by Elginoz and Bas [31]. This observation, it is achieved by two comparisons. Authors compare a multi-use semi-submersible concept with a single-use semi-submersible, which has smaller nominal power. Moreover, there is comparison of the base scenario with scenarios with different capacity factors. The base scenario includes a **multi-use semi-submersible** concept on a specific location. This concept is referred to offshore **floating** platforms that combine wind and wave energy. Specifically, an entire energy floating farm is under consideration for the LCA analysis. The farm includes **77** multi-use platforms consisting of one NREL **5 MW** wind turbine and three **1150 kW** Oscillating Water Column (OWC) type **Wave Energy Converter** (WEC**)** [31] (8450 kW each plant). The platforms have **25 years** lifetime and the farm is located **3-13 km** from shore. The functional unit is **1 kWh**. The considered **stages** are listed below in order to highlight the detailed separation of them in this investigation:

- ❖ Manufacturing and Processing, Transportation, Installation
  - ➢ Platforms (turbine, support structure, Wave Energy Converters)
    - ▪ Moving parts (including RNA)
    - ▪ Fixed parts
    - ▪ Mooring parts
    - ▪ Wave Energy Converters
  - ➢ Substation
    - ▪ Jacket Structure
    - ▪ Offshore Substation Equipment
  - ➢ High voltage (HV)
  - ➢ Medium voltage cables
- ❖ Operation and Maintenance
- ❖ End of Life

This detailed list allows the interpretation of the results. It is found that manufacturing of fixed parts of the wind turbine, moving parts and mooring systems, i.e. the wind turbine and the support structure, is the main contributor to the total environmental impact. This is a similar conclusion with Garcia-Teruel et al. [34], who report that turbine and substructure have large contribution to the GHG emissions which is the only impact category that they decided to examine. As other investigations, [30], [33], the results reveal a decisive contribution of steel quantities to the total environmental impact. For more detailed examination and for comparison reasons, different scenarios are formed and examined. The parameters that are changed by researchers are: (a) the electricity consumption in "Manufacturing and Processing" and "Installation" stages, (b) the recycle ratios of the materials at the EoL and (c) the sites of the farm. Moreover, there is a comparison between a modified platform of the base scenario, which is a single-use semi-submersible platform, i.e. non WECs are considered, and the Spar platform from the research of Weinzettel et al. [33]. The contributions of each concept to the environmental impacts, it depends on the examined impact category. For instance, single-use semi-submersible affects more at the Terrestic ecotoxicity and Spar has more effects to the Acidification category. All the determined **impact categories** are:

1. Abiotic depletion
2. Acidification
3. Eutrophication
4. Freshwater aquatic ecotoxicity
5. Global warming
6. Human toxicity
7. Ozone layer depletion
8. Photochem
9. Ozone creation
10. Terrestric ecotoxicity

The selection of these categories by authors, was determined from the possibilities of the tool that was in use (CML 2001) and the literature review.

In the other hand, in a latter investigation (2019), [35], only **GWP** is considered as an impact category. This simplification is justified as Bang et al. establish a basis for further relevant LCAs studies. In more explicitly, the masses which are calculated for the examined **floating offshore wind farms**, without a consideration of WECs, could be taken into account in investigations with more impact categories. As a previous investigation in 2014, [30], authors recommend that more impact categories should be examined. This is in accordance with the justified opinion of Elginoz and Bas who mention the need of finding solutions to reduce the GHG but no at other environmental expenses and specific relevant to water toxicity. In addition to this statement, Elginoz and Bas and Bang et al. agree to which stage is the major contributor to their examined categories. The “Manufacturing” stage, has a dominant position to the environmental burdens within these authors and others ([34], [37], [38], [40]). Specifically, within Bang et al. [35], Weinzettel et al. [33], Raadal et al. [30] manufacturing of steel masses is the largest source of pollution. Furthermore, it is found that between the turbine and the examined **Spar** support structure, the second is more effective to the overall environmental footprint, while Garcia-Teruel et al. [34] draw the opposite inference for their Spar floater and the same inference for their Semi-submersible. However, all the floating concepts seems to have lower environmental burdens from Coal power, as the examined onshore wind farm of Li et al. [36], and Natural Gas power. They are, also, competitive to other energy generators such as Nuclear, Hydro etc. In addition to “Manufacturing” stage, the other considered **stages** are: “Transportation”, “Installation”, “Operation”, “Decommissioning”, and “End-of-life treatment”. The stages apply to all the different considered cases. Six sites is under examination. As Tsai et al. [42], the concepts take place in USA (California), however the Ecoinvent database is in use and not a relevant with USA database. An uncertainty analysis, also, is conducted and the parameters that the author change are: CF, distance from shore, lifetime, water depth, distance for transportation, Installation operational factor, Visits per year for the maintenance, Major Maintenance Requirement and Turbine Failure and Replacement Requirement. There is comparisons among the results of the different formed concepts and also between them and the previous results from literature. For the needs of the comparisons, the functional unit that is in use, is the **1 MWh**. For the baseline scenario, the farm consists of **75** turbines with **8 MW** nominal power and **25** years lifetime. The floating substructures, mooring lines, anchors, inter-array cables, export cables and one substation are also considered at the system boundaries. The distance from shore is **35 km** and the water depth is **450 m**. The type of the turbines is inspired from the Hywind Scotland pilot park.

As the aforementioned investigation, the ref. [43] also have inspired from a pilot park. The pilot park is a **floating offshore wind farm**. For the baseline case study, is considered that the farm consists of **4** wind turbines (Haliade 150 model) with **semi-submersible** support structure, **6 MW** nominal power and **20 years** lifetime. The connection to the grid is also taken into the examined system. The farm is designed to be **16 km** from shore at the Mediterranean Sea. Authors mention that this floating technology can be used at water depths **50-200 m** and no reference is made about the accurate water depth. Here, the unit which direct is in use for the calculations is not the nominal power but the total net electricity production of 1.45 TWh during the lifetime which is calculated by a consideration of 34 % CF. The total electricity is calculated by taking into account the air speeds. A sensitivity analysis also is conducted. Author mentions that the LCA results have effects from the three categories below: (a) Model uncertainties and geographical variability linked to electricity estimates (b) Parameter uncertainties and variability of foreground data (c) Uncertainties in background data. To make the cases comparable the **1 kWh** is used as the functional unit. An analytical figure (***Figure 2.6***) describes the necessary features for the LCA model. At the last column of this figure the considered **stages** are illustrated. Namely are: “Extraction of raw materials”, “Manufacture of the system components (e.g., turbines, floaters, the mooring system)”, “Transportation”, “Offshore installation”, “Grid connection”, “Maintenance” and “End-of-life”. The **impact categories** that are examined are:

1. Climate change
2. Resource depletion
3. Water use
4. Marine ecotoxicity
5. Air quality
6. CED renewable (=Cumulative Energy Demand of renewable sources)
7. CED non-renewable

In contrast to the first investigation of this section [33], here it is also considered the Marine Ecotoxicity. Despite the large uncertainty of this impact category, as Weinzettel et al. [33] mention, and of the water use category, it is pointed out that results of these categories have dominant position to this type of technology, and should be taken into account. It is observed that marine ecotoxicity and categories of mineral, fossil and renewable resource depletion are drastically effected by the grid connection data. In comparison with Weinzettel et al. [33] results, at this research work farms have a larger contribution to GWP. Resource depletion and air quality significantly differ from previous studies. Resource depletion caused in a large extend from cables. Generally, the extraction and processing of raw materials is found to be a substantial contributor to the total environmental burden. As Garcia-Teruel et al. [34], the materials of their semi-submersible floater, and in lesser extend the turbine, have the main contribution to the overall impact. The same inference it is, also, mentioned from Bang et al. [35] for their spar type support structure. Of all materials, steel, is the material used in all components of the wind farm, thus, is responsible for the main impact. Last but not least, the fuel consumption at "Transportation", "Offshore installation", "Maintenance" and "End-of-life" stages contributes in a large extend to CED non-renewable and specifically the diesel for transfer vessels.

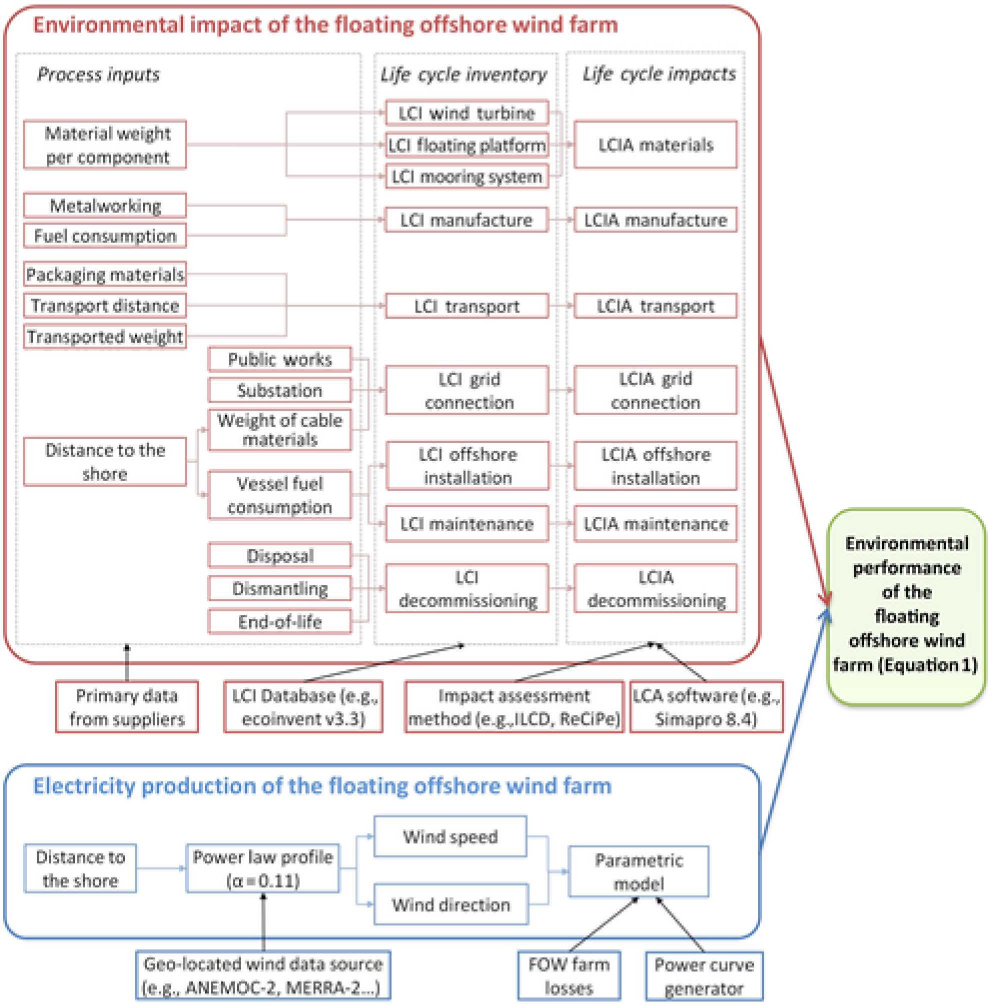

Figure 2.6: *LCA framework [43]*

2.5 Conclusions

As it can be seen in literature, only four research works take into consideration floating turbines with nominal power greater than 5 MW [34], [35], [43], [49]. The largest nominal power that aforementioned literature considers is 9.5 MW. There are already installed wind turbines with nominal power more than this value (e.g. 10 MW turbine was installed in December 2021 at

Scotland’s Seagreen offshore wind farm by Cadeler’s Wind Osprey [75]). Furthermore, the aspiration/ambitions for forthcoming period, meet 20 MW wind turbines [76]. This situation, points out that environmental investigations should consider larger turbines. Higher power means new technology with different types and quantities of raw materials, different installed/transportation/recycling etc. methods and different energy amounts either referring to production either to consumption. That is to say that research needs to follow up the rapid development of technology and the new way of things.

The selected impact indicators of an LCA investigation, requires the existence of datasets/inventories and access to them. If this access is possible, further research should take under consideration a variety of impact indicators [30], [36]. There are studies that focus only on the GHG emissions of the life cycle of a wind farm or a wind turbine [30], [32], [36], [37], [39], [40]. However, impact categories as “Eutrophication”, “Biodiversity”, “Ecotoxicity”, “Ionizing radiation”, “Land occupation” could be taken under consideration. On this pure and virgin marine environment we should concern about the fish and overall to the biodiversity and the inconvenience that might be caused from human activities. Moreover, the climate change shows the existence of several environmental problems. Earth suffers from air and water pollution, ozone layer depletion, acid rain and other problems that don’t caused only by GHG emissions. Therefore, categories as “Ozone depletion”, “Particulate Matter (PM)”, “Recourse depletion” is worth it to be taken into account. In addition, human also, receive the consequences of an implementation of a large project as the construction of a wind farm is. It is true that the decision of going offshore is to prevent aesthetic impacts and impacts in human activities however impact categories as “Human toxicity”, “Photochemical ozone formation”, “Visual pollution” and “Noise pollution” should be anyways taken into account. The energy consumption is also a useful indicator but literature shows that offshore wind power has an Energy Payback Time (EPT or EPBT) less than five years [34], [33], [76]. That is to say that a wind farm can produce the same amount of electricity with the energy consumed over its lifetime in a period less than five years from its operation start [67], so for an assumed 20-25 years lifetime of a wind turbine there is no concern about this indicator.

Furthermore, it can be seen that the consideration of the components of a wind farm differs from study to study. It is a need to concentrate to the holistic consideration of a wind farm (***Figure 2.7***). This may contain, all the necessary cables, the mooring of the components and an accurate description of the offshore substation. Also, the support structure type of a wind turbine, need an analytical investigation since LCA boundaries will change. That is because the materials, the stages and installation methods differ from onshore to offshore bottom-fixed and offshore floating turbines. In reference to support structure, is worth noting that floating wind turbines will become more popular since there is a need to go further away from the coast (i.e. deeper waters). The main material of the floating support structures can be steel or concrete. One LCA investigation [77] consider a concrete support structure. The different type of the used material and the different processes in manufacturing and transportations could lead to different results between steel and concrete support structures.

Last but not least, there are wind farms that already met their lifetime. At 2019 Topham et al. mention that 4 wind energy projects had already decommissioned. These projects are not floating wind farms or turbines however useful information can be obtained. Namely the projects are: “Yttre Stengrund (10 MW, Sweden) was the first, in 2015, after only 15 years of operation (Vattenfall Wraps Up First Ever Offshore Wind Farm Decommissioning, 2016). This was then followed by Lely (2 MW, Netherlands) which was removed from the sea in 2016 after operating for 20 years (Offshore Wind Farm Dismantled in the Netherlands, 2016). Vindeby (5 MW, Denmark), the first offshore wind farm to be installed in 1991, was the third project to be dismantled in 2017, operational for 26 years (World’s first offshore wind farm now dismantled, 2017). And the most recent project to be decommissioned was Utgrunden I (10.5 MW, Sweden), in operation for 18 years (ZITON completes decommissioning of Utgrunden Offshore Windfarm, 2018)” [66]. The decommissioning and, potentially, recycling, repowering, reuse processes have already conducted for projects. As a consequence, it is not necessary to assume hypothetical EoL scenarios about decommissioning and percentages of recycling of the components of the wind farms or turbines which may lead to uncertainties [41]. Reliable data for the decommissioning stage can be obtained from these farms with the contribution of companies that undertakes this kind of projects. Apart of decommission, the repowering also, is a special stage. The facilities of an offshore wind farm (e.g. the substation) and the rapidly development of technology, create the conditions of thinking a future after the lifetime of wind turbines. Only in one of the above-mentioned investigations is considered a repowering process and there is not literature about environmental assessment of repowering float wind farm. Although, the floating projects are in an early stage. Designs doesn’t predict information about repowering process. Nevertheless, in each case (repowering and decommission) data for the floating offshore wind concepts can, also, be obtained from the Ecoinvent database and other inventories.

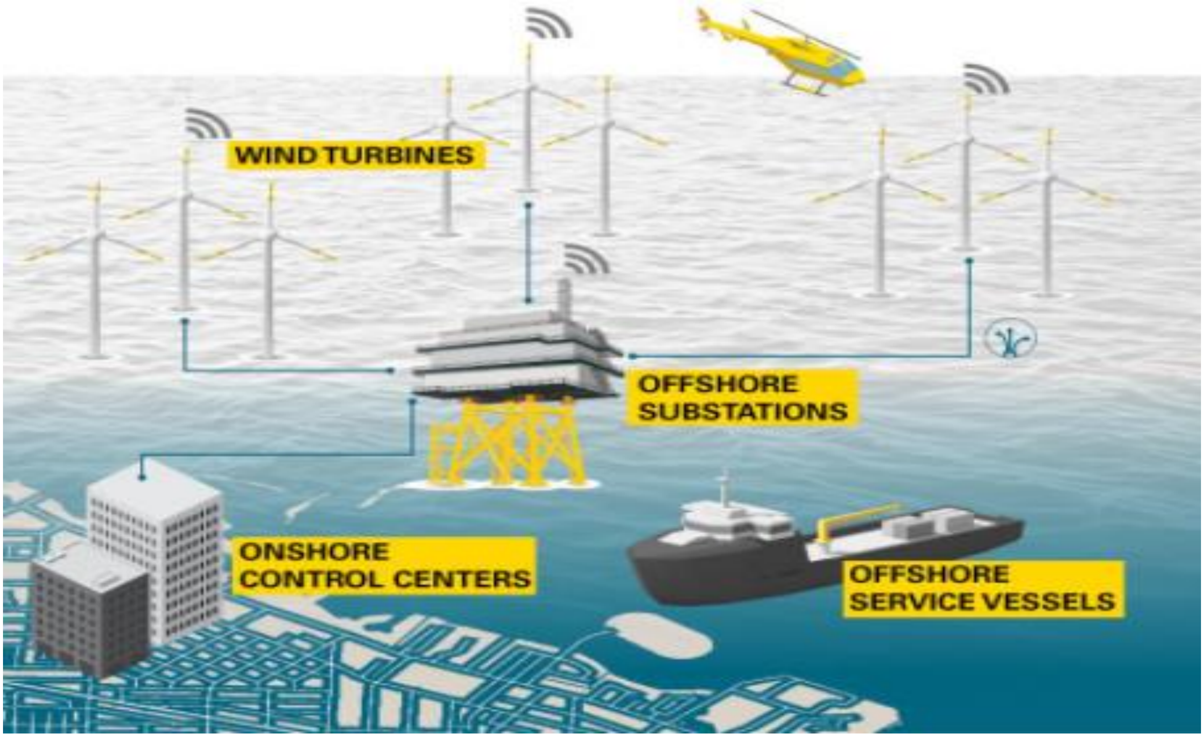

Figure 2.7: *Offshore win farm [79]*

Chapter 3

Methods

3.1 Goal and scope definition

3.1.1 Goal

In this research work, two floating offshore wind power systems were developed, and their environmental impacts were assessed with the LCA method. The two concepts differ in the main material of the support structure, which is steel in the first case study and concrete in the second. The aim is to investigate these innovative technologies. Until now, only limited floating concepts are investigated within the environmental perspective, let alone for the most established platform cases in the marketplace (Spar, Semi-submersible) and ascending platform (Sath).

Firms and manufacturers will be able to use the results to improve their technology and, also, for advertising. An optimal design and mitigation of pollution can be achieved by combining the power of companies and scientific research. The results can be taken under consideration to find related solutions. Further research may rely on this investigation and look for other related issues with this multifaceted subject. Researchers may decide to orient to one of the two concepts due to better environmental performance. It is worth for the public to be informed about total effects, the benefits and the disadvantages of this type of projects. The public opinion affects the development and procedures, and public actions need to be substantiated and reasonable.

To identify these environmental impacts, a comprehensive LCA framework which responds to the needs of these two types of technology is considered. The impacts of each whole system will be determined, and the results will be compared to each other. Moreover, the contribution rate of each component and each stage will be investigated. All the results will be compared with the results of previous literature. However, to allow this process and form this LCA framework, the limitations should be taken into account. The lack of related literature, the limited data or even absence of them, and the available time are parameters standing in the way of forming the concepts. The assumptions should be extensively examined and assessed during the LCA process. Additionally, due to the involution of companies that plays a pivotal role in the development of offshore wind energy, data from companies need to be updated and accurate. To conclude, it can’t be ignored that the science sector which deals with floating offshore wind, move on alongside with the marketplace.

3.1.2 Scope

i) System boundaries

To subserve the purpose of this research with the synchronous consideration of the limitations and obstacles, the method, the FU and the system boundaries need to be elucidated. These are included at this section, the scope definition. ISO 14044:2006 [61] has specific requirements about the key elements of the scope. Initially, the functional unit (FU) must be determined. In the case of this investigation, 1 kWh of the electricity produced by the farm during its lifetime is used as the FU. This FU is selected in order to i) make the results between the two examined cases and with the rest results of the literature, comparable, ii) stress to the differences with other results from literature that are coming from the assumption of the highest nominal power (15MW), and therefore higher electricity production, iii) see the environmental impacts in relation with the product finally gained by people. In other words, the impacts are defined relatively with the energy that profits society.

Besides the FU, the system boundaries were defined. ISO 14044:2006 [61], provides an accurate configuration for buildings life cycle, however, some modifications were required for the floating offshore wind technology. It is noted that the studies at the state-of-the-art don't follow the same convention in the names of the stages and the selection of the stages with ISO or among themselves. This technology differs from a building in the design, the physical site (sea/water element), technical issues, mechanisms etc. For the needs of this research, the initial consideration about the life stages, are described schematically at ***Figure 1.3***. It is considered a cradle-to-grave system that starts from the extraction of raw materials and ends-up with the end-of-life of the wind farm.

In ***Figure 1.3*** the first seven stages represent the first two main stages, "product" and "construction", in the LCA method according to ISO [45] and Kathrina's book [57] (illustrated stages at **Figure 3.*1***). The "Extraction of raw materials", the Transportation between the extraction site to the production site (T_1), the "Production/Fabrication" represent the stages "Raw material supply" (A1), "Transport" (A2) and "Manufacturing" (A3). The transportation from the production site to the assembly site (T_2), the "Assembly", the transportation from the Assembly site to the installation site (T_3) and the "Installation" represent the stages "Transport" (A4) and "Construction + Installation" (A5). It is noted that the transportation that joins the production site with the assembly site (T_2) is the stage "Transport to final location" at the ref. [33].

The next main stage concerns the "use" of the examined system. Stage "Operation/Maintenance" includes the B2-B4 suggested stages by ISO which are "Maintenance" (B2), "Repair" (B3) and "Replacement" (B4). The suggested stages from ISO, "Use" (B1), "Refurbishment" (B5), "Operational energy use" (B6), and "Operational water use" (B7), stages are not in the examined system, as other LCAs investigations, due to their trivial contribution as the examined system concerns a renewable energy generator.

Last but not least, is the last main stage, "End-of-life" (C). At ***Figure 1.3*** "Decommissioning" and transportation from the site of the park to the landfill (T_4) are the "Demolition" (C1) and "Transport" (C2), respectively. Transportation from the site to the landfill (T_4) contain the transport only to the landfill, and not to recycling factories etc., for simplification reasons and to be in line with other studies and life cycle inventories. “Waste processing” (C3) and “Disposal” (C4) are not taken under consideration.

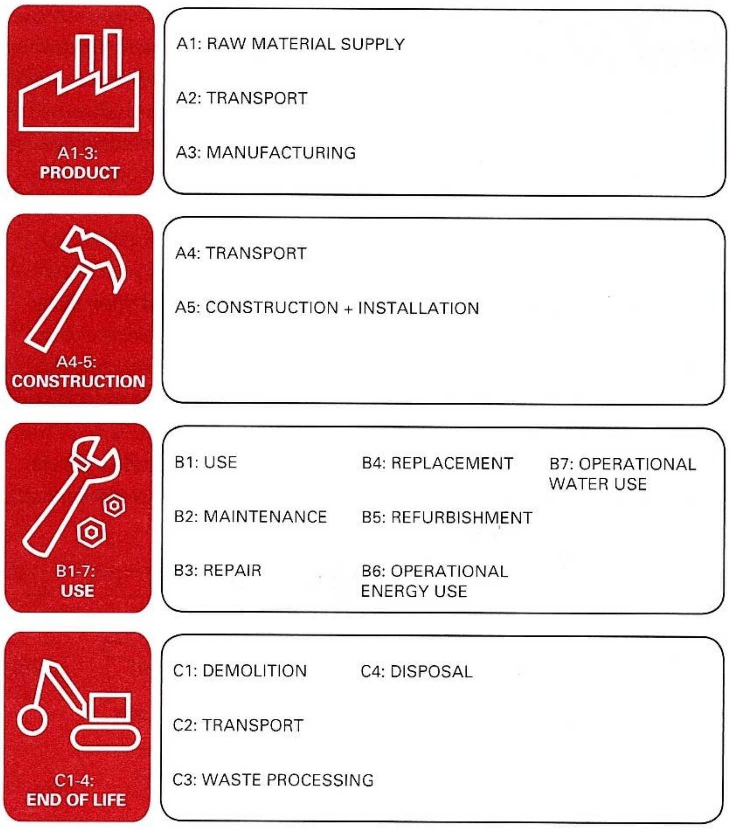

Figure 3.1: *LCA scope in building life cycle [57]*

Finally, the determination of the stages for the purposes of this examination, was assumed by taking into consideration the lack of appropriate data, the formation of the obtained data and the need of making the results comparable with other studies. First of all, the emissions from the three first stages, “Extraction of raw materials”, transportation from the extraction site to the production site (T_1) and “Production/Fabrication”, are considered together at the Ecoinvent database and they can’t be divided. In addition, in the literature, stages “Assembly”, transportation from assembly site to installation site (T_3) and “Installation” are merged into one stage which is named “Installation”. In literature [42], data for this stage are obtained from studies that examine bottom-fixed offshore wind turbines where the “Assembly” is part of the “Installation” and is taking place at the farm site so that might be the reason of merging these lifespan phases. Additionally to the above, the terminology of these stages isn’t in line with ISO. Thus, the final considered system boundaries for a baseline scenario are depicted at the **Figure 3.*2***. The system boundaries are modified where it is appropriate for the two concepts.

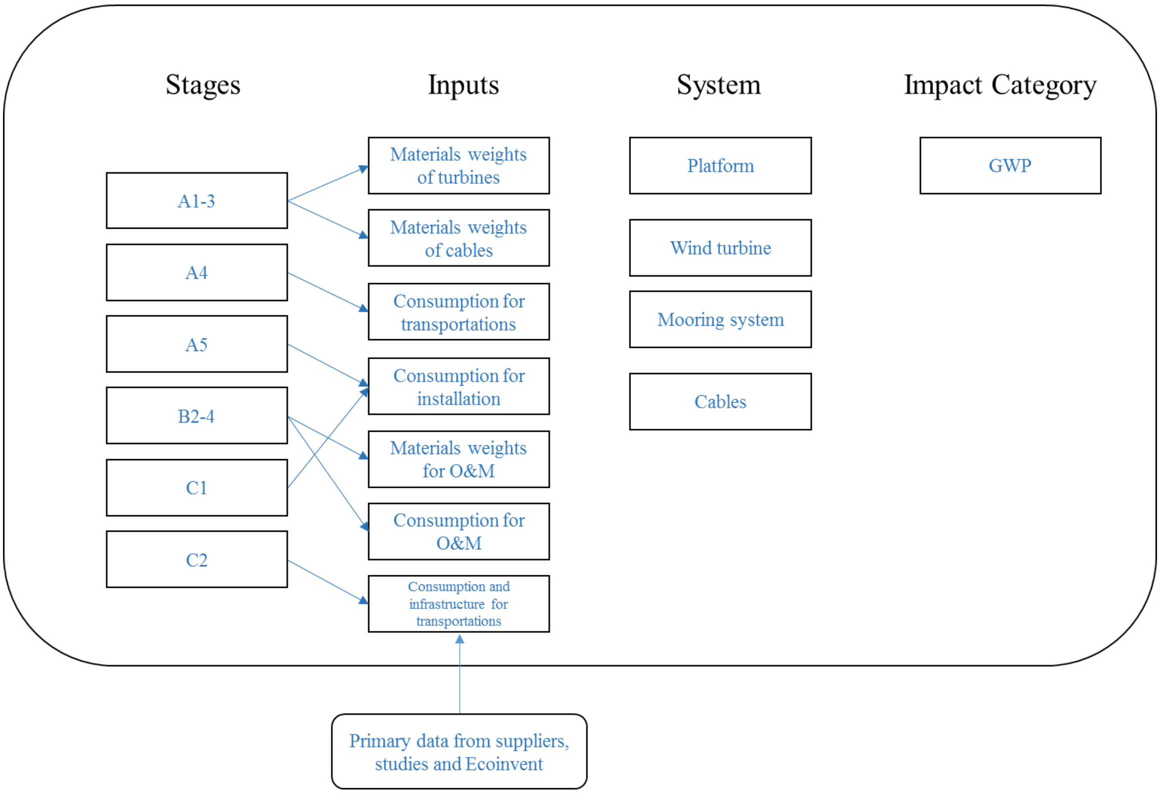

Figure 3.2: *System boundaries*

According to ISO [45] and Kathrina's book [57] the definitions of the stages that are examined in this research are:

- A1: Raw material supply
- A2: Transport
- A3: Manufacturing
- A4: Transport
- A5: Construction and Istallation
- B2: Maintenance
- B3: Repair
- B4: Replacement
- C1: Demolition
- C2: Transport

Where A1, A2, A3 are merged to A1-3, B2, B3, B4 to B2-4 and C1, C2 to C1-2 due to the data formation and the nature of the project.

ii) Wind farm components

By applying these stages and by doing modifications where necessary, two case studies were examined. The examined cases are two floating wind farms consist of one 15 MW windmill and the necessary cable. The windmill consists of a floating platform, a wind turbine and the mooring system. The cable is a High Voltage export cable which transfer the electricity from the wind turbine till the grid connection of the Crete in shore. The main difference in the two cases is the floating platform, where the first platform (Platform A) is made from steel and for the second case (Platform B) the concrete material is, mainly, used.

The decision for the type of platforms was determined with specific criteria. An extensive assessment was made for the decision of steel platform since there are different options. The most popular floating platforms at the marketplace, recently, are the Spar (Hywind Scotland by "Equinor") type platforms and the Semi-Submersible (Windfloat project by "Principal Power"). The main materials of these support structures are steel and iron. The impact results of these two platforms in literature [30], [34] are close and only one of these is enough for a comparison with a concrete support structure. Raadal et. al. [30] mention that their reference Semi-Submersible platform (UMaine Semi-S) it is found to have more CO_2 emissions than the other examined concepts. In comparison to Spar platform, which is the next more effective case at GWP, it is found to have 6.1 g CO_2-eq/kWh less than Semi-S. According to the same authors, the energy performance is, also, the worst at the Semi-S case. Moreover, according to Garcia-Teruel et. al. [34], at the most of the examined impact categories, Semi-S substructure, seems to have lower environmental performance at the total amount of each category than the Spar. Hence, it is an environmental conservative choice to investigate the Semi-Submersible concept. In addition to the environmental performance, accurate and real data was found for the semi-submersible concept to apply the LCA model. On the other side, the concrete material isn't widespread for the wind turbines platforms. Examples of this technology are the Spar platform of Hywind Tampen project by "Equinor" and the Sath platform by "Saitec". The Sath platform is considered for this study due to the accurate data from the "Saitec" company. Conclusively, the two different support structures that are investigated are: i) Semi-submersible, iii) Sath.

The description of the investigated **Semi-Submersible** platform is derived from the technical report [79] of National Renewable Energy Laboratory (NREL). At the report there are data for the University of Maine (UMaine) VolturnUS-S platform that is designed to support a 15 MW wind turbine. This Semi-Submersible platform is a four-column (three-radial and one central) steel Semi-Submersible platform (**Figure 3.*3***).

Figure 3.3: *Semi-Submersible UMaine's University [80]*

About the **Sath** concept, data were obtained from Saitec company [81]. This platform is an innovative solution that can make use of local materials and manufacturing processes. The floater consists of two horizontal twin hulls made of concrete, a steel frame structure, a transition piece to allow the tower of the turbine to be joint, a heave plate to reduce the vertical motion and a single point mooring (**Figure 3.*4***). **Figure 3.*5*** depicts an assembled wind turbine with the Sath platform.

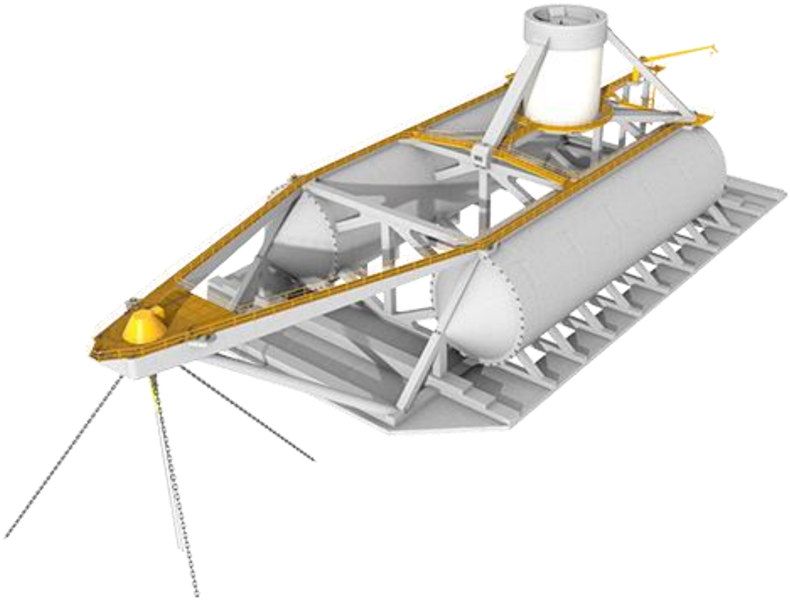

Figure 3.4: *Saitec's platform*

Figure 3.5: *Windmill with Saitec's platform*

The reference **turbine** that will be assembled on the platforms is the same for the two cases. The IEA-15-240-RWT that is described at the technical report [82] of the International Energy Agency (IEA) it is used. A modification is conducted at ref. [79] on the tower mass due to the different needs of the floating platform instead of the bottom-fixed (monopile). The turbine's nominal power was decided to be **15 MW** in order to follow up the forthcoming commercial projects (V236-15 MW wind turbine by Vestas, Geroa and Cademo projects by Saitec) that increase the current nominal power and produce more energy. Furthermore, this selection follows the rapid growth of this technology.

iii) Ecoinvent values

For these constructions, the environmental factors were derived from the version 3.8 (v3.8) of the Ecoinvent database. The Ecoinvent database is also preferred from most of the literature. The widespread use of the Ecoinvent makes the investigation comparable with literature. The database is internationally and scientifically recognized and it is worth to utilize the access to these Ecoinvent database. The v3.8 is the latest of the Ecoinvent. This version is the only one which includes the system model "Allocation, cut-off, EN15804". The version also includes enhanced documentation with 360 new datasets and 700 updated datasets for various sectors (metals, electricity, electronics etc.). It is a calculation tool that is in accordance with the GHG protocol [83] and it has factors particularly for the GWP. GWP100 (global warming potential) values are the base for the factors that are derived from the IPCC 2013 AR5 report [84]. Factors represent the electricity end consumers and refer to the location-based reporting method. Moreover, CML (v4.8 2016) and EF (v3.0, and adapted for EN15804) were added to LCIA methods where the GHG emission factors are mentioned.

From Ecoinvent database, the "Allocation, cut-off, EN15804" and the LCIA data were used. This dataset expresses the ISO 21930 and EN15804&A2:2019 that can be used for EPDs. This model is a cut-off model and is suitable for our study. Cut-off approach has widespread application [85]. By-products of waste treatment processes are cut-off, based on the end-of-waste criteria of the European Waste Framework Directive. The "Allocation, cut-off by classification" could also be used and there isn't a big discrepancy in values. However, it is preferred to be in line with EU rules and suggestions. The other models, "Undefined", "Allocation at the point of substitution" and "Substitution, consequential, long-term" are judged irrelevant with the study. This is due to the data formation and emissions contents. For instance, "Undefined" system model, includes gate-to-gate data. Gate-to-gate data include only a single step of the manufacturing of a product (i.e. extraction of raw materials) and data couldn't be matched with the components of the system. Moreover, in this system model, there isn't any calculation for the total GWP impact category. At the "Allocation, cut-off, EN15804" system model, the LCIA dataset were used since LCIA means Life Cycle Impact Assessment. At this dataset, the greenhouse gas emissions are gathered and are expressed in CO_2 equivalent (CO_2-eq). CO_2-eq express the GWP of various greenhouse gases in reference to the GWP of the carbon dioxide (CO_2).

iv) Site

For applying the Ecoinvent values, the site needs to be specific. Site selection is based on Greek data. The farm takes place on the Mediterranean Sea and specifically east of Crete (**Figure 3.*6***). Crete characterized by its offshore wind speeds and, generally, wind conditions (sea wind potential). Crete is a big region and a common touristic place. To maintain the high percentages of social acceptance in this region, to the offshore wind technology, and to be sure that ecosystem burdens from this technology will not affect tourist movement and therefore the future economy of the island, the determination of these burdens is necessary. From a technical point of view, the grid system in Crete is sufficient enough to be used for the energy distribution of high-capacity wind farms. The farm location of the investigated concepts is based on ref. [86] and it is the case EMA13. The water depth at the assumed location is 200 m and the distance from shore is around 21-50km.

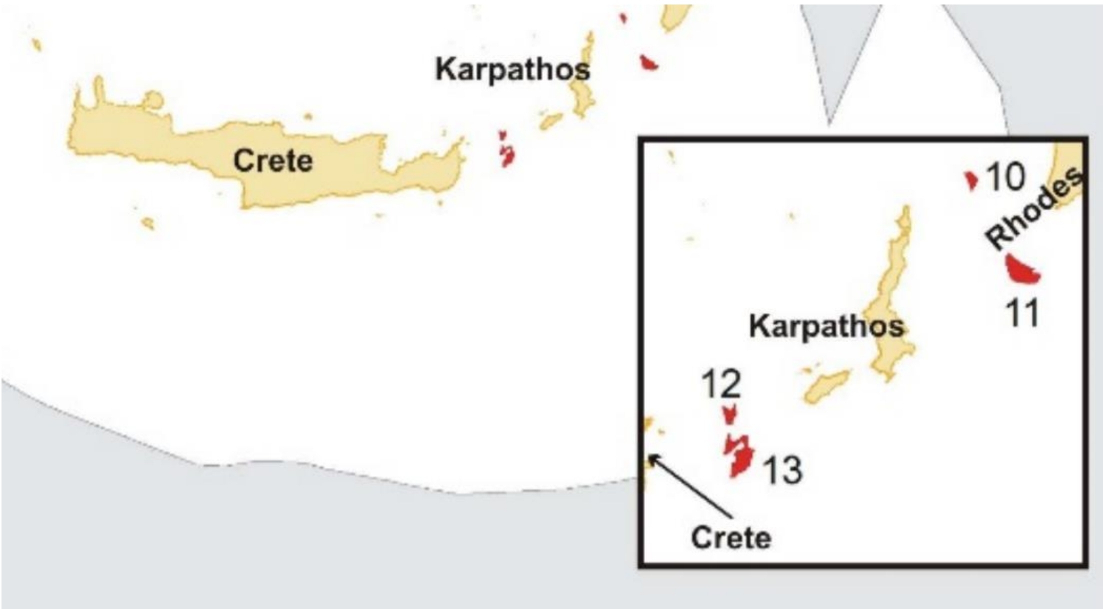

Figure 3.6: *EMA13 location [86]*

The site is, normally, related with the Capacity Factor (CF). The CF expresses the actual annual electricity generated by the turbine divided by the maximum amount of electricity that is possible to be produced by the turbine in a year (full load for the 8760 h of the year). In our case, the CF isn't calculated by applying equations and models for the geographical site. Is assumed a specific CF that is in line with literature. According to [34], an average CF, of the first 2 years of operation of an existing floating demonstration project (Hywind Scotland) is 53.8 %. However, Bang et al. [35], mention an achieved Capacity Factor of 65 % for the same park. They use this value (65 %) as the highest in their uncertainty analysis and a 35 % value as the lowest. At their baseline scenario a CF of 50 % is assumed. In the studies [33], [77], [85], [87] the assumed CF are 53 %, 34.2 %, 34 %, 51 %, respectively. Raadal et al. [30], assume 46 % CF for their baseline scenario and they conduct a sensitivity analysis with values from 27.6

% to 59.8 %. The papers [31], [34] and [42] use a range of 28-38 %, 39.6-50.2 % and 23-49 % respectively. Moreover, previous literature about bottom-fixed projects reports 38.4 % in average [88]. In conclusion, it was decided to use an average of 43 % for the CF.

To calculate the actual electricity generation the CF needs to be multiplied with the nominal power (15 MW) and the lifetime of the turbine. The decision making for the years of lifetime was based on the literature. Ref. [30], [33], [42], [85] consider 20 years lifetime and ref. [31], [34], [35], 25 years. Moreover, it has been observed [37], [39], that by increasing the lifetime, and therefore the total energy production, GHG emissions intensity is decreased. It may be, also, considered that floating offshore wind power is new technology that it is in trial level and there isn't a park that, already, reached its lifetime. Thus, there is uncertainty about the lifetime. As it stems from the above, considering a lifetime of 20 years is a canonical and conservative assumption for the examined wind farm.

With the afore-mentioned values of nominal power, CF and lifetime, the actual electricity generation of the wind farm it was estimated to be 1130040000 kWh (1.13 TWh). The formula below was implemented:

$$\mathrm{E} = \mathrm{Y} \cdot 8760 \cdot \mathrm{CF} \cdot \mathrm{NP} \tag{1}$$

where, E is the total electricity generation (in kWh), Y are the years of lifetime (20 years), 8760 is the number of hours in one year CF is the capacity factor (0.43) and NP is the nominal power (15000 kW)

The estimation of the electricity production is necessary since the FU of the investigation is 1 kWh. That means that the emissions from every calculation are divided with the total amount of the electricity to express the emissions per kWh energy generation. The process of calculating emissions from every stage is described below

3.2 Stage A1-3 – Raw material supply, Transport and Manufacturing

3.2.1 Ecoinvent coefficients

Specifically for this stage of the model, data are, mainly, derived from the reports [79] and [82] and from Saitec company. It is worth noting that information and data from some other studies are obtained and combined. This is because there isn't any accurate methodology for the determination of the environmental performance of this energy technology. It was decided to apply the LCA method with the materials data and to match them with the environmental factors from the Ecoinvent database [89]. This is because there is a lack of detailed EPDs (Environmental Product Declarations) documents (e.g. from EPD Norge or one click LCA) for this particular product (wind farm) and even for all the components of the wind farm. With this approach the study will give i) the opportunity to define more impact categories than GWP because of the material per material examination, and ii) the achievement of a clearer and accurate picture of the total system. It is worth noting that since there isn't any accurate methodology for the determination of the environmental performance of this energy technology, information and data from some other studies are obtained and combined.

Emissions from the life cycle phases of Raw material supply (A1), Transport (A2) and Manufacturing (A3) are included at the “market activities” datasets. For example, the environmental coefficients from the market activity dataset “market for steel, low-alloyed - GLO” contains an estimate of emissions from the extraction of raw materials (mining stage), from the pig iron production, from transportations to the factories/production sites and from the processes with which steel will take its final shape [90]. Besides the material production, some manufacturing processes for specific components were required. The “transforming” and “service” activities were utilized. According to Ecoinvent guideline, the activities for these manufacturing processes don’t include any transports or raw material extraction. The processes are considered to take place in the same place the production processes (emission factor for A2=0). Therefore, by using the “market activities”, and not the “transforming” and “service” activities, the data refer only to a larger region and they have larger uncertainties.

The uncertainties stem from the fact that each “market activity” represents the consumption mix of a product in a given geography. The aforementioned term “GLO” declares that the given geography is the world (GLO=global). For this investigation the RER (Europe) geography was preferred. However, relevant data are not available for every needed dataset. Therefore, the GLO or the ROW (Rest of World) geographies were utilized when necessary.

3.2.2 Components

The Ecoinvent values can be applied to specific materials. The wind farm is divided into components and their materials, for which weights and processes are defined. For the two cases (concrete and steel platforms), the materials, weights and processes related to each platform differentiates the emissions calculations. The two figures below (**Figure 3.*7*** and **Figure 3. *8***), are schematic overviews of the division of the two systems into components (left) and hints for the calculation process (right). The elements that differentiate the two cases are, also, depicted.

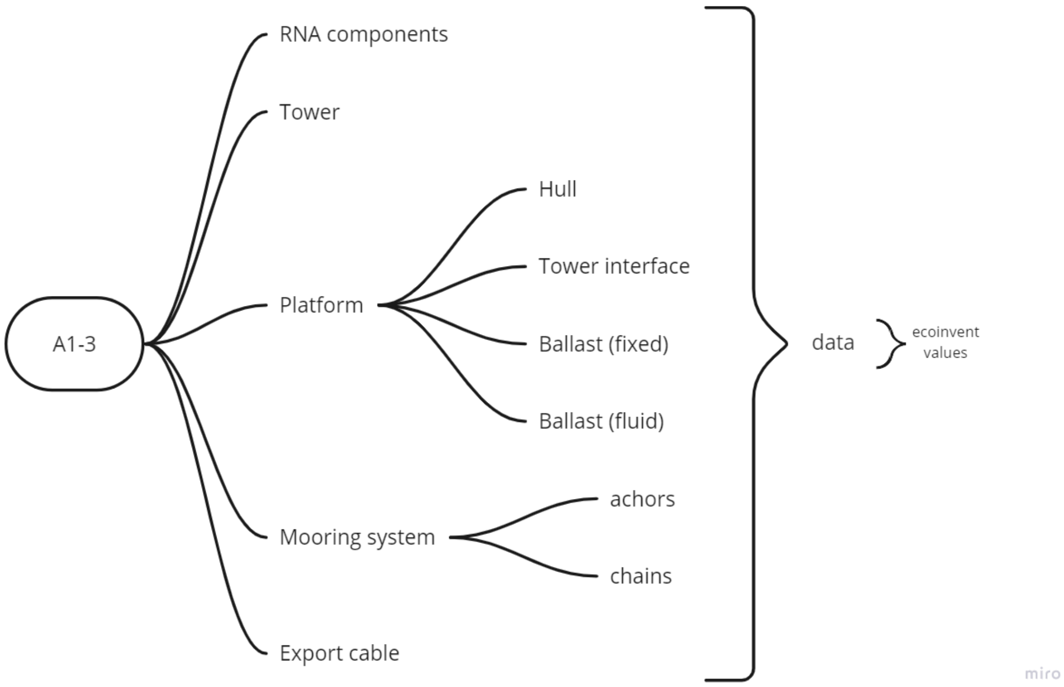

Figure 3.7: *Stage A1-3, components and calculations for the steel platform (Platform A)*

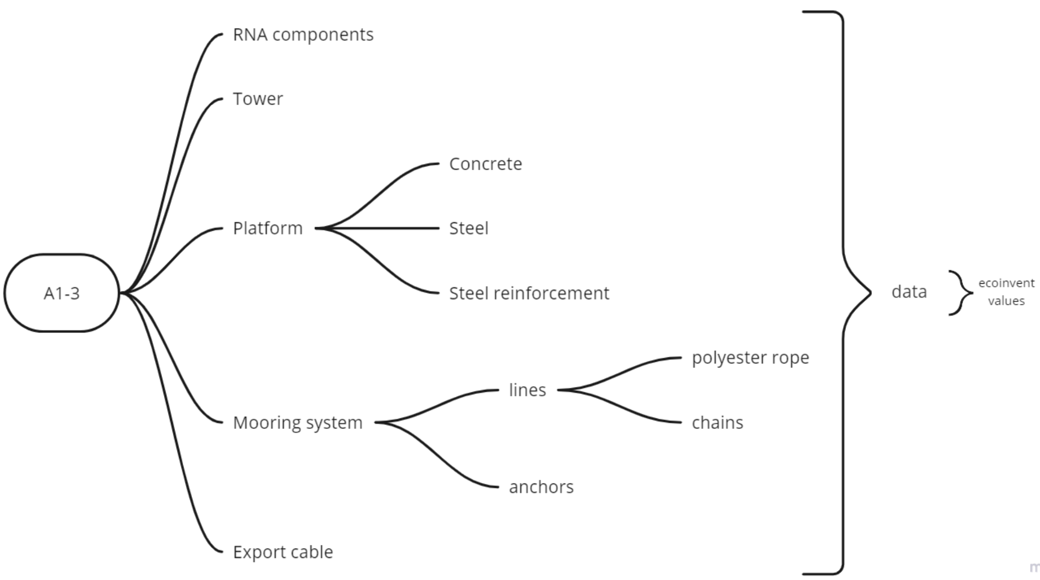

Figure 3. 8: *Stage A1-3, components and calculations for the concrete platform (Platform B)*

As described in the figures above, the main components of the system are: "RNA", "Tower", "Platform", "Mooring system" and the "Export cable". Each component has unique characteristics. ***Table 3* - *Table 9*** (pages 54-57), describe all the weights, the materials, the required manufacturing processes and the data sources for the two platforms. ***Table 3***, ***Table 4*** and ***Table 5*** are referred to the "RNA", "Tower" and "Export Cable" of the two platforms, respectively. The two cases have the same characteristics for these components. ***Table 6***, ***Table 7*** and ***Table 8***, ***Table 9*** are referred to the steel and concrete case, respectively. ***Table 6*** includes data for the "Platform A", ***Table 7*** includes data for "Mooring system" of the Platform A, ***Table 8*** describes the materials of the platform B without details and numbers since the data are confidential and ***Table 9*** has data for "Mooring system" of the Platform B.

i) RNA

The RNA is the Rotor-Nacelle-Assembly. It consists of the nacelle, the three blades and the hub (**Figure 3.*9***) which assembles the nacelle with the blades. For this investigation, the nacelle is subdivided into components as in ***Table 3***.

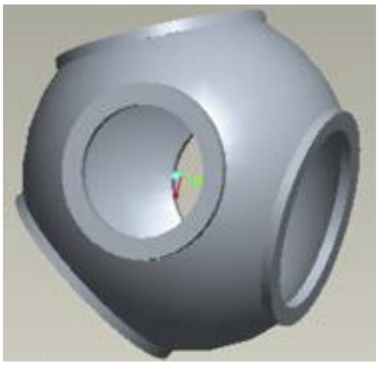

Figure 3.9: *Hub of a wind turbine [91]*

At ***Table 3***, for the reference turbine IEA-15-240-RWT, the distributions of the yaw system mass to ball bearing, drive and brake it is assumed to be equivalent with the 2 MW offshore wind turbine from ref. [39]. Moreover, the distribution of the Outer generator rotor to steel, iron, copper and magnet masses and of the Misc. equipment to "Transformer, low voltage" and "Power electronics", are assumed to be equivalent with the distribution at ref. [34]. In addition, blades contain 25 % of epoxy resin and 75 % of glass fibre reinforced plastic [92]. It can be seen, also, in ***Table 3*** *t*hat the lubricating oil isn't taken under consideration, because there are only small amounts in a turbine.

ii) Tower

The wind tower has a height of 135 m (**Figure 3.*10***). Its diameter is a function of height, and the relation is illustrated in ***Table 1***. The average diameter is calculated as the average of the maximum outer diameter and the top outer diameter. It is a steel wind tower (***Table 2***). The processes of "welding, arc, steel – RER" and "sheet rolling, steel – RER" were applied. For the welding length not only the tower's height was assumed, as [34], but welding for assembling sub-sections of the tower was also under consideration. According to Loukogeorgaki [93] the used sheets in a Bertsch Plate Rolling Machine are 3-6 m and the maximum value, 6 meters, is assumed as the length of metal sheets, L_s, for the welding calculation due to the project's dimensions.

It is worth noting that tower painting amounts [31] aren't taken under consideration due to their unsignificant value.

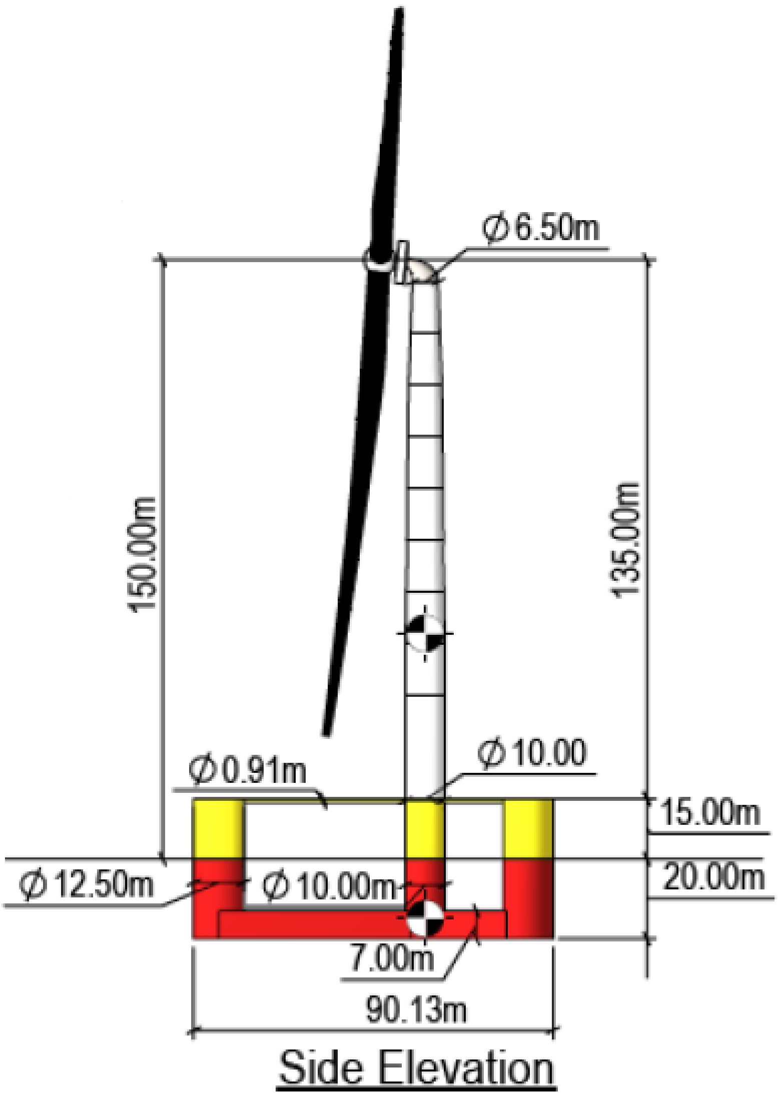

Figure 3.10: *UMaine's wind turbine with the components' dimensions [79]*

Table 1. *Tower Dimensions as a Function of the Height* [79]

Height [m]	Outer Diameter [m]	Thickness [mm]
15.000	10.000	82.954
28.000	9.964	82.954
28.001	9.964	83.073
41.000	9.967	83.073
41.001	9.967	82.799
54.000	9.927	82.799
54.001	9.927	29.900
67.000	9.528	29.900
67.001	9.528	27.842
80.000	9.149	27.842
80.001	9.149	25.567
93.000	8.945	25.567
93.001	8.945	22.854
106.000	8.735	22.854
106.001	8.735	20.250
119.000	8.405	20.250
119.001	8.405	18.339
132.000	7.321	18.339
132.001	7.321	21.211
144.582	6.500	21.211

Table 2. *Steel Material Properties for the Floating Tower* [79]

Parameter	Symbol	Value	Units
Young's Modulus	E	200e11	Pascals (Pa)
Shear Modulus	G	793e10	Pa
Density	ρ	785e3	kg/m^3

The welding length, L_{w_t} (718.2 m), was calculated as below:

$$L_{w\_t} = P \cdot \left(\frac{L_t}{L_s}\right) + L_t \tag{2}$$

where, L_{w_t} is the total tower's welding length, P is the average tower' s perimeter (25.92 m, **eq. 3**), L_t is the tower's length (135 m) and L_s is the length of metal sheets (6 m)

The tower's perimeter was calculated as:

$$P = \pi \cdot D_{t\_a} \tag{3}$$

where, D_{t_a} is the tower's average diameter (8.25 m, **eq. 4**)

$$D_{t\_a} = \frac{D_{max\_out} + D_{top\_out}}{2} \tag{4}$$

where, D_{max_out} is the maximum outer diameter (10 m) and D_{top_out} is the top outer diameter (6.5 m)

iii) Export cable

In other investigations for offshore wind [30], [31], [34], [35], two types of cables are considered. The one is the "Export cable" and the other is "Inter-array dynamic cable". In literature, these cables can also be observed as "High Voltage" and "Medium voltage" respectively [31]. The "Export cable" transfers the electricity from the substation, if existing, or from the park to the shore and the grid system. "Inter-array dynamic cable" connect wind turbines with each other and, potentially, with the offshore substation. Their length depends on distances between turbines and the substation where five rotor diameter is a typical distance [94]. A substation collects and export the power generated by the wind turbines.

There are investigations that examine only the turbines [77] without cables or a substation. In the examined case the export cabling is under consideration because of the importance in GHG emissions of the copper consumption [31]. Inter-array cables and a substation are considered unnecessary for the system. There is only one turbine and the inter-array cables are irrelevant. The farm doesn't need a substation due to the total low capacity of the farm (15 MW) [95]. The cabling materials were derived from ref. [96]. The length of the export cable is assumed to be equal with the distance from shore [31] plus two times the water depth. According to [86] the distance from shore may vary from 21 to 50 km. It has been assumed use the shorter distance for the calculations, 21 km. Therefore, the cable's length (CP) is the 21 km distance plus two time the 200 m water depth which is equal to 21.4 km.

iv) Platform A

The main characteristic of Platform A is that it is a steel platform. All the details were derived from report [79]. ***Table 6*** presents its characteristics. For the calculation of the welding length the inputs are: i) the diameter of the three buoyant columns, D_{b_col} (12.5 m), ii) the dimensions of the three rectangular bottom pontoons, 12.5-m-wide-by-7.0-m-high and iii) the diameter of the three radial struts, 0.9 m. The platform's welding length, L_{w_p}, was calculated to be 486.584 m by using the **eq. 5** below.

$$L_{w\_p} = P_{t\_col} + P_{pon} + P_{st} \tag{5}$$

where, P_{t_col} is the total perimeter of all the columns (235.619 m, **eq. 6**), P_{pon} is the total pontoons perimeter (234 m, **eq. 8**) and P_{st} is the total radial struts perimeter (16.965 m, **eq. 9**)

$$P_{t\_col} = P_{each} \cdot N_{col} \cdot N_{col\_s} \tag{6}$$

where, P_{each} is the perimeter of each column (39.270 m, **eq. 7**), N_{col} is the number of columns (3) and N_s is the number of sides (bottom and top, 2 in total)

$$P_{each} = \pi \cdot D_{b\_col} \tag{7}$$

$$P_{pon} = P_{sec} \cdot N_{pon\_s} \cdot N_{pon} \tag{8}$$

where, P_{sec} is the section's perimeter (38 m) which is a rectangular section with 12.5 m wide and 7 m high, N_{pon_s} is the number of pontoons' sides (right and left, 2 in total) and N_{pon} is the number of pontoons (3)

$$P_{st} = \pi \cdot D_{st} \cdot N_{st\_s} \cdot N_{st} \tag{9}$$

where, D_{st} is the struts diameter (0.9 m), N_{st_s} is the number of struts' sides (right and left, 2 in total), N_{st} is the number of struts (3)

v) Mooring system for platform A

The mooring system is catenary mooring system. It consists of three R3 studless mooring chains and three anchors. Mooring chains have a Dry Line Linear Density (DLLD) 685 kg/m and a length of 850 m each. Their total weight, W, was calculated to be 1746.750 t by using the equation below (**eq. 10**):

$$W = DLLD \cdot L_{moor} \cdot N_l \tag{10}$$

where, W is the total weight for the three lines, L_{moor} is the mooring chain's length (850 m) and N_l is the number of lines (3)

In contrast with Garcia-Teruel et al. [34], hot-rolled steel is assumed as the material, since Cheng et al. [97] use hot-rolled steel for their study for a mooring system. This is a conservative assumption because Ecoinvent value for “market for steel, low-alloyed, hot rolled – GLO” is higher than “market for steel, low-alloyed – GLO”.

It has been assumed the anchors type to be drag-embedded (**Figure 3.*11***) as it is observed in other floating concepts [34], [35]. Although Bang et al. [35] mention that the characteristics of the anchor are strongly related with the ocean floor, the assumption of a sustainable seabed was made for the park site. About their weight, in other studies, drag-embedded anchors weight 20 t [34] or 30 t [35]. Anchors for semi-submersible concepts weight 45 t [30] or 31 t [31]. Finally, 30 t per anchor is assumed for the calculations.

Its main parts are the fluke and the shank. The fluke interacts directly with the ground and the shank connects the anchor with the mooring chain. For the welding length of the parts, the same approximation with paper [34] was made. The welding length is equal with the square root of the area that an anchor occupies in a transport vessel [98]. That is to say, that for every anchor, that takes 30 m^2 according to the research [98], the welding length, is 5.477 m. And for the three anchors that are in use, the total welding length is 16.432 m.

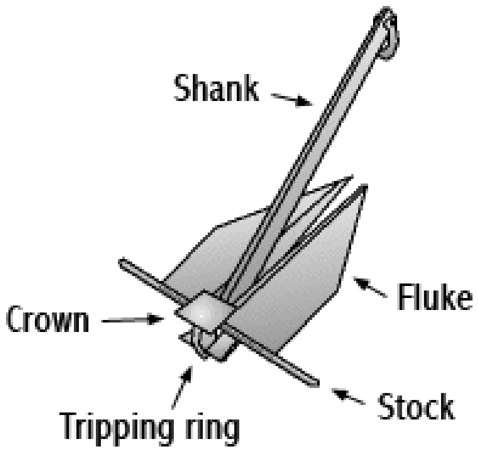

Figure 3.11: *Drag-embedded anchor [99]*

vi) Platform B

Data for the materials and its weights were derived from Saitec company [81]. No processes were assumed for the final formation of the platform as the concrete material is ready-mix in Ecoinvent database. The processes welding and sheet rolling are irrelevant with this platform because its main material is concrete.

vii) Mooring system for platform B

This mooring system is a single point mooring system. It consists of hybrid mooring lines, as another floating concrete platform from ref. [77]. The first "Sath" concept of Saitec [59], "demoSath", had six mooring lines and six drag anchors. The second "Sath" concept, "Blue Sath", had three mooring lines. The second Saitec's project has larger nominal power (10 MW) than the first (2 MW) and it is closer to the reference wind turbine (15 MW). In this research platform B has three lines.

There are two types of hybrid mooring lines, the lines that consist of chain and polyester and the lines that consists of chain and nylon [100]. The second material for the examined mooring system is polyester, as in study [101].

Saitec [81] provided accurate confidential data for the used materials and their weights. The lines, consist of one upper chain, a polyester rope and a lower chain. Each part has its own length, weight per meter of length and diameter. The derived data about these characteristics were based on metocean data for the specific site of the park.

Table 3. *RNA components data for A1-3, Platforms A and B*

Level	RNA component	Mass (t)	Dataset for materials	Dataset for processes	Notes
1	Blades	195.75[1]			Mass distribution [2]
1.1	Glass fibre Reinforced Plastic	146.81[2]	market for glass fibre reinforced plastic, polyamide, injection moulded – GLO[2]	-	
1.2	Epoxy resin	48.94[2]	market for epoxy resin, liquid – RER[2]	-	
2	Nacelle	820.89[1]			
2.1	Yaw system	100.00[1]			Mass distribution [3]
2.1.1	Ball bearing	53.93[3]	market for steel, low-alloyed – GLO[3]	steel turning, average, conventional – RER[4]	0.23 kg per 1 kg of the component is processed [4]
2.1.2	Drive	27.65[3]	market for steel, chromium steel 18/8 – GLO[3]	-	
2.1.3	Brake	18.42[3]	market for steel, chromium steel 18/8 – GLO[3]	-	
2.2	Turret nose	11.39[1]	market for steel, low-alloyed – GLO[4]	steel turning, average, conventional – RER[4]	0.23 kg per 1 kg of the component is processed [4]
2.3	Inner generator stator	226.63[1]			Mass distribution [4]
2.3.1	Structural steel	226.63[4]	market for reinforcing steel – GLO[4]	steel turning, average, conventional – RER[4]	0.23 kg per 1 kg of the component is processed [4]
2.4	Outer generator rotor	144.96[1]			Mass distribution [4]
2.4.1	Structural steel	41.61[4]	market for reinforcing steel – GLO[4]	steel turning, average, conventional – RER[4]	0.23 kg per 1 kg of the component is processed [4]
2.4.2	Iron mass	87.33[4]	market for cast iron – GLO[4]	-	
2.4.3	Copper mass	4.35[4]	market for copper, cathode – GLO[4]	-	
2.4.4	Magnet mass	11.68[4]	market for permanent magnet, for electric motor – GLO[4]	-	
2.5	Shaft	15.73[1]	market for steel, low-alloyed – GLO[3]	steel turning, average, conventional – RER[4]	0.23 kg per 1 kg of the component is processed [4]
2.6	Hub	190.00[1]	market for cast iron – GLO[3]	casting, steel, lost-wax – RoW[4]	The whole component is processed [4]
2.7	Bedplate	70.33[1]	market for steel, low-alloyed – GLO[4]	steel turning, average, conventional – RER[4]	0.23 kg per 1 kg of the component is processed [4]
2.8	Flange	3.95[1]	market for steel, low-alloyed – GLO[4]	steel turning, average, conventional – RER[4]	0.23 kg per 1 kg of the component is processed [4]

2.9	Misc. equipment	50.00[1]			Mass distribution [4]
2.9.1	Transformer, low voltage	47.50[4]	market for transformer, low voltage use – GLO[4]	-	
2.9.2	Power electronics	2.50[4]	market for electronics, for control units – GLO[4]	-	
2.10	TDO shaft bearing	2.23[1]	market for steel, low-alloyed – GLO[4]	steel turning, average, conventional – RER [4]	0.23 kg per 1 kg of the component is processed [4]
2.11	SRB shaft bearing	5.66[1]	market for steel, low-alloyed – GLO[4]	steel turning, average, conventional – RER [4]	0.23 kg per 1 kg of the component is processed [4]

Table 4. *Tower data for A1-3, Platforms A and B*

Level	Tower	Mass (t)	Dataset for materials	Dataset for processes	Notes
1	Tower	1263.00[5]	market for steel, low-alloyed – GLO [4]	welding, arc, steel – RER [4]	718.200 m welding length (calculated in the text)
				sheet rolling, steel – RER [4]	The whole component is processed [4]

Table 5. *Export cable data for A1-3, Platforms A and B*

Level	Export Cable	Mass (t)	Dataset for materials	Dataset for processes	Notes
1	Export cable	770.61			Mass distribution per km [6]
1.1	Copper	173.77[6]	market for copper, cathode - GLO	-	8.12 t/km [6]
1.2	Polyethylene	49.01[6]	market for polyethylene, high density, granulate - GLO	-	2.29 t/km [6]
1.3	Polypropene	32.96[6]	market for polypropylene, granulate - GLO	-	1.54 t/km [6]

1.4	Lead	206.51[6]	market for lead - GLO	-	9.65 t/km [6]
1.5	Steel	308.37[6]	market for steel, low-alloyed - GLO	-	14.41 t/km [6]

Table 6. *Platform A data for A1-3*

Level	Platform A	Mass (t)	Dataset for materials	Dataset for processes	Notes
1	Hull steel mass	3914.00[5]	market for reinforcing steel – GLO [4,5]	welding, arc, steel – RER [4]	486.584 m welding length (calculated in the text)
				sheet rolling, steel – RER [4]	The whole component is processed [4]
2	Tower interface mass	100.00[5]	market for steel, low-alloyed – GLO [4]	sheet rolling, steel – RER [4]	The whole component is processed [4]
3	Ballast mass (fixed)	2540.00[5]	market group for concrete, normal – GLO [5]	-	
4	Ballast mass (fluid)	11300.00[5]	-	-	

Table 7. *Mooring system data for A1-3, Platform A*

Level	Mooring System (Platform A)	Mass (t)	Dataset for materials	Dataset for processes	Notes
1	Mooring chains	1746.75[5]	market for steel, low-alloyed, hot rolled – GLO[7]	-	weight calculated is in the text with data from [5]
2	Anchors	90.00[8]	market for steel, low-alloyed – GLO[4]	welding, arc, steel – RER[4]	16.432 m welding length (calculated in the text) [4]

Table 8. *Platform B data for A1-3*

Level	Platform B	Mass (t)	Dataset for materials	Dataset for processes	Notes
1	Platform	Confidential [9]	-	-	-

1.1	Concrete	-	-	-	-	
1.2	Steel	-	-	-	-	
1.3	Steel Reinforcement	-	-	-	-	

Table 9. *Mooring system data for A1-3, Platform B*

Level	Mooring System (Platform B)	Mass (t)	Dataset for materials	Dataset for processes	Notes
1	Mooring lines	68.75			
1.1	Chain	68.52 [10,11]	market for steel, low-alloyed, hot rolled – GLO	-	Mass calculated in the text
1.2	Polyester	0.23 [10,11]	market for fibre, polyester - GLO	-	Mass calculated in the text
2	Anchors	90.00[8]	market for steel, low-alloyed – GLO[4]	welding, arc, steel – RER[4]	(30^0.5*3) welding length (calculated in the text) [4]

[1]: [82], [2]: [92], [3]: [39], [4]: [34], [5]: [79], [6]: [96], [7]: [97], [8]: [35], [9]: [81], [10]: [100], [11]: [101]

3.3 Stage A4 – Transportation to the construction site

3.3.1 Supply chain

i) Endpoint

For this stage, after assessing literature data, it was decided to make research about the supply chain. The research work [30] only takes into account the transport from shore to the wind farm which is 200 km. Investigations [31], [33], [42] assume 200-1500 km of transport without mentioning specific sites of manufacturing and resonate these numbers. In study [35], distances were calculated with the assumption that the supply of most of the components was made in Europe, specifically shipped from Rotterdam. Rotterdam is in Western Europe where there is a big market for offshore wind. More specific data were used in study [34], where the distances from the headquarters of the manufacturers to the site were calculated with GPS. Therefore, accurate data about the components supply from potential suppliers/manufacturers were collected in this examination. The transport distances were calculated with Google Maps [102] when there was a possible journey and with Google Earth [103] for some sea transportations.

Firstly, the endpoint of transportations needs to be defined. As assembly (or installation in other studies) port, the port of Heraklion is assumed. Heraklion is close to the wind farm site. The construction site includes the sub-areas (**Figure 3.*12***):

1. Heraklion port
2. Assembly site
3. Installation site / site of operation

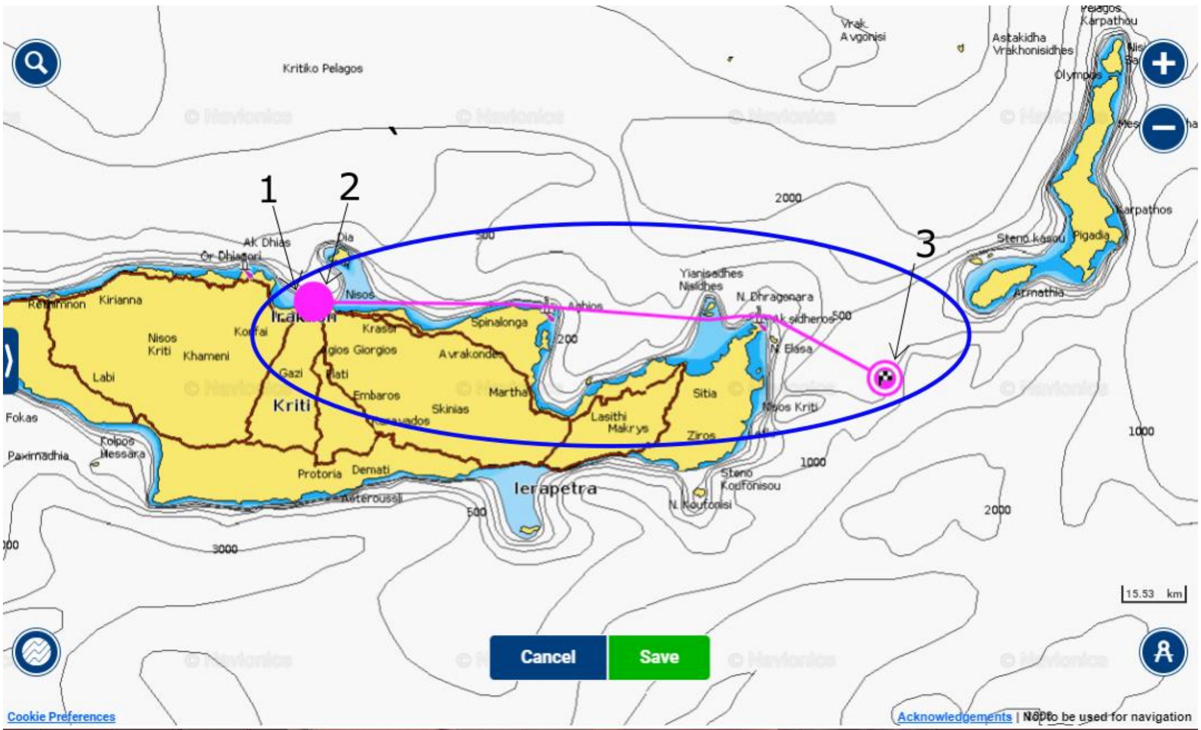

Figure 3.12: *Area of interest with Navionics map [104]*

Heraklion port can, potentially, meet the requirements of the investigated project. It is considered that this port has the required space for storage and assembly of wind turbines and the appropriate machines i.e. cranes. Potential issues of space limitation could be solved by a floating "extension" offshore of the port. However, there is a concern about the draft of the port. The maximum draft is 14.20 m [105]. The concrete platform has lower draft than 10 m [106] as its design with heave plates lead to stable structure without high drafts. On the other hand, semi-submersible case has 20 m draft [79]. In addition, this structure requires around five meters of Under Keel Clearance (UKC). According to ref. [107] and [108], vessels need at least 10 % of their draft or 1 m whichever greater, for port approach and more than 5 m in deep waters. If the floating platform is considered as a vessel close to the port, 2 m of UKC are required. In this particular case, even using a conservative value of 5 m UKC doesn't make a big difference in distances (**Figure 3.*13***). Therefore, for reasons of safety, a minimum depth of 25 m is decided.

This situation can be solved by using a floating crane for assembly and appropriate activities. To find the required position of the platform, the software Navionics [104] is used. This software presents the water depths at the sea around the world. The floating crane and the, temporarily, stabilized steel platform, will stand 800 m from shore (**Figure 3.*13***) where the water depth is the required one. The other components will be transferred from the port with a PSV vessel.

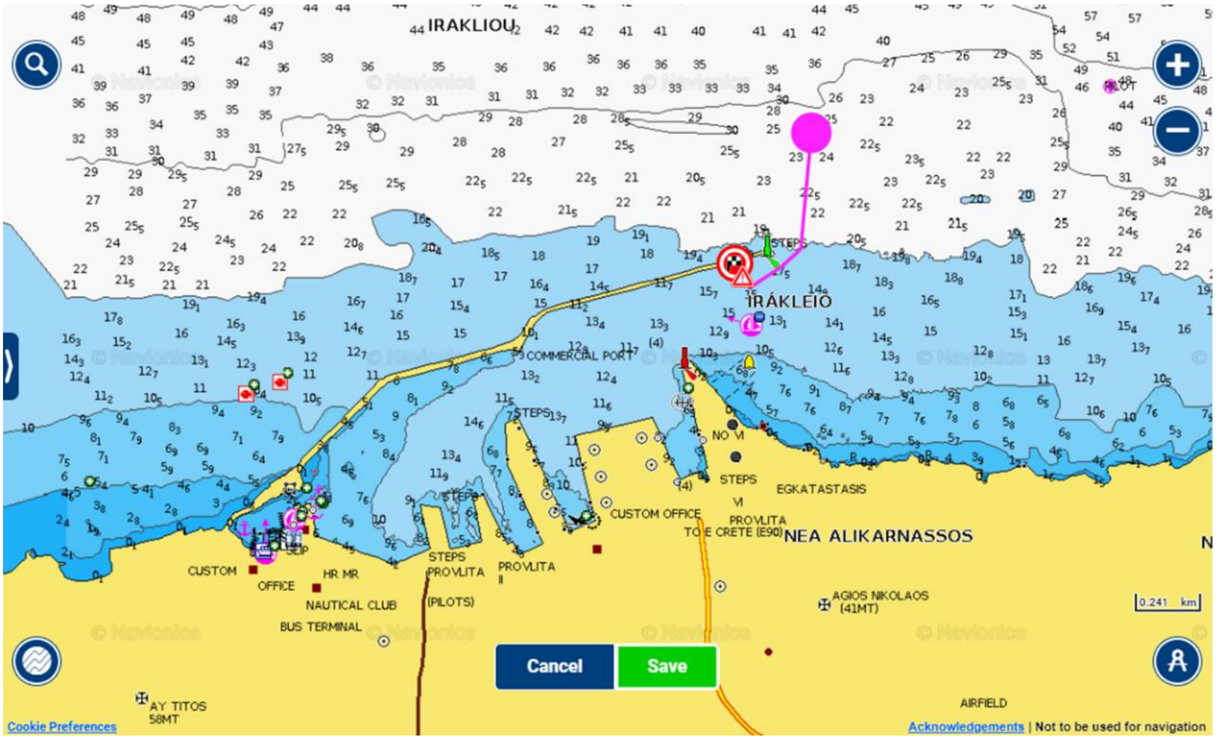

Figure 3.13: *Navionics calculations [104]*

Therefore, the final positions for the first case are as follows: i) the steel platform will be transported to its position offshore of Heraklion port, ii) the wind turbine components to the Heraklion port and iii) the cables will be transported to the park site where their installation will begin.

The second case, concrete platform, the platform will be manufactured at the Heraklion port. The nature of concrete material allows this assumption, and the transportations are considered as zero.

Another Greek port for such a large-scale project, could be the port of Alexandroupolis. In contrast with Heraklion port where the berths are dedicated to specific traffic, the berths in Alexandroupolis port, can handle general cargo and multi-purpose traffic. However, three reasons lead to choose the Heraklion port: i) the maximum water depth in Alexandroupolis, 13.7 m, is lower than Heraklion (14.2 m), ii) The total length of the berths, 3.715 km, is shorter than in Heraklion port (4.050 km) and iii) the port of Alexandroupolis is far from the installation site and the transport of the assembled wind turbines is considered to be dangerous and technically demanding in the Aegean Sea.

ii) Start point and distances

The start point of transportation is at the manufacturing site of each component. The Wind Europe's "Wind supply chain map" [109] (**Figure 3.*14***) were used for identifying the Europe's potential suppliers. The main criteria for choosing the supplier were its ability to produce the required dimensions for this, 15 MW, great nominal power.

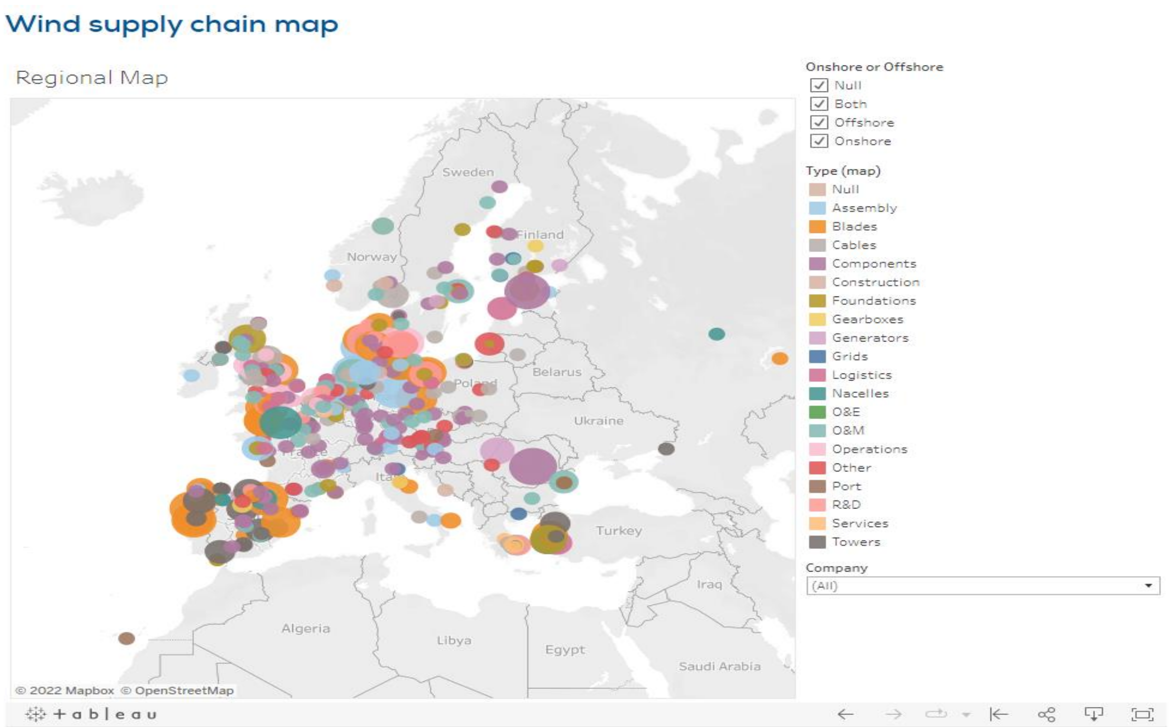

Figure 3.14: *Wind Europe's Wind supply chain map [109]*

A) Blades

Firstly, the blades are assumed to be produced in Nakskov, Denmark. The factory there is the only factory that develops blades for a 15 MW turbine. That is to say that in the web site of the company it is mentioned that this factory is now capable to handle 115.5 m blades of their 15 MW prototype wind turbine. This is only 4.5 m less than IEA Wind 15-MW reference wind turbine and is considered as acceptable discrepancy. There was one more company that has a project with 15 MW turbine (14 MW with a booster) but related data for manufacturing factories, were not found.

The distance was calculated with Google Earth [103]. The blades are considered to be transported only by the sea (**Figure 3.*15***). There are difficulties in carrying them by road because of the large dimensions. Turns in the route and route dimensions are deterministic conditions for the decision of transport manner.

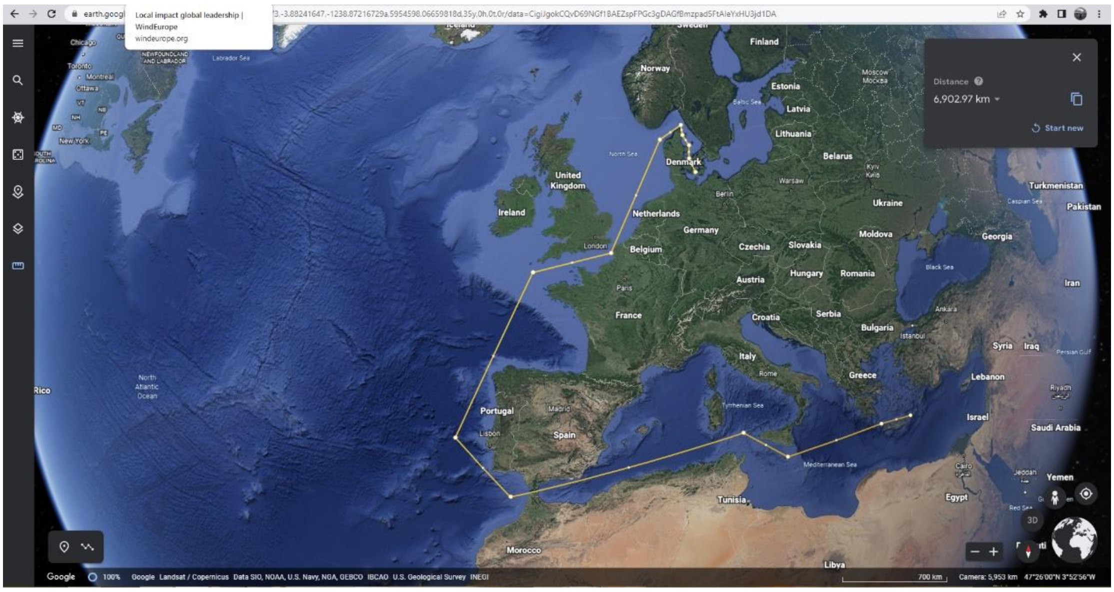

Figure 3.15: *Blades trip, calculated with Google Earth [103]*

B) Nacelle

The nacelle is assumed to be manufactured at Lindø, Denmark. The factory there is owned by the same company that produces the blades. These information about their 15 MW wind turbine project, were found at their website [110].

The distances by shore (**Figure 3.*16***) and sea (**Figure 3.*17***) were calculated with Google maps.

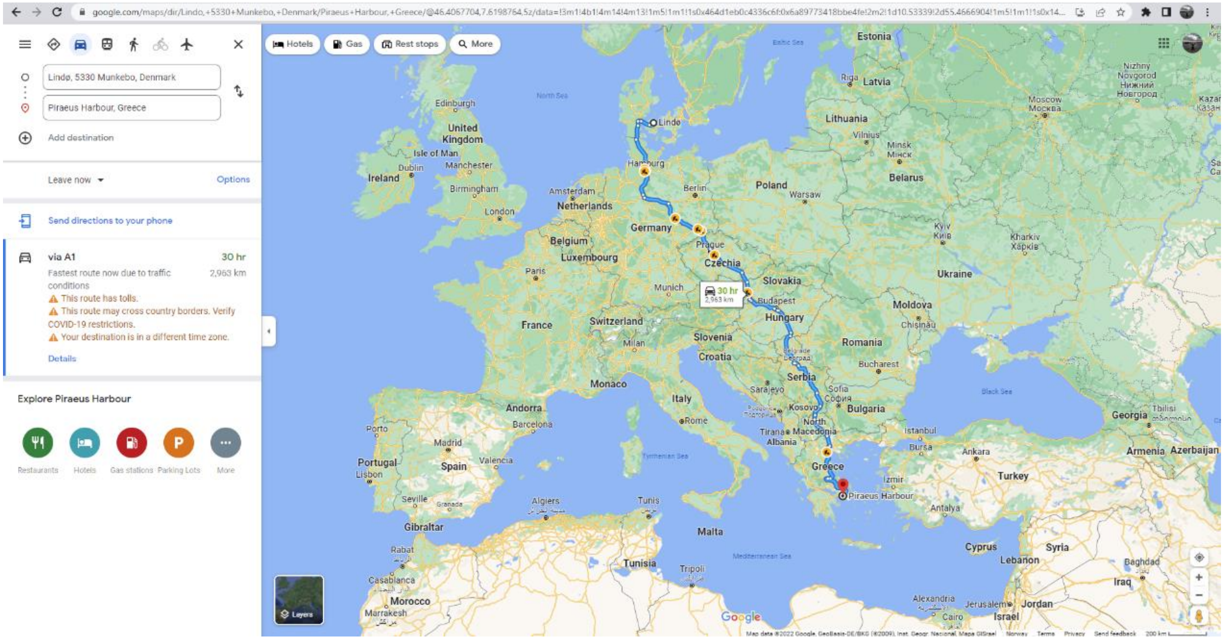

Figure 3.16: *Lindø to Pireus Harour (2963 km)*

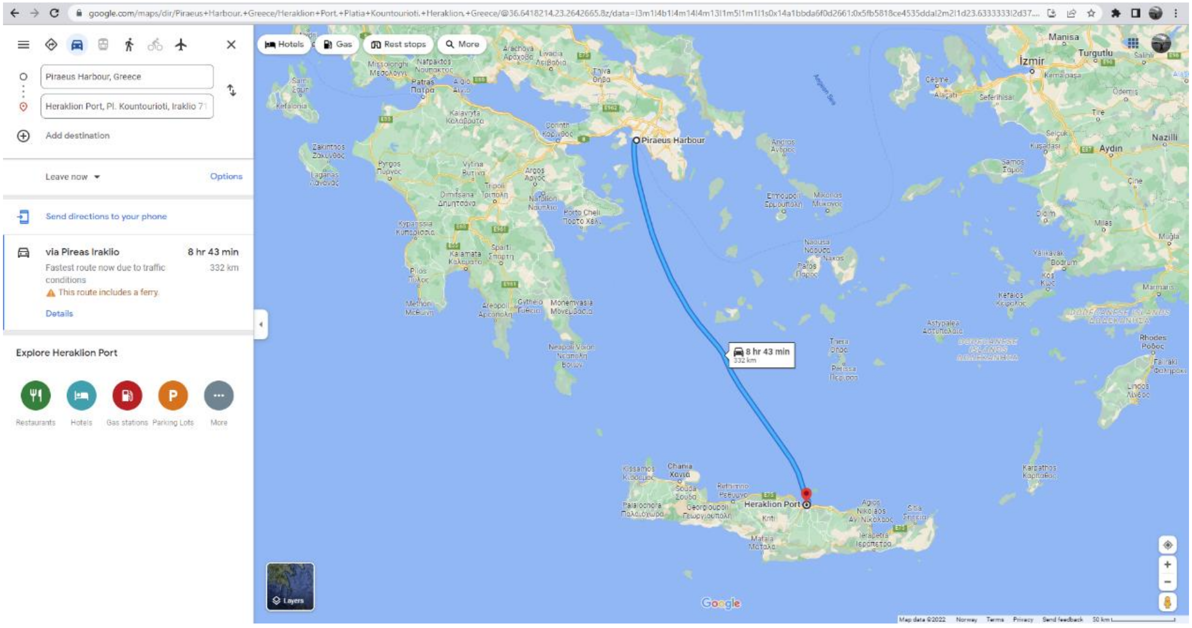

Figure 3.17: *Pireus Harbour to Heraklion port (332 km)*

C) Tower

The tower is assumed to be manufactured at Aliağa, Turkey. The aforementioned company, which is assumed to manufacture the blades and the nacelle, has agreements with another company that produces wind towers. Therefore, is assumed that for the 15 MW project, this company, that produces towers, will produce the tower. At Wind Europe's map [109], two factories of this company exist. The one is at Campbeltown in UK and the other at Aliağa in Turkey. The second has easy access to the sea by the Port of Aliağa. This is necessary due to the difficulties in transport of the wind tower with these great dimensions but, also, for the supply of raw materials (flanges and metal sheets) [1]. According to their website, the Turkish facilities, were constructed more recently (2018) than UK's and have the potential of growing. Thus, the Turkish location is assumed.

The total distance was calculated with Google Maps (**Figure 3.*18***) and Google Earth (**Figure 3.*19***).

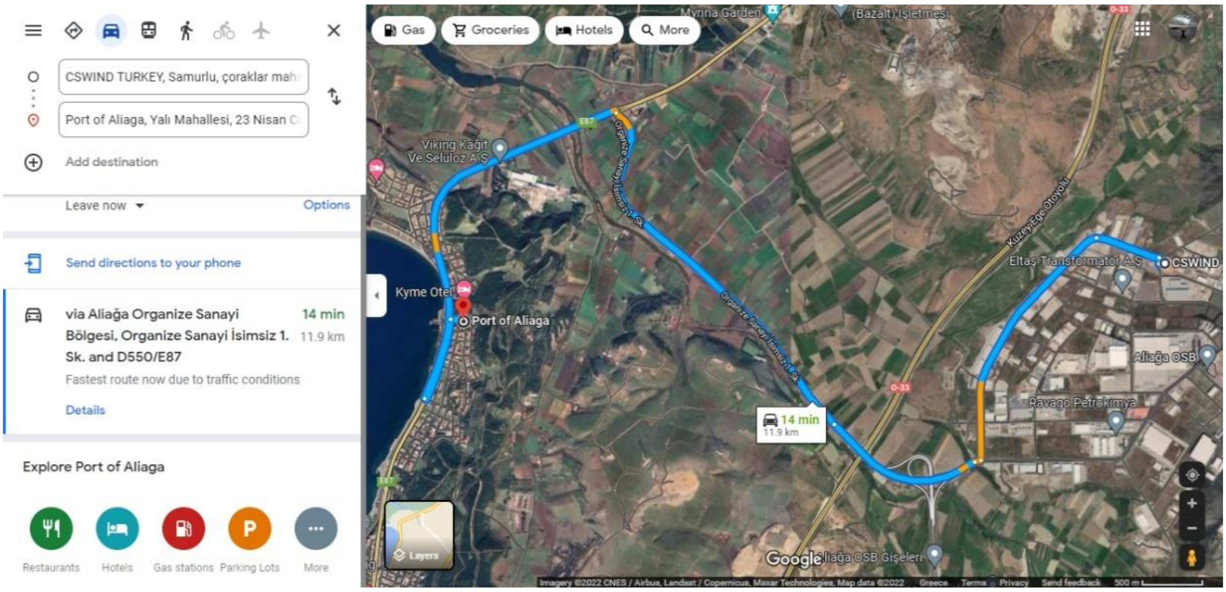

Figure 3.18: *Company's facilities to Aliağa port*

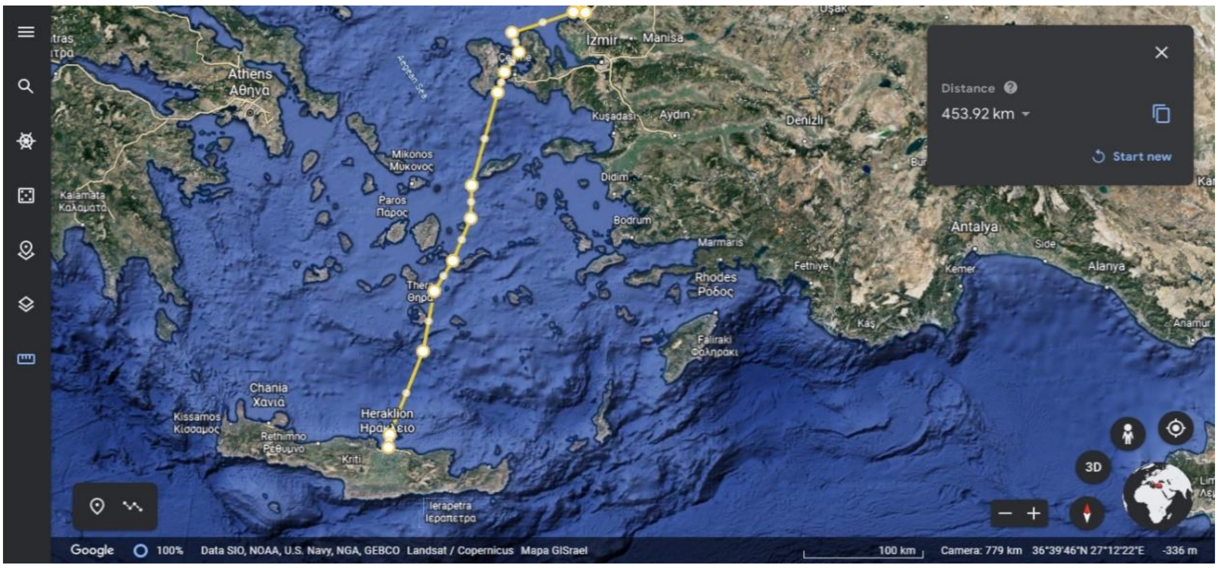

Figure 3.19: *Aliağa port to Heraklion port*

D) Platform A

The steel support structure (Platform A) is manufactured at Berth, Romania. The supplier there has undertaken offshore projects for oil and gas industry. It is assumed to be adequate for the production of this platform.

The journey from Berth to Heraklion port was conducted by sea (**Figure 3.*20***).

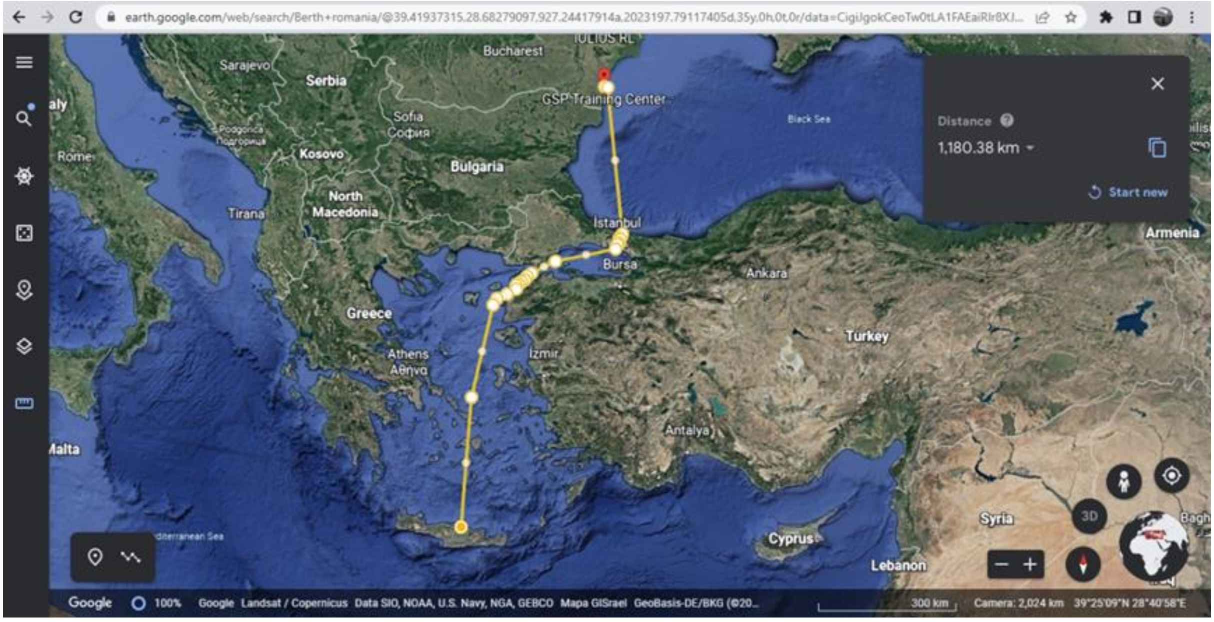

Figure 3.20: *Support structure's transportation from Berth to Heraklion port*

It is worth noting that for the production of the tower and the support structure, Volos port is, also, considered as a potential fabrication yard for this large-scale project. Article [111] is about future investments in Volos for floating wind energy. Towers and platforms for large-scale projects will, potentially, be constructed there. This can be considered as a second scenario for our calculations to enhance Greek economy and suppliers. However, the project hasn't started yet. Anyway, the choice of Volos over Aliağa and Berth for the transportation of the tower and the support structure, respectively, is estimated to have negligible contribution to the final result.

E) Mooring system

The mooring lines (chains and ropes) will be manufactured by a Greek company which has its factory in Thiva, Greece. This company supply R3 studless chains and ropes. Thus, it is assumed as sufficient for all the mooring lines of the examined systems.

The distances were calculated with Google Maps (**Figure 3.*21***) and Google Earth (**Figure 3.*22***).

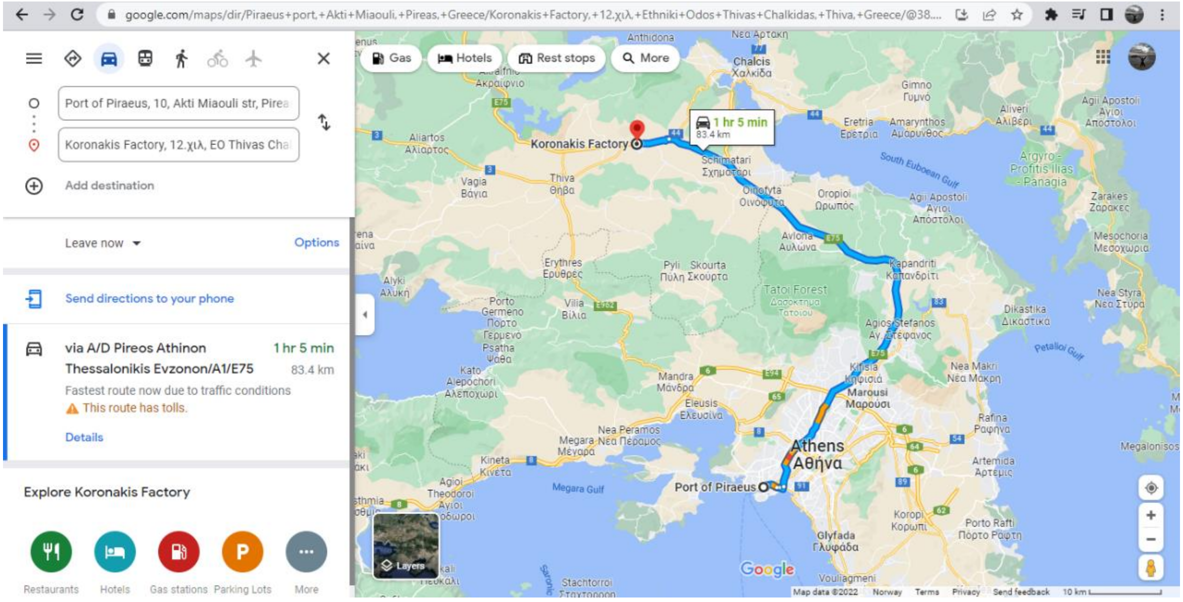

Figure 3.21: *Onshore required transportation from Thiva to Pireus port.*

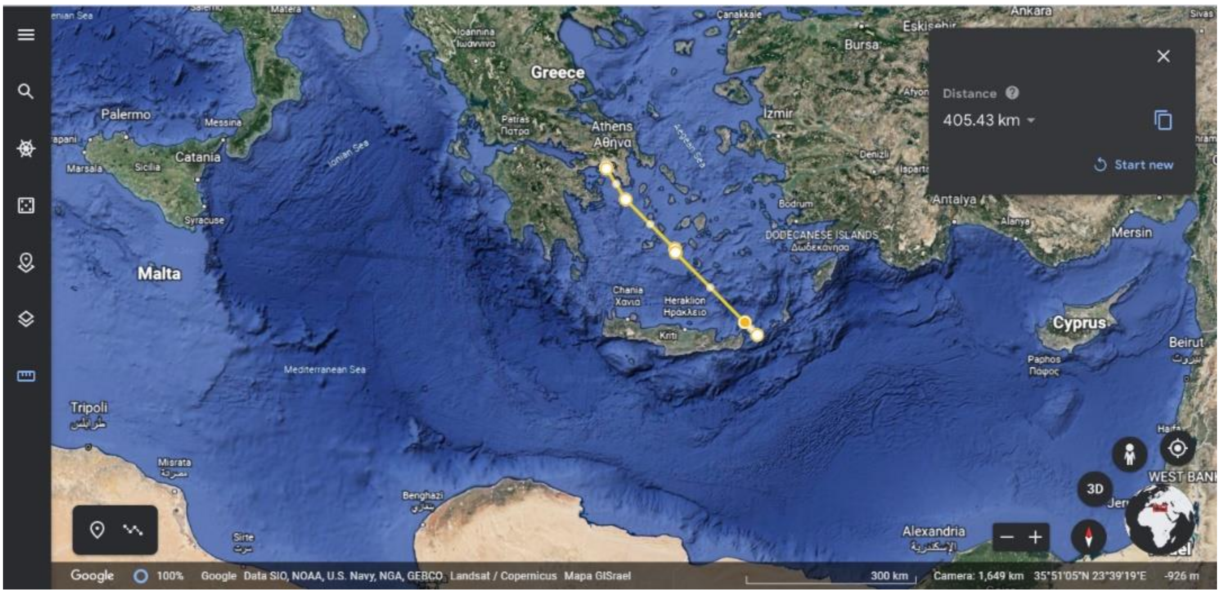

Figure 3.22: *Journey from Pireus port to the site of the park*

Anchors are produced by the same company as mooring lines. This company produces different types of heavy anchors.

Journeys are the same with **Figure 3.*21*** and **Figure 3.*22***.

G) Export cable

The last component of the system that should be transported is the export cable. Its production company has three cable production plants in Thiva and Corinth (Greece) and Bucharest (Romania), and one auxiliary production plant in Oinofyta (Greece). The Corinth production unit is one of the largest and most advanced submarine cable factories in the world. Therefore, Corinth is assumed as the start point of cables transportation.

The distance was calculated with Google Earth (**Figure 3.*23***).

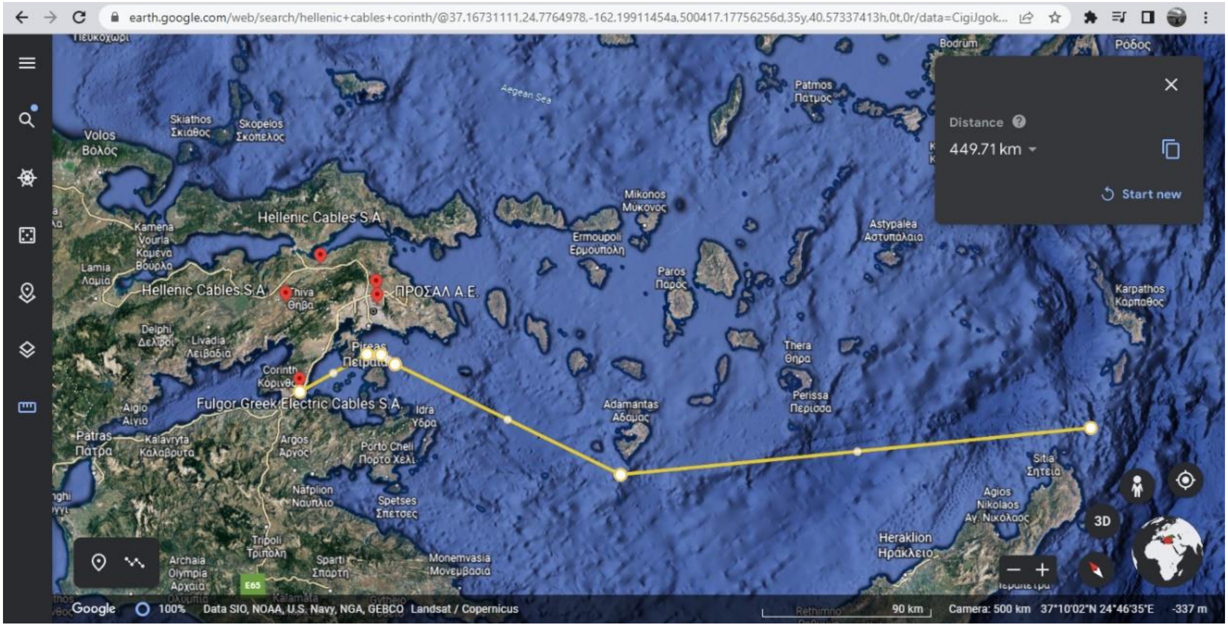

Figure 3.23: *Cabling transportation from Corinth to the site of the park*

3.3.2 Emissions calculations

i) Method A4- i

In the A4 stage the emissions from the transportation of all the components of the system to the "construction site" are investigated. For this stage, two methods were applied for reasons of comparability and accuracy.

The first method (A4-i) uses the inputs below:

- Freights
- Distance by sea
- Distance by shore
- Ecoinvent coefficient for "transport, freight, sea, ferry - GLO"
- Ecoinvent coefficient for "transport, freight, lorry >32 metric ton, EURO6 – RER"

From the first three inputs the tkm are calculated. Then, tkm are multiplied with the corresponding Ecoinvent value and then they are divided with the total amount of energy production of the turbine, to have finally the gCO_2-eq/kWh. **Figure 3.*24*** and **Figure 3.*25***, describe schematically this process for the Platform A (steel) and B (concrete), respectively.

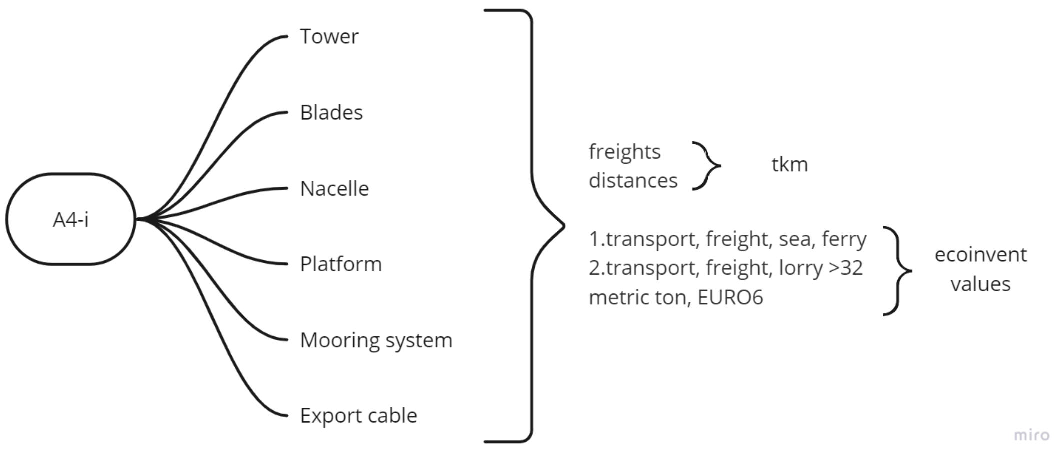

Figure 3.24: *A4 stage, method A4-i for Platform A*

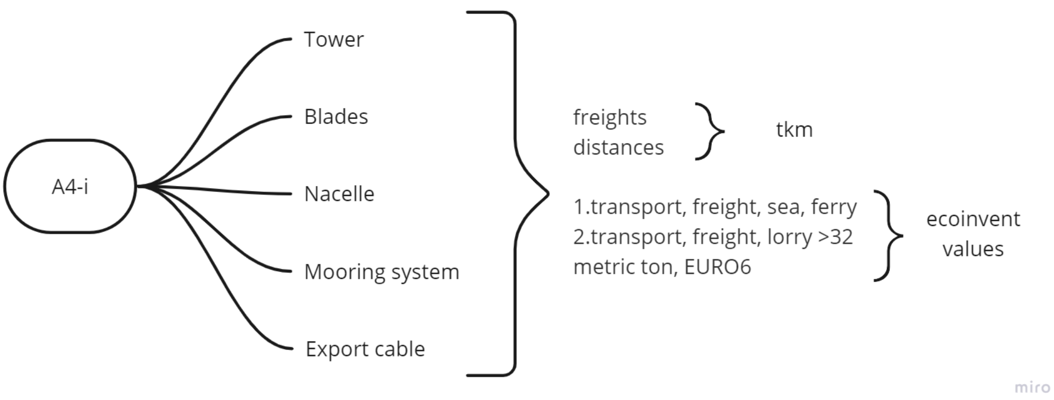

Figure 3.25: *A4 stage, method A4-i for Platform B*

Table 10 and ***Table 11***, below, show the inputs and the calculated tkm for the transportation by the sea and by shore, respectively. The calculated tkm in ***Table 10***, are multiplied with the Ecoinvent coefficient from the dataset “transport, freight, sea, ferry – GLO”. This dataset it is used by other studies, e.g. by Garcia-Teruel et al. [34], for the calculation of emissions for sea transport. This dataset has the same value with the dataset “market for transport, freight, sea, ferry – GLO” because the non-market dataset is used itself for the market dataset. Moreover, as paper [34] agrees, in comparison with “transport, freight, sea, container ship”, and “transport, freight, inland waterways, barge – RER”, ferry gives conservative results (more kg CO_2-eq per tkm). Furthermore, DWT (dead weight) (load capacity) of the ferry (1200 t) is lower than the used means of transport (the higher demand is for the platform transportation which weighs

around 4000 t) but is closer than the DWT of the reference container ships (43000 t) or barges (average load 852 t). Last but not least, barges represent transportations in canals and rivers and not offshore. It is worth noting that in previous Ecoinvent version, instead of the “transport, freight, sea, ferry – GLO” and “the transport, freight, sea, container ship”, the “transport, freight, sea, transoceanic ship” was existing.
The dataset includes not only the emissions from fuel consumption, but also emissions from the life cycle of the ferry. That is to say, that emission values from the production of the ferry, maintenance activities, transportation of materials, construction of the construction port and factors for empty trips during its 25-years lifetime are considered.
The calculated tkm in ***Table 11***, are multiplied with the Ecoinvent coefficient from the dataset “transport, freight, lorry >32 metric ton, EURO6 – RER”. This dataset has the same value with the market activity for this transport. The “EURO6” is the most recent European emissions standard (2014) which is referred to light passenger and commercial vehicles. In addition, most of the wind turbines’ components are more than 32 t and are transported around Europe.

Table 10. *Transportations by sea for A4-i*

Component	Freights (t)	Distance (km)	tkm
Tower	1263.00	450.00	568350.00
Blades	195.75	6900.00	1350675.00
Nacelle	820.89	330.00	270893.37
Platform	4014.00	1200.00	4816800.00
Mooring system	1836.75	330.00	606127.50
Export cable	770.61	450.00	346776.30

Table 11. *Transportations by shore for A4-i*

Component	Freights (t)	Distance (km)	tkm
Tower	1263.00	10.00	12630.00
Blades	195.75	-	-
Nacelle	820.89	3000.00	2462667.00
Platform	4014.00	-	-
Mooring system	1836.75	80.00	146940.00
Export cable	770.614	-	-

ii) Method A4-ii
About the second method for A4 stage, the inputs are:

- The specific vehicles that are in use (vessel or trucks)
- The approximate mean fuel consumption of the vessels and their mean speed (according to Ship Atlas [112])
- The approximate mean fuel consumption of a truck

- The type of the fuel (bunker or diesel)
- The distances
- The Ecoinvent values for “heavy fuel oil, burned in refinery furnace, Europe without Switzerland” and “diesel, burned in building machine, GLO”

By using the approximate mean fuel consumption, the speeds and the distances, the total fuel consumption in kg was calculated. This value is then converted in MJ by dividing with 0.0243 as Ecoinvent suggest. MJ reflect the energy produced by burning a certain amount of fuels. With MJ amount and Ecoinvent values for the burned fuels, the calculation of the total emissions was made. These emissions were divided with the total amount of energy production of the turbine (as in all stages) and result in the gCO_2-eq/kWh. **Figure 3.*26*** and **Figure 3.*27*** describe this process for the Platforms A (steel) and B (concrete), respectively.

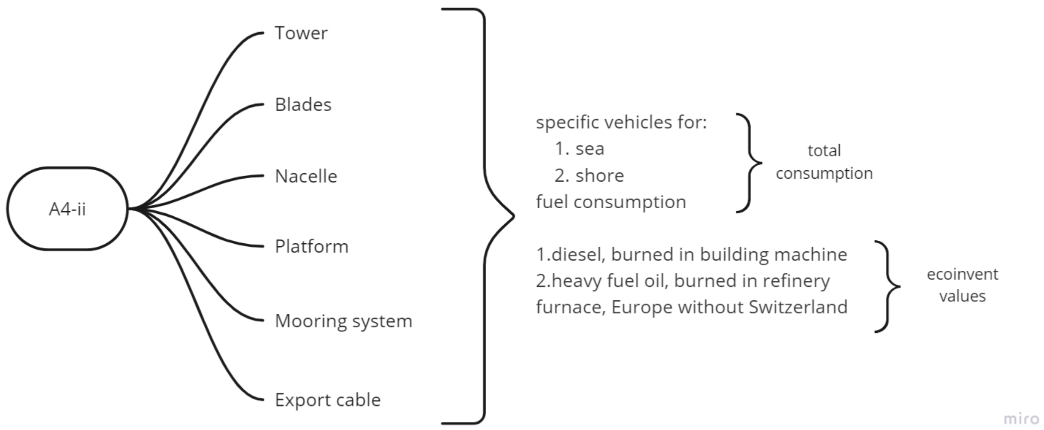

Figure 3.26: *A4 stage, ii method for Platform A*

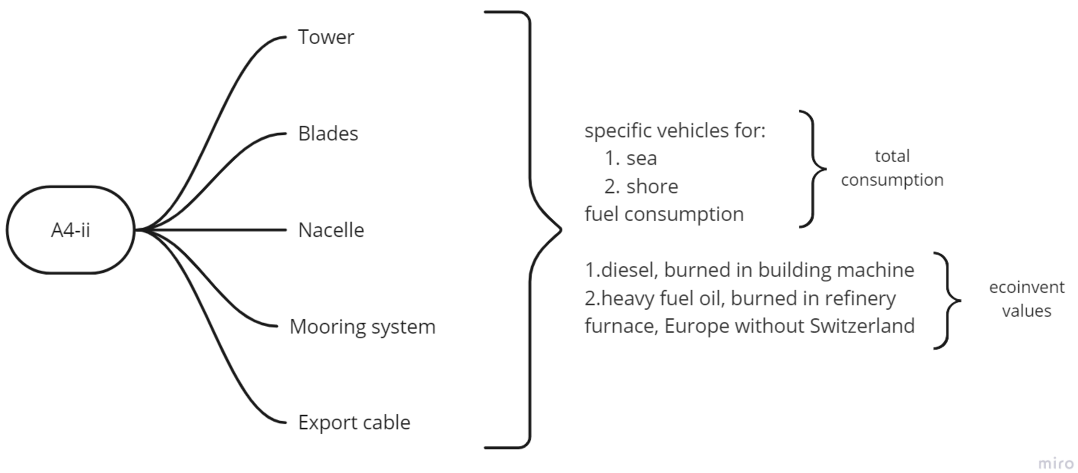

Figure 3.27: *A4 stage, ii method for Platform B*

Below, specific transport means for each component are described.

A) Blades

The blades will be transported with the IMO: 9770713. This is a general cargo vessel (**Figure 3.*28***) with deadweight (DWT) of 10624 MT [112] i.e. 9637.942 t (1 t = 1.10231 MT). The three blades weight only 195.75 t in total. That is to say that only the 2 % of the available DWT it is used. Besides the DWT, there is space limitation due to the shape of the blades. Here the assumption that the vessel it is used for other purposes (transportation of goods etc.), in addition to the transportation of the blades, is considered. Thus, the actual fuel consumption for the transportation of the blades is considered to be 50 % of the vessel total fuel consumption.

Figure 3.28: *Blades transportation with a general cargo vessel (IMO: 9770713) [113]*

B) Nacelle

Nacelle's components will be transported onshore by trucks (**Figure 3.*29***) and offshore by the IMO: 9805568 vessel (**Figure 3.*30***). The emissions from trucks were assumed to be equivalent with emissions from twenty-one 40-tons trucks. The number of the trucks was estimated taking into account the nacelle's weight which is 820.889 t (21 times larger than the capacity of 40 t). About the offshore transportation, the vessel is general cargo with DWT of 8100.262 t (8929 MT). It can be seen that the nacelle's weight is 10 % of the total capacity of the vessel. Thus, the same assumption as for the blades was made, i.e. the actual fuel consumption for the transportation of the nacelle is considered to be 50 % of the vessel total fuel consumption.

Figure 3.29: *Onshore transportation of nacelle*

Figure 3.30: *Loading of the nacelle to ROTRA VENTE for offshore transportation [114]*

C) Tower

The tower's sections will be transported with a truck for the short distance onshore (**Figure 3.*31***) and with the IMO: 9808845 by sea (**Figure 3.*32***). The emissions from the onshore transportation are considered as negligible due to the very short distance. About the sea transport, IMO: 9808845 is a general cargo vessel with 12753.218 t DWT (14058 MT) and the tower weights 1263 t which is the 10 % of the available DWT. Therefore, as with the blades and nacelle, the actual fuel consumption for transportation of the tower is considered to be 50 % of the vessel total fuel consumption, taking into consideration that the vessel is used for other purposes, in addition to tower transportation.

Figure 3.31: *Onshore transportation of the tower [115]*

Figure 3.32: *Tower offshore transportation [113]*

D) Platform A

The steel platform is transported by the “Black Marlin” vessel (**Figure 3.*33***). Its IMO number is 9186326. This vessel is a heavy load carrier with DWT of 51728.643 t (57021 MT). Besides the weight capacity, it is considered that it can carry only one platform per journey.

Figure 3.33: *Offshore transportation with Black Marlin of a semi-submersible oil and gas platform [116]*

E) Mooring System

The mooring system components will be transported onshore by trucks (**Figure 3.*34***) and offshore by an Anchor Handling Tug Supply (AHTS) vessel (**Figure 3.*35*** and **Figure 3.*36***). The emissions from trucks were assumed to be equivalent with the emissions from forty-six 40-tons trucks. The number of the trucks is selected according to total weight of the mooring system which is 1836.75 t (46 times larger than the capacity of 40 t). The AHTS vessel is assumed to be the “MP AHTS 1” (IMO: 9320910) which has a DWT of 2173.617 t (2396 MT). The total weight of the mooring system approaches the DWT; therefore, the vessel is assumed to carry only the mooring system’s equipment.

Figure 3.34: *Onshore transportation of mooring lines [117]*

Figure 3.35: *Mooring chains in a vessel [118]*

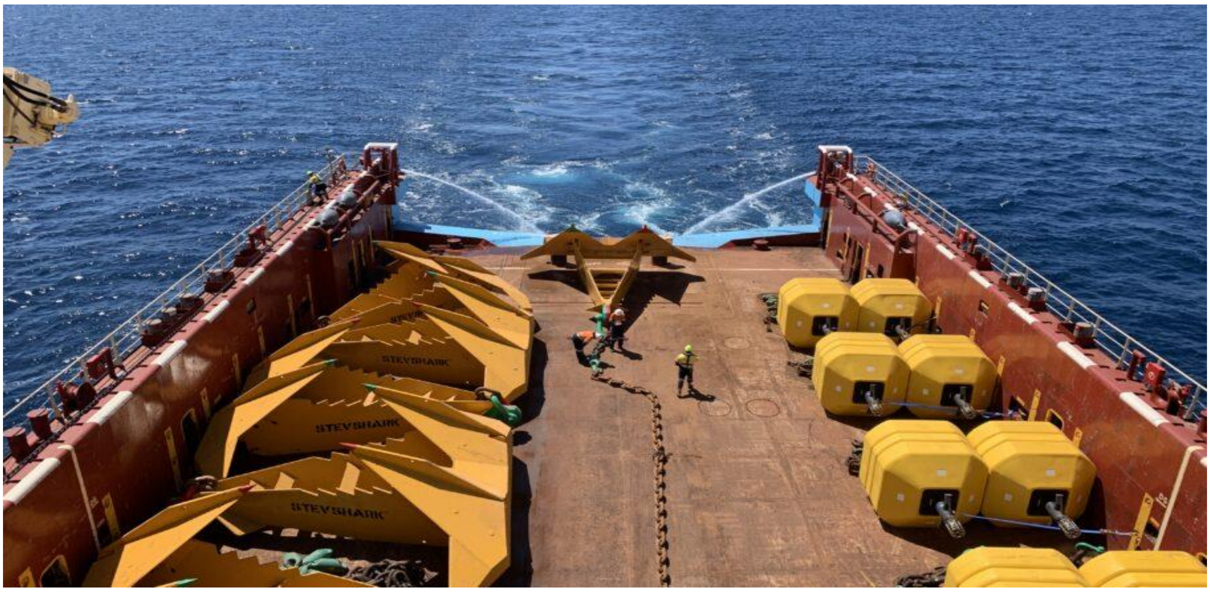

Figure 3.36: *Anchors transportation in a vessel [119]*

F) Export cable

The last transported component is the export cable. The export cable will be transported with the "ISAAC NEWTON" vessel (IMO: 9707297) (**Figure 3.*37***). This is a Cable Laying Vessel (CLV) with DWT of 12186.227 t (13433 MT). Here, the DWT is more than the transported freight, but the vessel is very specialized and it is assumed to carry only the cable for the examined wind farm.

CLV Isaac Newton has already been used in Greece by the company that is assumed to produce the cables. Specifically, it was used for the installation and protection of a submarine power cable between the island of Crete and the Peloponnese region [120].

Figure 3.37: *Isaac Newton vessel [120]*

The fuel for trucks is diesel and therefore the emissions from burned fuels are derived from the dataset "diesel, burned in building machine, GLO". About truck consumption, according to Guinness World Record [121], the most fuel-efficient 40-ton truck uses about 20 l per 100 km. According to web site [122], diesel consumption for large capacities, such as 23 t, is up to 38 litres per 100 km. Therefore for 40-ton truck a consumption of 40 litres per 100 km is a normal value. ***Table 12*** shows all the inputs and the main calculated values (Total fuel and MJ) for the emissions calculations for onshore transport. It is mentioned that one liter of diesel is equal to 0.84 kg and this is taken under consideration.

The fuel for vessels is bunker [112] and the dataset "heavy fuel oil, burned in refinery furnace, Europe without Switzerland" is used. This dataset includes, inter alia, emissions from the combustion of fuel in generators. The related "market activity" includes percentages from RoW geography, consequently less accurate coefficients for the examined system. ***Table 13*** shows all the inputs and the main calculated values (Total fuel and MJ) for the emissions calculations for offshore transport.

Table 12. *Emissions calculations for onshore transports*

Component	Vehicle	Number of trucks	Fuel consumption per km (l/km)	Distance (km)	Total fuel (t)	MJ
Tower	-	-	-	-	-	-
Blades	-	-	-	-	-	-
Nacelle	trucks	21	0.40	3000.00	1008.00	21978021.98
Platform	-	-	-	-	-	-
Mooring system	trucks	46	0.40	80.00	26.88	586080.59
Export cable	-	-	-	-	-	-

Table 13. *Emissions calculations for sea transports*

Component	Vehicle (IMO)	Speed (knots)	Fuel consumption per hour (t/h)	Distance (km)	Total fuel (t)	MJ
Tower	9808845	15.00	0.83	450.00	1.35	28283.01
Blades	9770713	12.50	0.35	6900.00	2.07	43524.98
Nacelle	9805568	13.50	0.57	300.00	0.68	14284.35
Platform	9186326	15.00	1.33	1200.00	57.15	1199885.25
Mooring system	9320910	11.90	0.19	330.00	2.83	59418.09
Export cable	9707297	13.20	0.68	450.00	12.52	262961.87

3.4 Stage A5 – Installation

3.4.1 Stage description

The A5 stage is the construction/installation phase according to Kathrina's Figure [57] (**Figure 3.*1***). In this stage, the emissions from the processes that are taking place when the components arrive in the construction site, till they are totally installed, are included. In other words, this stage includes emissions from three phases:

1. the Assembly of the turbine in the area of Heraklion port
2. the Transportation of the turbine to the site of the park
3. the installation of
    a. the windmill
    b. the export cable

The assembly of the windmill starts when all the components are gathered at the Heraklion port. Nacelle is considered as already assembled and emissions for its assembly are considered as negligible. At first, an important process is the floater launching. The floater of the Platform A is unloaded off the heavy load carrier vessel and is stabilized in the sea. This process can be done with the contribution of a semi-submersible heavy-lift ship. For the Platform B there is the opportunity of doing the assembly onshore and to do later the launching of the assembled wind turbine. Thus, a shore crane can be used. This will reduce the emissions from the lifts since the shore cranes has less fuel consumption than crane vessels. However, it was assumed that the same method is used with the steel platform to make the results more comparable and because of the large dimensions of the turbine (technical issues). After the launching, the floater of Platform A is ballasted with a crane vessel. Platform B is not subjected to ballast.

As the platform isn't inside the port and is in deeper waters (rose bullet **Figure 3.*13***), a Platform Supply Vessel (PSV) will carry the components till the platform. Specifically, the MMA VALOUR (IMO: 9651929) is assumed to be used. This is a specialized vessel with 7.35 maximum draft and 5509 t DWT [123]. Because of the draft, PSV can sail inside the port and take the components. The DWT allows to carry all the components of the wind turbine (nacelle, blades and the tower) simultaneously (around 2250 t in total). This vessel has a dynamic position system which facilitate the assembly activities. It is worth noting here that emissions from this transportation is considered as negligible since the distance is only 800 m.

When the components are arrived close to the floater, semi-submersible cranes will lift each component and the assembly process will be done. This type of offshore cranes was utilized for their possibility of conducting heavy lifts. Jack-ups crane vessels were also under examination for this process due to their stability in shallow waters (25 m water depth) but the lifts are considered heavy and semi-submersible is considered safer due to sea conditions (dynamic moving etc.).

The assembled wind turbine is then towed by an AHTS and 2 tugboats to the installation site. At the installation site, the mooring system is already installed with the contribution of an AHTS vessel. The wind turbine is, then, assembled with the mooring system with the operation of an AHTS vessel.

The remaining process, here, is the cable installation. This process includes the laying and the burial of the export cable. This is achieved by a CLV vessel.

The operating hours for the processes of ballast, components lifts, mooring system installation, mooring hook-up (=assembly floater-mooring system) and laying and burial export cables were assumed to be the same with ref. [98] where a cost analysis is conducted. As in the Saitec's [81] recommendation the duration of floater launching is assumed to be 18 hours. For the emissions calculation this process is considered to occupy a semi-submersible heavy-lift ship for 18 hours and two tugboats for 4 hours to assist and to berth the launched platform to quay.

Data for fuel consumption per hour, were determined as follows:

- for the processes of floater launching, ballast, components lifts, towing, mooring system installation and assembly of the wind turbine to the mooring system, values for mean fuel consumption for all the machines were derived from ref. [124]
- for laying and burial of the cable, the CLV's consumption was determined by the software Ship Atlas [112]

Fuel consumptions were given in tonnes or Metric Tons. Heavy fuel oil (bunker) was converted to liters by dividing with 0.96 [125]. This factor is used for converting liters of heavy fuel oil to kilograms. Diesel amounts were divided with 0.84 which is a factor that connects liters of diesel with kilograms [125], [126].

For the emissions from towing process, the speed and distance needed to be determined. Speed for towing is assumed to be the same as the Windfloat project in ref. [98], i.e. 5 knots. Distance is from the port to the installation site. A boat draft of 20 m is assumed (=draft of the semi-sub) for the journey calculation in Navionics software [104]. The output from the software was that the distance between the assembly site (point 2 in **Figure 3.*12***) to the installation/operation site (point 3 in **Figure 3.*12***) is 138 km.

The two platforms have different weights. The steel floater weights 17854.00 t and the concrete floater weights 16446.97, i.e. 7.9 % difference. This percentage is considered as unsignificant to change the load-out data, since by changing the fuel consumption even by 10 l/h (from 32.5 l/h that the AHTS is considered to consume approximately to 42.5 l/h) the impact at the total emissions from the life cycle is 0.011 / 26.5 = 0.04 % (=change in "Installation" phase / total emissions for Platform B).

For this stage, are also applied two different methods as in A4 stage. The common fact of the methods is the way that total fuel consumption is calculated. Specific types of vessels (not specific IMO as the A4 stage) are used.

3.4.2 Method A5-i

With the first method (A5-i), the tkm are calculated from the total fuel consumption of the vessels, using Ecoinvent values. The dataset "transport, freight, sea, ferry" is used (this method was followed, also, from ref. [34]). For the cranes operation, a different calculation is applied. According to operation hour the value from dataset "machine operation, diesel, >= 74.57 kW, high load factor, GLO" is used. The two figures below, describe the method schematically for the two platforms.

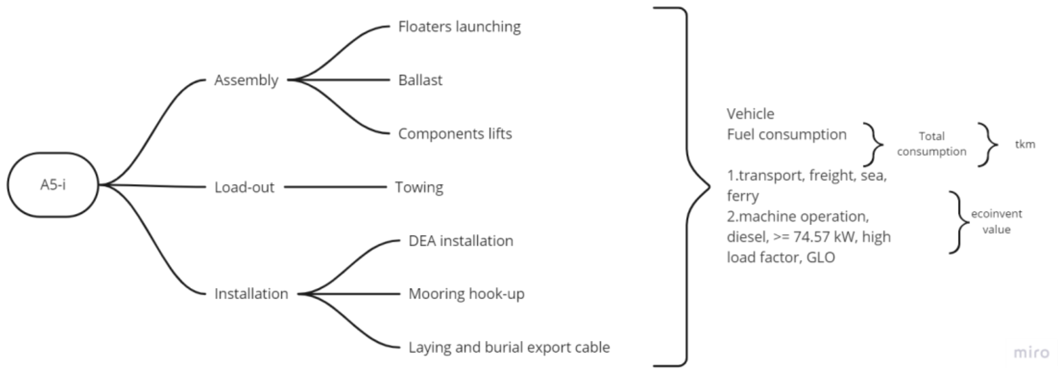

Figure 3.38: *Schematic description of A5-i, Platform A*

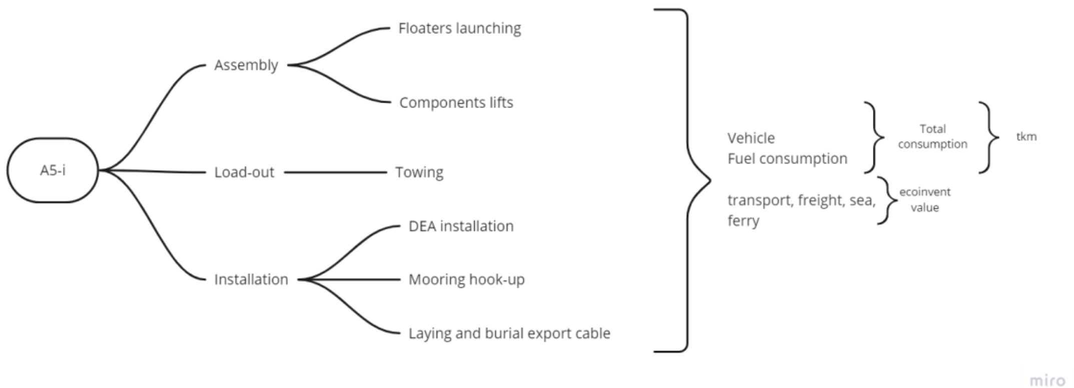

Figure 3.39: *Schematic description of A5-i, Platform B*

The table below (***Table 14***) describes the calculations with A5-i method for the platform A. The only difference with Platform B is that there is not ballast at the concrete platform. Notes about the operating hours are included in the last row.

Mean consumptions at the third column (Fuel consumption per hour (l/h) approach the related values in paper [34] which is a check for these values that were derived from investigation [124] and the software Ship Atlas [112].

Table 14. *A5-i inputs and calculated values for the calculation of the emissions for Platform A*

Process	Vehicle	Fuel consumption per hour (l/h)	Total time (h)	tkm
Floaters launching	Semi-sub heavy-lift ship	-	18.00	-
	2 tugboats	669.64	4.00	161622.28
Ballast	Crane vessel	-	24.00	-
Components lifts	Semi-sub crane vessel	-	14.00[1]	-
Windmills towing	AHTS	1410.59	14.90[2]	634215.68
	2 tugboats	669.64	29.81[3]	602156.43
Mooring system installation	AHTS	1410.59	24.00[4]	1021362.99
Mooring hook-up	AHTS	1410.59	18.00[5]	766022.25
	2 tugboats	669.64	36.00[6]	727300.24
Laying and burial export cables	CLV	781.25	100.80[7]	2375847.46

Notes:
[1] each lift lasts 2 hours. 9 lifts are considered. 3 for the blades, 1 for nacelle and 5 for the tower's sections (approximately 30 m each section)
[2] with speed of 5 knots and distance 138 km
[3] the emissions from the 2 tugboats with 5 knots speed and distance 138 km
[4] each anchor takes 8 hours of installation, and the system has 3 anchors
[5] it takes 6 hours per line and the system has 3 lines
[6] it takes 6 hours per line, there are 3 lines and the boats are 2 (6*3*2=36)
[7] After an investigation, the most applicable data about this process was from ref. [32]. 10 km of laying per day and 10 km burial per day leads to a complete job of 10 km per 2 days. For the 21 km of the system, 4.2 days are needed which is 100.8 hours in total

3.4.3 Method A5-ii

With the second method (A5-ii), the total emissions were calculated from the total fuel consumption by using the Ecoinvent datasets: “heavy fuel oil, burned in refinery furnace, Europe without Switzerland” and “diesel, burned in building machine, GLO”. The figures below describe the method schematically for the two platforms.

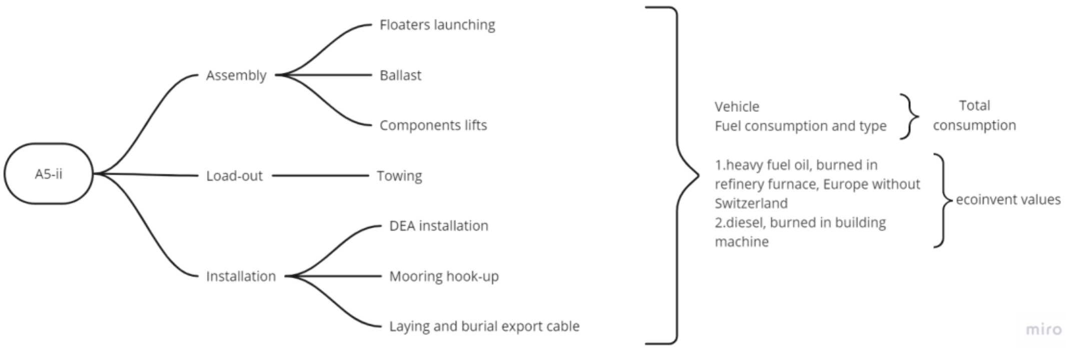

Figure 3.40: *Schematic description of A5-ii, Platform A*

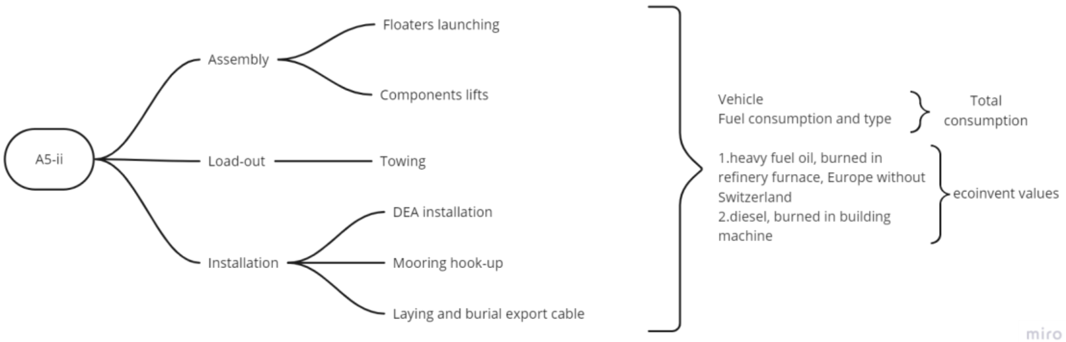

Figure 3.41: *Schematic description of A5-ii, Platform B*

This is a more direct calculation method therefore it is potentially more accurate. The vehicles, fuel consumptions and operating hours are the same as in with ***Table 14***. Additionally, the type of the applied fuel, the conversion of the total fuel consumption to MJ and the fuel consumptions for the Floating launching, the Ballast and the Components lifts are determined. The fuel type for all the vehicles instead of tugboats, is heavy fuel oil (bunker) according to study [98]. According to a LCA study, [127], a typical tugboat burn diesel. ***Table 15*** shows the additional required information for the A5-ii approach for the Platform A. As with the first method A5-i, calculations for platform B differ in ballast absence.

Table 15. *A5-ii approach*

Process	Vehicle	Fuel consumption per hour (l/h)	Total fuel consumption (l)	MJ
Floaters launching	Semi-sub heavy-lift ship	2113.72[1]	38046.88	100318.71
	2 tugboats	669.64	5357.14	116804.96
Ballast	Crane vessel	2113.72	50729.17	1203824.55
Components lifts	Semi-sub crane vessel	2113.72[2]	38046.88	902868.42
Windmills towing	AHTS	1410.59	21021.76	498822.14
	2 tugboats	669.64	19959.12	435180.48
Mooring system installation	AHTS	1410.59	33854.17	803373.68
Mooring hook-up	AHTS	1410.59	25390.63	602530.26
	2 tugboats	669.64	24107.14	525622.34
Laying and burial export cables	CLV	781.25	78750.00	1868770.76

Notes:
[1] this fuel consumption is assumed to be the same with semi-sub crane vessels because at the ref. [98] the cost of the floater launched is assumed to be equal with 1 quayside lift. Therefore, the cost parameter, fuel consumption, is assumed to remain the same.
[2] it is assumed to have the same fuel consumption with the crane vessel of ref. [98]

3.5 Stage B2-4 – Operation and Maintenance

This stage includes the O&M emissions of the system. Emissions from the A1, A2, A3 of the spare parts, the burned fuels for transportations and replacement works and the burned fuels for the scheduled maintenance are under consideration.

About spare parts, data were gathered from various investigations (***Table 16***). The data were assessed. There were no common assumptions for spare parts in literature.

Table 16. *Spare parts in various investigations*

Reference	Number of turbines	Lifetime	Spare parts
Garcia-Teruel et al. [6]	5	25	*
Raadal and Vold [57]	100	20	1-3% of total mass
Yildiz et al. [17]	1	20	lubricate 2 times per year & 1 gearbox
Elginoz and Bas [31]	77	25	lubricating oil·10
Tsai et al. [3]	100	20	0.24 nacelle
Weinzehettel et al. [2]	40	20	2 turbines (5%)
Bang et al. [16]	75	25	5% major maintenance per year
*4 generators, 18 changes of lubrication oil, 17 changes of different power electronics components, 24 mooring lines, 25 anchors			

Finally, the main failure rates were determined using ref. [128]. "Transmission" and "Pitch System" (**Figure 3.42**) have the highest share of failure rate. These are components of the nacelle. In addition, Tsai et al. [42] mention a 0.012 nacelle failure rate per turbine and year, which means that the 24% (0.012*20years) of the nacelle will be replaced once in the lifetime. Furthermore, Garcia-Teruel et al. [34] assume changes of generators and power electronics components which are also content of the nacelle. That is to say that a realistic assumption is the failure of "Turret nose", "Inner generator stator" and "Outer generator stator" which are the 50% of the nacelle's mass and around 2% of the total system mass of each of the two cases.

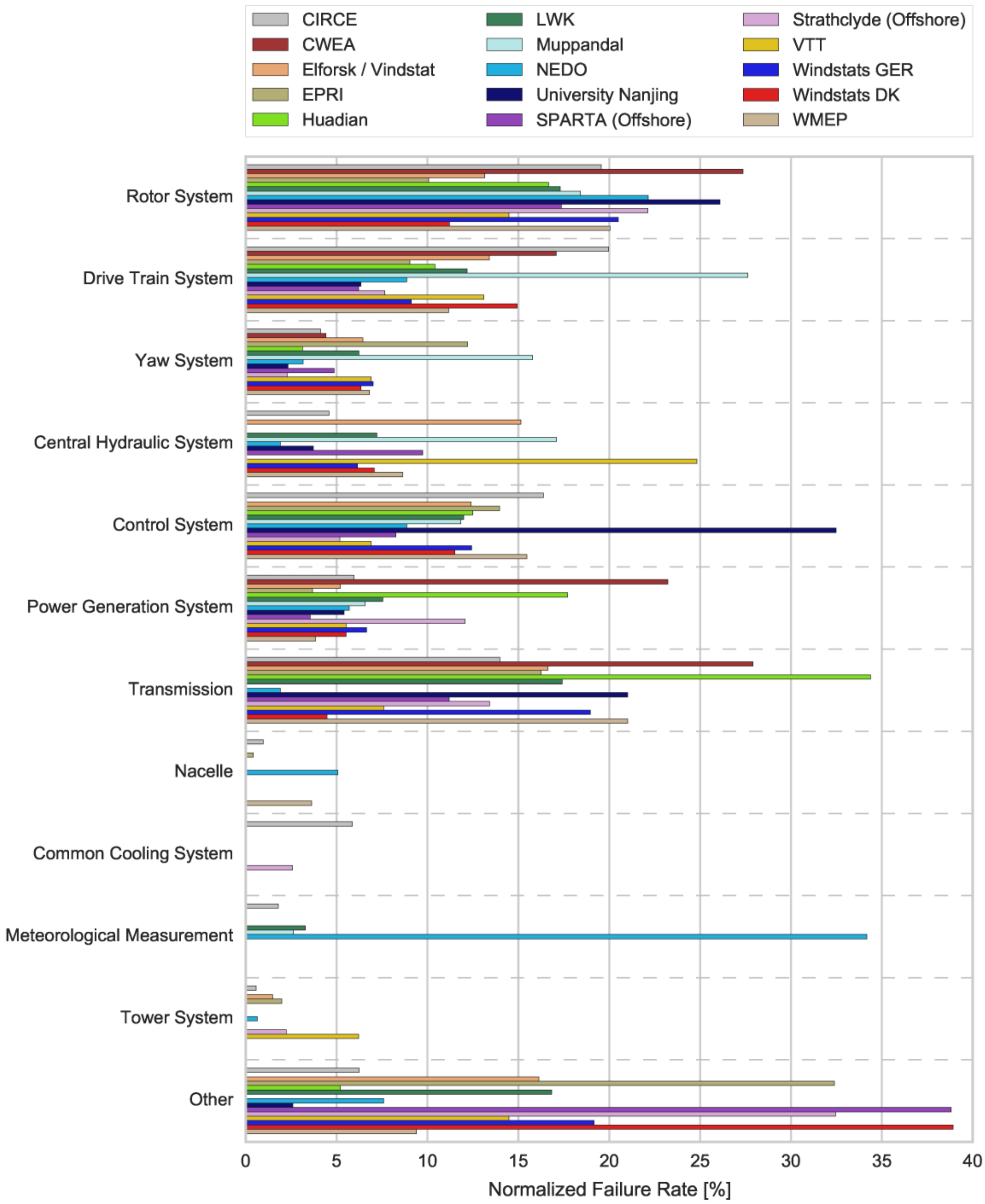

Figure 3.42: *Normalized failure rates according to [128]*

About the fuel consumption for replacement, one round trip with helicopter and a small boat and in total 9 hours (3 hours for each of the main replaced components) of replacement time is assumed where the helicopter will be in operation and the small boat moored.

The third part of this stage "Fuel consumption for the scheduled maintenance", includes also repairs (the B3 stage). Data from various studies were gathered (***Table 17***). For the purpose of this research, it was decided to obtain data from Bang et al. [35]. Tsai et al. [42] has, also, similar assumptions but the decided assumptions were more applicable, specifically for the cables. Furthermore, with these assumptions, we make our study more comparable with the other studies that didn't apply O&M models, as Garcia-Teruel et al. [34] did. The stage is divided in two parts: i) Cables maintenance and ii) Turbine maintenance. For the Cables, a CLV and a ROV operation is assumed and 1 km of a cable per hour every 2 years are inspected. For the turbines, a small boat and a helicopter is assumed to go to the park 2 times per year for the one turbine. In this visit the fuel consumption for the round trip is assumed and the vehicles spend in the park 3 hours where the small boat is moored and the helicopter is in operation.

Table 17. *Scheduled maintenance in seven studies*

Reference	Number of turbines	Lifetime	Maintenance
KOWL project [129]	6	25	6 days/turbine/year & 1 day/year for mooring and cables
Vold and Sanden [87]	100-1000	25	1 visit/year & one major overhaul
Yildiz et al. [77]	1	20	2 times examination/per components/year
Bang et al. [35]	75	25	*
Elginoz and Bas [31]	77	25	10 visits/year with barge+1 visit/year with helicopter
Tsai et al. [42]	100	20	2.5 days/wind turbine/year, 7.5 days/substation/year, 14 days for cables (day=24 hours)
Weinzehettel et al. [33]	40	20	3 visits/year
*2 visits/year with 3 turbines per day fuel= trip+3 hour idling & 1km inspected/hour/2 years (fuel= vessel+machine operation of ROV)			

The following figure (**Figure 3.*43***) describes this stage. The calculation manner is the same for the two platforms.

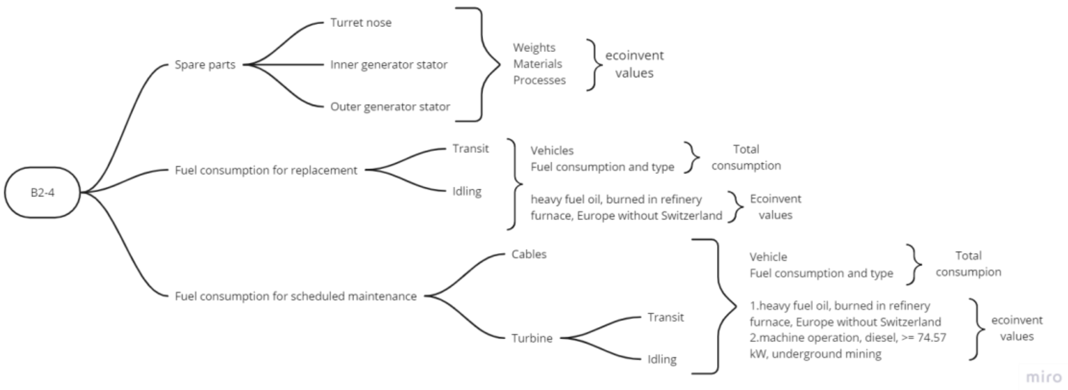

Figure 3.43: *B2-4 for Platforms A and B*

3.6 Stage C1-2 – Demolition and Transport

Demolition and transportation to landfill, constitute the end-of-life scenario.

The first part of this stage is the "Demolition". This stage is mentioned as Decommissioning in the literature due to the technology's nature. Some investigations ([30], [34], [35]) assume the decommissioning stage to be equivalent and reverse with the installation stage. The current investigation assumes that C1 stage is equivalent and reverse to the "Installation" stage (A5) without the towing part (Transportation of the turbine to the site of the park). The environmental impact from windmills towing is excluded because towing expresses a type of transportation which is included in the emissions of transportation to landfill.

The C2 stage (Transportation to landfill) is the second part of the end-of-life. At the C2 stage, the emissions from transportations to landfill are considered. Here, recycling ratios are considered, and the recyclable materials exit the system as in investigation [34]. The transportations concern only the freights from non-recycled materials. That is in line with the Ecoinvent data that were used in the first stage (A1-3) which include credits from recyclable materials and include, also, the emissions from transportations of these recyclable materials. According to Raadal et al. [30], credits from recycling are excluded to be "in line with Product Category Rules for electricity generation, in accordance with the International EPD System".

The assumed recycling ratio for the study of the steel and other metals (copper, cast iron, aluminum) is 90% which is in line with [30], [34], [35], [42], [130] and with a small discrepancy with Yildiz et al. [77] (85%). For the concrete, 85% recycling is assumed which is in accordance with [30] and [131].

The metal materials are assumed to be transported to the municipality landfill of Heraklion, as Garcia-Teruel et al. [34] assume. The concrete wastes are assumed to be transported to the Heraklion Industrial Area where a Construction, Demolition and Excavation (CD&E) wastes processing and utilization unit exists. The transferred distance is assumed to be only the 138 km since the distance in shore has unsignificant contribution. The dataset "transport, freight, sea, ferry – GLO" is used for the emissions calculations.

The following figure describes the elements of this stage for the two platforms. Due to different materials and weights of the two platforms, the result is different, but the process is the same.

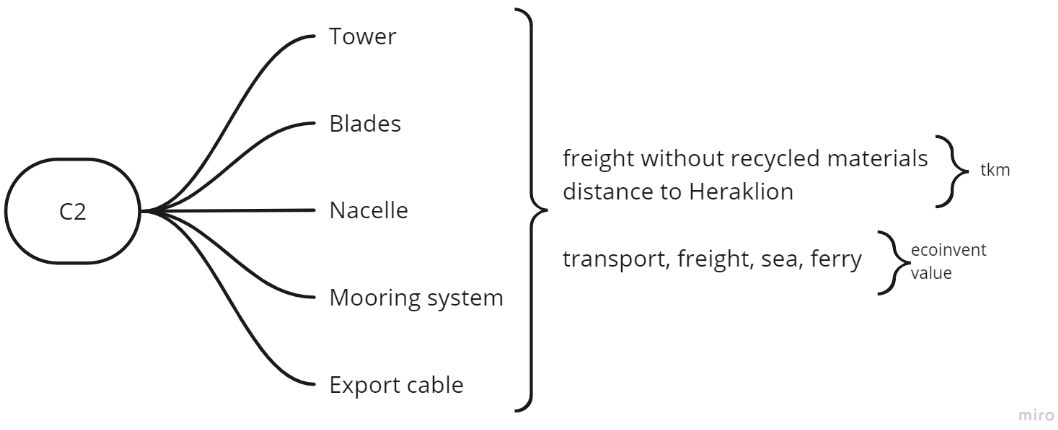

Figure 3.44: *C2 for the two platforms*

The table below, shows the transported components, the initial metal and concrete mass per component, the final transported freight and the tkm which are calculated by multiplying the final freights with the distance 138 km.

Table 18. *Transportation to landfill calculations*

Component	Freight (t)	Metal mass (t)	Concrete mass (t)	Final freight (t)	tkm
Tower	1263.00	1263.00	-	126.30	17429.40
Blades	195.75	-	-	195.75	27013.50
Nacelle	820.89	759.21	-	137.60	18988.58
Mooring chains	5240.25	1746.75	-	3668.18	506208.15
Anchors	90.00	90.00	-	9.00	1242.00
Export cable	770.61	482.14	-	336.69	46462.70
Platform A	17854.00	4014.00	-	14241.40	1965313.20
Platform B	15553.00	383.84	15169.16	2313.76	319298.69

Chapter 4

Results and Discussion

The GWP of a wind farm was calculated by applying the LCA method. As it stems from the above-mentioned in section 3.3 and 3.4, results were calculated using two methods in stages A4 (Transportation to the construction site) and A5 (Installation). In order to make some comparisons, the one of the two methods in each stage was assumed as the baseline method. Specifically, for the two stages, the second method (A4-ii and A5-ii) was assumed as the baseline scenario. This is because the emissions are referred to the specific case. The particularity of the case is that specialized vessels are in use. These vessels have their specific DWT and fuel consumptions. Moreover, as it appears in results, A4-ii is more conservative method for the two platforms since its results (2.0 and 2.0 gCO_2-eq/kWh) have higher values than the results from A4-i (1.0 and 0.5 gCO_2-eq/kWh).

4.1 Comparison between steel and concrete platforms

Initially, the baseline scenarios for the platforms are compared with each other. The results from the two platforms are written in ***Table 19***. Discrepancies in A1-3, A5, C1 and C2 stages between the two cases, cause 24.5 % discrepancy in the total result of the life cycle evaluation. It can be seen that for the first stage, A1-3, emissions from Platform B (concrete platform) are lower about 27.7 % from Platform’s A (steel platform). This is related with material consumption and processes for the platforms and the mooring lines manufacturing. Platform and mooring lines for the first case weight more in respect with the second case. Therefore, the emissions from the production of the materials for the first case are lower due to the material production process. Moreover, in the Ecoinvent database a specific amount of concrete material has lower impact on climate change than the same amount of steel material. When comparing GWP of the dataset that was used for ready-mixed concrete and the dataset “market for steel, low-alloyed – GLO”, it is found that the production of 1 kg material has higher GWP for the steel’s dataset. In addition to materials, the process of “welding, arc, steel – RER” adds emissions at the steel platform. Besides manufacturing, a difference is observed in A5 (16.7 %) stage where ballast process of the Platform B is missing and in C1 (20.0%) stage. There is a big difference in stage C2 (Transportation to landfill). Emissions from C2 stage for Platform B are lower about 50.0 % from Platform’s A. Platform B has more amounts of concrete which cause more transportations due to their smaller percentage of recycling. However, the emissions for Platform A are higher due to the seawater that is used for ballast. The seawater is assumed to be transported till the landfill due to its need for wastewater treatment. The 50.0 % percentage is relatively big as an absolute value, but compares two, already, small values relatively with the total emissions.

Table 19. *Baseline scenarios for Platforms A and B and their variation for each stage*

Stage	Platform A-ii (gCO_2-eq/kWh)	Platform B-ii (gCO_2-eq/kWh)
A1-3	27.4	19.8
A4	2.0	2.0
A5	0.6	0.5
B2-4	1.7	1.7
C1	0.5	0.4
C2	0.2	0.1
Total	32.6[1]	24.6[1]
Note: [1] The discrepancy between the sum of A1-3, A4, A5, B2-4, C1 and C2 and the total result is because of rounding the numbers		

Figure 4.*1* is a comprehensive schematic overview of the results.

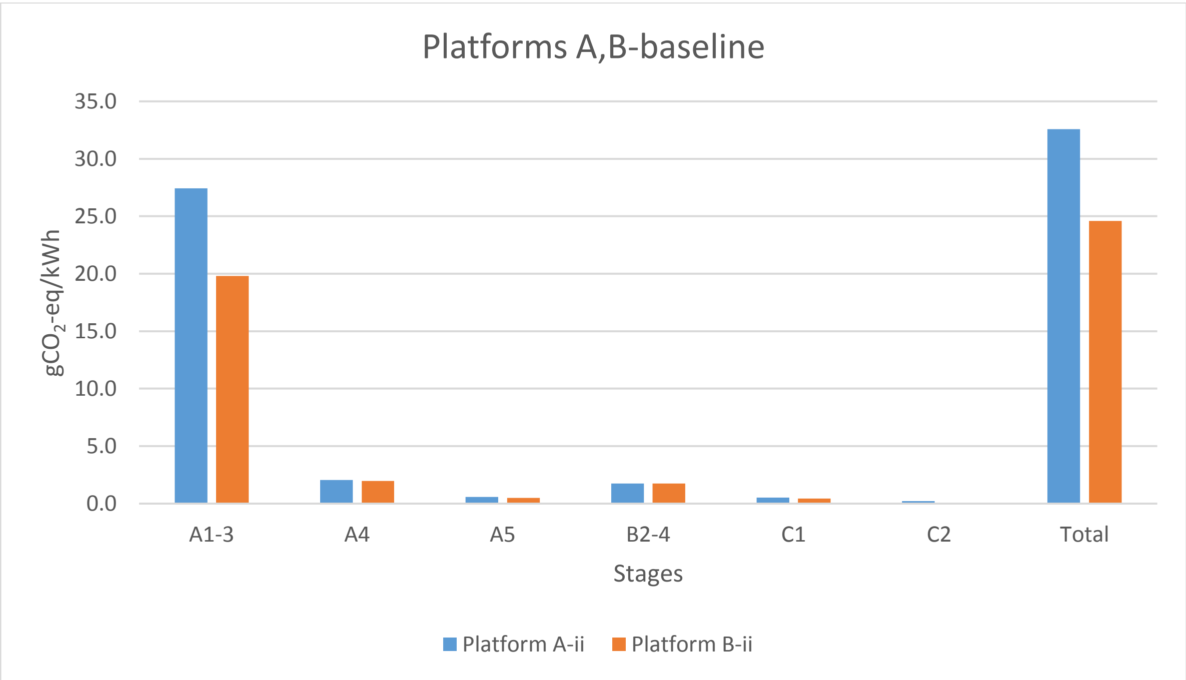

Figure 4.1: *Schematic overview of the two platforms for the methods A4-ii and A5-ii*

4.2 Comparison with other investigations

4.2.1 Total result

Floating

It is interesting to compare the two cases with other floating concepts. At first, it is compared with the GWP from other floating concepts with lower nominal power. Yildiz et al. [77], mention 18.6 gCO_2-eq/kWh for the lifespan of their concrete 2 MW wind turbine. This is 24.4 % lower than the examined concrete case (24.6 gCO_2-eq/kWh). The fact that the examined system is a wind turbine and not a wind farm could be the reason for this discrepancy due to the absence of cabling. Furthermore, the 2 MW turbine has lower dimensions than the 15 MW. Therefore, the material production is much lower at the 2 MW case. However, it can't be overlooked that Yildiz et al. [77] assume a CF of 34.2 % which is lower than the assumed of 43.0 % in this investigation. The 34.2 % CF will lead the result of the Platform B to 30.9 gCO_2-eq/kWh which is higher than for the assumed 43.0 % CF.

Another study that examines small wind turbine (3 MW) is ref. [42]. Results for floating concepts from Tsai et al. [42], vary between 32.9 and 38.1 gCO_2-eq/kWh. These results are close to the 32.6 gCO_2-eq/kWh of Platform A. The assumed CF is close at the two examinations (28 - 38 % for examination [42]) and a wind farm is examined. In the wind farm, there is also a transformer substation which increase its gCO_2-eq/kWh.

In contrast with Tsai et al. [42], Wang et al. [39] examine only one wind turbine. Their result for the offshore concept is 468.0 gCO_2-eq/kWh. This number is different that literature's results. Authors noticed this discrepancy, but they didn't justify it. If it is considered that the examined stages are similar with other studies, this result may stem from the low electricity production due to the wind conditions and nominal power. Although the study examined a floating support structure, the structure was fixed in the sea.

The same support structure technology is examined by Weinzettel et al. [33]. However, Weinzettel et al. [33] consider a wind farm. Their wind turbines have 33.3 % of the nominal power of the 15 MW turbine, i.e. 5 MW. Weinzettel et al. [33] case study, result in 3.2E-3 kgCO_2-eq/1 $MJ_{electricity}$ which is equal with 11.5 gCO_2-eq/kWh. This number is 64.7 % and 53.3 % lower than the two case studies with Platform A and Platform B, respectively. This might stem from the fact that their wind farm consists of 40 windmills (not only one) and due to the massive electricity production emissions from cable's production have lower contribution to the total emissions. Moreover, material production for each windmill is lower than for the 15 MW windmill due to the smaller dimensions and different support systems technology. In addition, Weinzettel et al. [33] have assumed shorter distances for the transportation to the construction site and they use the Ecoinvent's values for the transport process which leads to some contribution to the total result. It can, also, presumed that they didn't use the "Allocation, cut-off, EN15804" system model since it didn't exist in 2009.

Ecoinvent values are also used from Raadal et al. [30]. Raadal et al. [30] found that for the floating concepts, results vary between 18.0 and 31.4 gCO_2-eq/kWh. Actually, the 31.4 value, is referred to a semi-submersible steel platform which is similar with Platform A but is for 5

MW turbine. The difference between 31.4 and 32.6 is small. The significancy of the technology of the support structure for floating concepts can be inferred here.

A semi-submersible from the investigation [34] result has values 31.1 – 37.4 gCO_2-eq/kWh. It is important to mention that impact from the O&M stage in study [34] is more than the one third of the result (40.7 %) which has a large discrepancy with the O&M (B2-4) stage in the present investigation for the semi-submersible case which is 5.2 % of the total result. In the examination of Garcia-Teruel et al. [34], the discrepancy between the emissions from O&M stage is, also, observed in the Spar platform where the O&M stage to the total result is 41.0 %. The case with the Spar platform results in 36.0–44.0 gCO_2-eq/kWh which is higher than the semi-submersible cases.

Spar platform in study [35] seems to have only 15.35 kgCO_2-eq/MWh which is 15.35 gCO_2-eq/kWh. The studied nominal power is 8 MW and hence the material use is lower. Furthermore, CF is 50 % and lifetime is 25 years. These numbers are larger than the system's assumed numbers in this thesis. It can, also, be observed that the number of turbines is 75 which expresses a massive energy production.

More than one turbine is, also, considered by Poujol et al. [85]. Poujol et al. [85] consider 5 years less lifetime for their baseline scenario than the previous study. This could be the reason for the larger GWP (22.3 gCO_2-eq/kWh).

Other concepts

In bottom-fixed wind energy concepts, the results are varied and sometimes are similar with results from floating concepts. Tsai et al. [42] report values of 25.6 - 44.3 gCO_2-eq/kWh. Weinzettel et al. [33] report for the Ecoinvent's 2 MW offshore wind power plant 13.7 gCO_2-eq/kWh. Raadal et al. [30] calculate 18.9 gCO_2-eq/kWh for their Jacket platform. A value of 25.5 gCO_2-eq/kWh is concluded in LCA [96]. Most of these results, seem to be lower than Platform's A and seem to be higher or close to the concrete platform.

In comparison with the most studies that examine onshore wind energy concepts, Platform A has larger contribution to GWP. Wang et al. [39] investigated an onshore concept. They found 295.2 gCO_2-eq/kWh which exceeds the Platform's A result by 805.5 %. However, Garret & Rønde [132] conclude to only 7.7 gCO_2-eq/kWh for their V80 2.0-MW GridStreamer™ turbine. A more moderate value is the 18.0 gCO_2-eq/kWh from the 2 MW turbine by Alsaleh & Sattler [133]. Although the results from Platform B, seems to be larger than the aforementioned onshore studies, Platform's B result is similar with the results from Li et al. [37] which are 16.4–28.2 gCO_2-eq/kWh.

A comparison between the studied concepts and other energy sources needs to take place here. Varun et al. [134] made a comprehensive table that includes values for GHG emissions from different types of energy (***Table 20***). However, for coal power, Alsaleh & Sattler [133] present a value of 220.0 gCO_2-eq/kWh which concerns coal fired power plant with carbon capture and sequestration (CCS). Their value for coal fired power plant without CCS is 838.0 gCO_2-eq/kWh which is closer to the value for the coal fired power plant of Varun et al. [134]. Biomass and

PV sources in this study [133] coexist in values from ***Table 20***. However, natural gas combined cycle has 450.0 gCO_2-eq/kWh and nuclear has 10.0 gCO_2-eq/kWh. In investigation [37] the nuclear is similar to this pervious mentioned value. Li et al. [37] gather various values of different types of energy:

- nuclear: 10.9–13.9 gCO_2-eq/kWh
- hydropower: 3.1–3.9 gCO_2-eq/kWh
- photovoltaic power: 16.0–40.0 gCO_2-eq/kWh
- thermal power: 810–820 gCO2-eq/kWh
- biomass power: 200 gCO_2-eq/kWh

As it can be concluded by all these results, emissions from Platform A and Platform B are higher than emissions from nuclear in all the aforementioned references. Solar PV energy, solar thermal and hydropower are sometimes higher and sometimes lower. However, in all cases, coal fired, oil fired, natural gas, biomass and thermal power contribute more in GWP than the examined platforms here.

Table 20. *Comparison of Life Cycle GHG Emissions (gCO_2-eq/kWh) of conventional electricity generation with renewable electricity generation sources* [134]

S. No.	Conventional systems		S. No.	Renewable systems	
System		gCO_2-eq/kWh	System		gCO2-eq/kWh
1.	Coal fired	870.0-975.3	5.	Wind	9.7-123.7
2.	Oil fired	742.1	6.	Solar PV	9.4-300.0
3.	Gas fired	607.6	7.	Biomass	35.0-178.0
4.	Nuclear	24.2	8.	Solar thermal	13.6-202.0
			9.	Hydro	3.7-237.0

4.2.2 Stages

The contribution (%) of each stage to the total GHG emissions from the two baseline studies cases is depicted in **Figure 4.2**. These results are compared with results from other LCA investigations for floating offshore wind. The results from other studies were gathered and their format (graphs and numbers) were changed to make them comparable. **Figure 4.3**, **Figure 4.4** and **Figure 4.5** illustrates the results from four studies, [30], [35], [77] and [85].

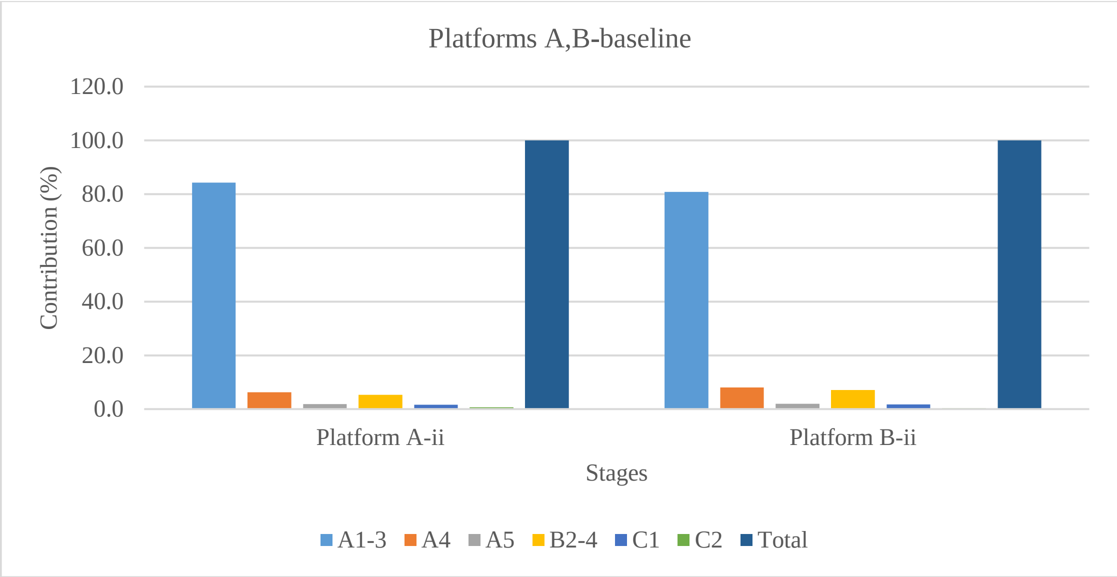

Figure 4.2: *Stage's contribution to the total result of the baseline scenario for each of the two platforms*

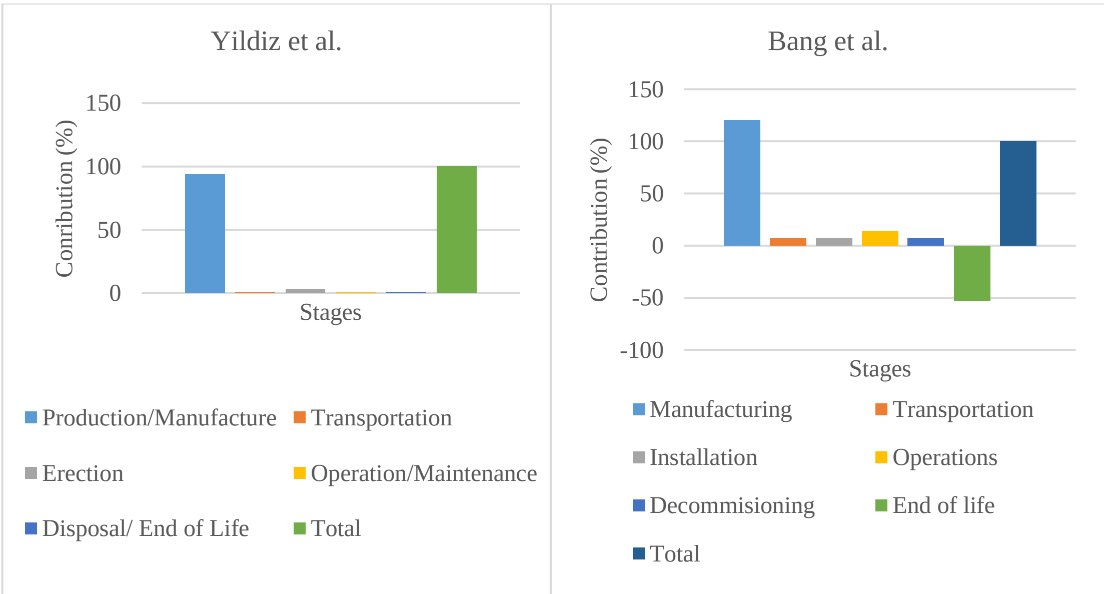

Figure 4.3: *Results from Yildiz et al. [77] (left) and Bang et al. [35] (right)*

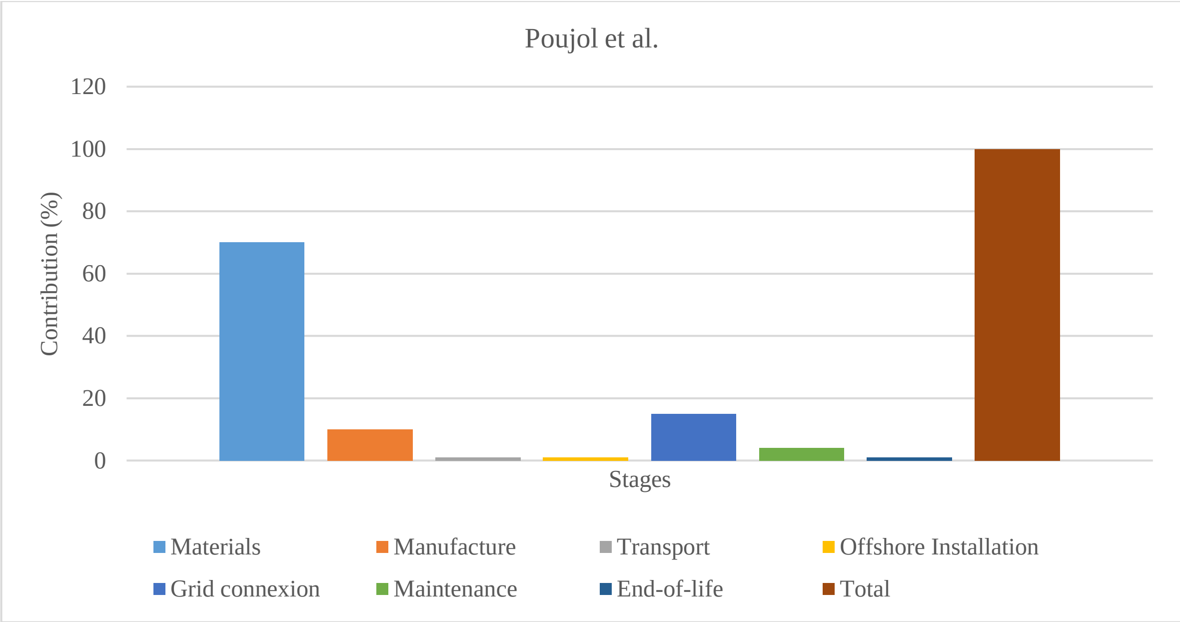

Figure 4.4: *Results from Poujol et al. [85]*

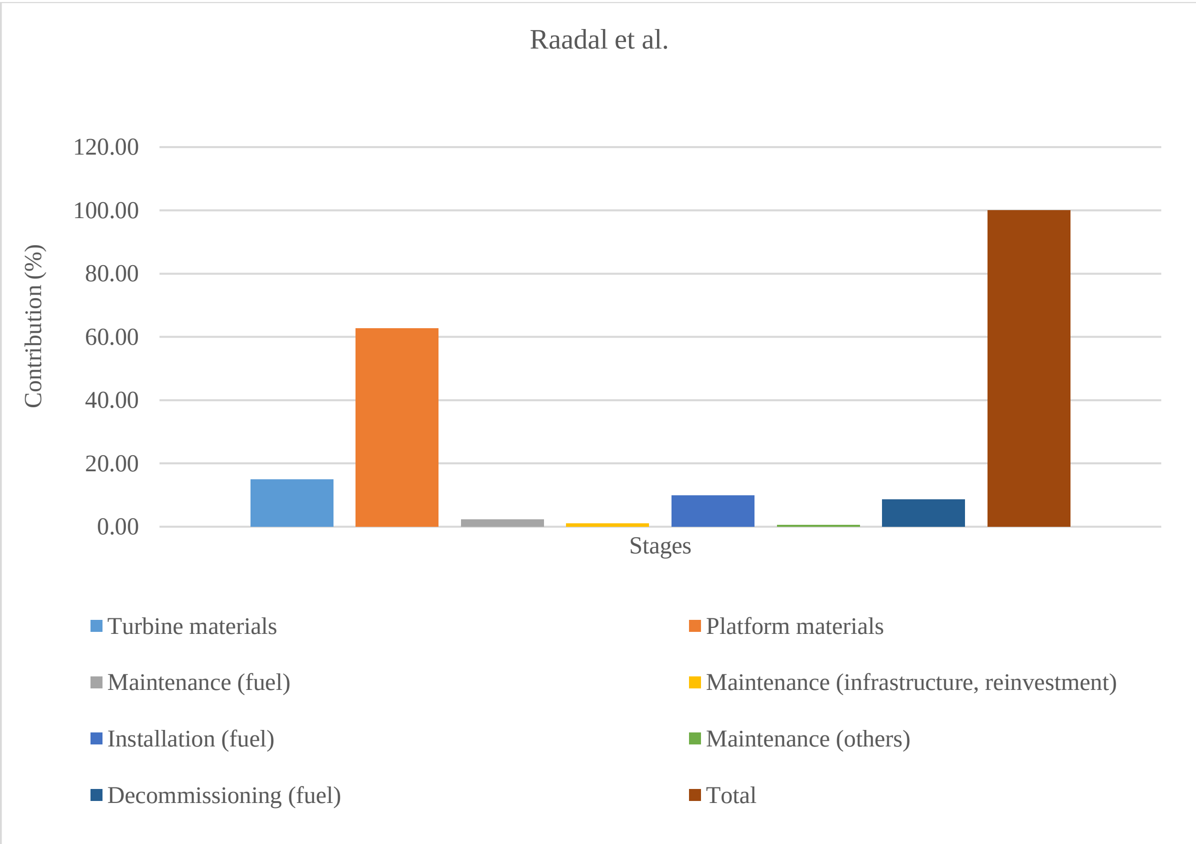

Figure 4.5: *Results from Raadal et al. [30]*

It is observed that in all graphs, stages that include the production of the materials (in **Figure 4.5** the first and the second bars) have the largest contribution to the total emissions from the life cycle. It is worth noting that the A4 stage (Transportation to the construction site), has more contribution than the transportation stage in other studies. This might be caused by the use of bigger and more accurate distances in the current investigation.

4.3 Each platform characteristics

4.3.1 Stage contribution

The contribution of each stage to the total result for each platform is depicted clearly in **Figure 4.6**. Stage A1-3 has the higher contribution to GWP. A4 and B2-4 stages follow the A1-3 stage. As A4 stage contribute only 6 % and 8 % to the total emissions, the assumption that concrete platform is constructed in the "construction site" and therefore not subjected to any transportation, may not influence significantly the resulting GWP.

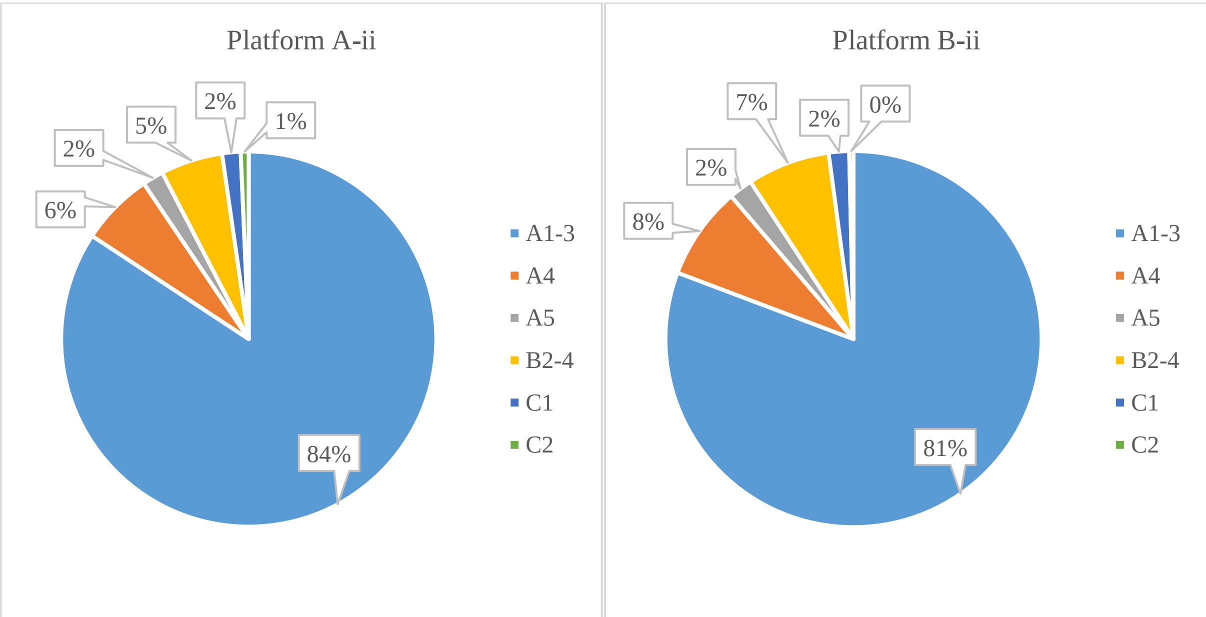

Figure 4.6: *Pie graphs for stage contribution for Platform A (left) and Platform B (right)*

4.3.2 Comparison of the two methods

Table 21 compares the results of the two methods (i and ii). For Platform A, the two methods differ by 3.4 % for the total emissions. For Platform B, the two methods differ 5.3 %. In the two cases method ii has larger results. For A5 stage, the two methods produce same results for Platform A and a small discrepancy for Platform B. Nonetheless, the calculated emissions by the A4-i method for the first case differ 50.0 % from A4-ii. Moreover, result from A4-i method for the second case differs 75.0 % from the A4-ii. These two percentages are relatively high. In contrast with A5 stage, A4 includes onshore transportations. These transportations might be the reason for the high discrepancy. Transportations with trucks have large contribution to the result from the A4-ii method, specifically 89.8 % and 93.8 % for Platform A and Platform B respectively. That is to say that the assumption that the number of trucks is directly related with the weight might be not accurate assumption and other assumptions should be taken into account (e.g. volume). Moreover, it is concluded that the assumptions about the use vessels capacity (50 % vessel's use for blades, nacelle and tower) have negligible contribution to the results.

Table 21. *All the results from the two platforms with the two methods*

	Platform A-i	Platform A-ii	Platform B-i	Platform B-ii
A1-3	27.4	27.4	19.8	19.8
A4	1.0	2.0	0.5	2.0
A5	0.6	0.6	0.6	0.5
B2-4	1.7	1.7	1.7	1.7
C1	0.5	0.5	0.5	0.4
C2	0.2	0.2	0.1	0.1
Total	31.5[1]	32.6[1]	23.3	24.6
Note: [1] The discrepancy between the sum of A1-3, A4, A5, B2-4, C1 and C2 and the total result is because rounding the numbers				

4.3.3 Observations in stage A1-3 – Raw material supply, Transport and Manufacturing

i) Component contribution

In this section specifications are described for A1-3 stage since this stage is the most important stage. First of all, **Figure 4.7** illustrates the contribution of each component to the emissions for A1-3 stage of each platform. In contrast with Raadal et al. [30] (**Figure 4.5**) the main contributor is the RNA and not the platform. The platform follows the RNA in the two cases but in case B there is a significant discrepancy (52.5 %) between emissions from the RNA and from the platform. The reason might be the larger number of processes that takes place in RNA manufacturing. Projects such as "HIBIKI" that its RNA consists of two blades instead of three, might reduce the emissions from RNA's manufacturing. The smaller contributor is the export cable where no manufacturing processes were taken into account.

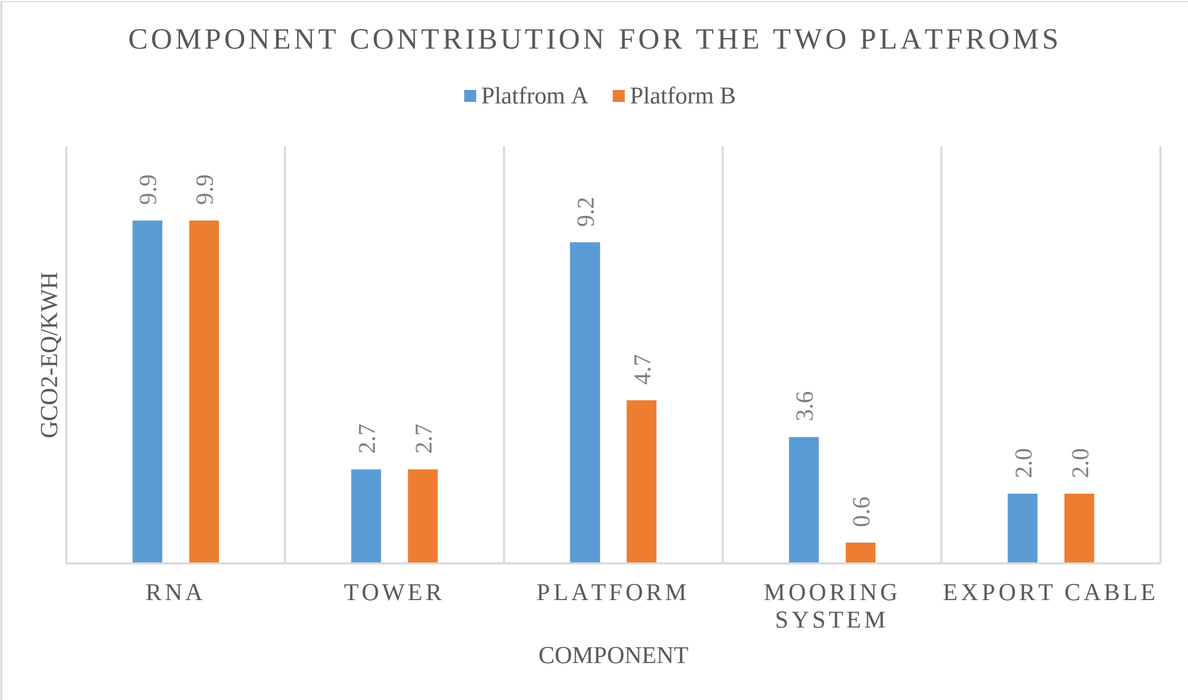

Figure 4.7: *Component contribution to A1-3 stage for each of the two platforms*

ii) Material contribution

In addition, impact of the materials is significant in A1-3 stage. **Figure 4.*8*** and **Figure 4.*9*** demonstrate the differentiation in material contribution for the two platforms. The steel's and cast-iron's emissions include the material production and their processes. The term "Miscellaneous" refers to the Epoxy resin, Magnets, Transformer, Electronics, Polyethylene, Polypropylene, Lead and Polyester.

In these two figures, it is observed that steel remains the main contributor to this stage, even for the second case. Moreover, cast iron which is used for the hub and the outer generator stator, is second in emissions intensity in the two cases. In the case of Platform B, regardless of the use of concrete, concrete is still being in next places of steel and cast-iron.

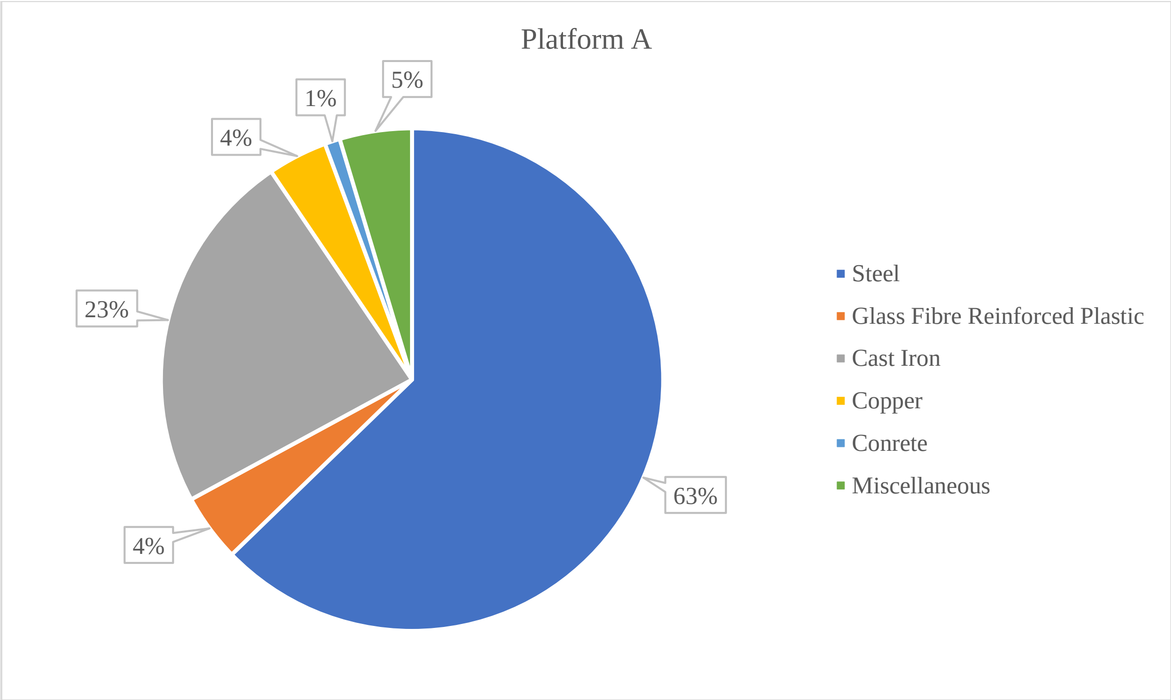

Figure 4.8: *Material contribution at stage A1-3 for Platform A*

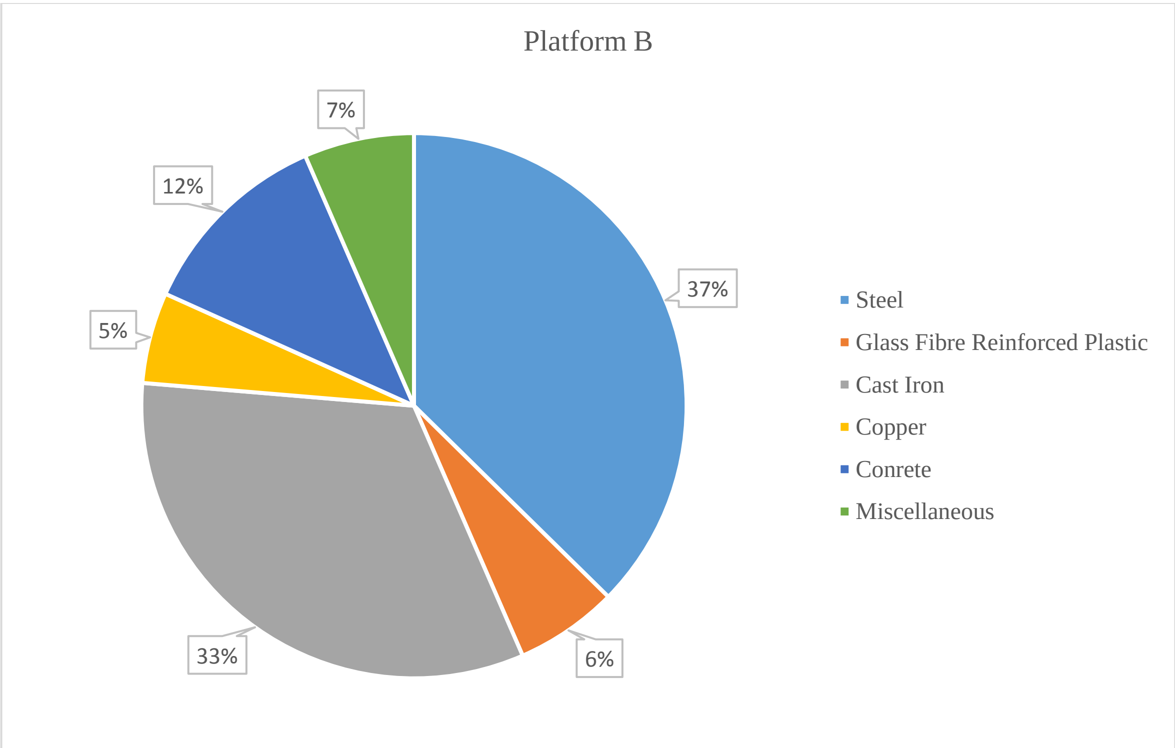

Figure 4.9: *Material contribution at stage A1-3 for Platform B*

4.4 Parameters

The CF and the lifetime are parameters which contribution is very important to the GHG emissions intensity. Changes only in capacity factor leads to results from 21.5 gCO_2-eq/kWh to 46.7 gCO_2-eq/kWh for the first case and from 16.2 gCO_2-eq/kWh to 35.2 gCO_2-eq/kWh for the second case. The consideration of a low value for the capacity factor of 30 % the total emissions from the baseline scenario with Platform A and B is 46.7 gCO_2-eq/kWh and 35.2 gCO_2-eq/kWh, respectively. The consideration of the largest CF in literature [35], 65 %, results in 21.5 gCO_2-eq/kWh and 16.2 gCO_2-eq/kWh for the concept with Platform A and Platform B, respectively. On the other hand, changes only in lifetime leads to a variation between 21.7 gCO_2-eq/kWh and 43.4 gCO_2-eq/kWh for the concept with the Platform A and between 16.4 gCO_2-eq/kWh and 32.7 gCO_2-eq/kWh for the concept with the Platform B. By considering 15 years of lifetime, the calculated values are 43.4 gCO_2-eq/kWh for the first case and 32.7 gCO_2-eq/kWh for the second. With 30 years of lifetime, the value for the first case is 21.7 gCO_2-eq/kWh and the value for the second case is 16.4 gCO_2-eq/kWh.

Chapter 5

Conclusions

In conclusion, the environmental performance of two different floating offshore wind energy parks was assessed. The first case had a floater made of steel and the second case had a floater made of concrete. These two cases were assessed by using two different methods in A4 (Transportation to the construction site) and A5 (Installation) stages. The second method, (ii), was assumed as a baseline scenario which was more conservative. However, in method (ii), there is a need of improvement for the calculation of the emissions of the onshore transports with trucks.

It was found that the first case has more impact on GWP (Global Warming Potential) than the second case. The baseline scenario of the two cases has similar results with results from other investigations for wind energy sources with different nominal power than 15 MW. Some similar results are observed, also, with other energy sources such as hydropower and solar PV power. The examined systems have less emissions than power associated with hydrocarbons and thermal power and more emissions than nuclear power. The main contributor of the emissions is the A1-3 stage (Raw material supply, Transport and Manufacturing) which is also observed in other investigations of floating offshore wind energy systems. In this stage, RNA is the main contributor in emissions followed by the platform. Furthermore, the steel material has the largest impact in the results of the A1-3 stage. Finally, by considering different capacity factors and years of lifetime, the results vary between 21.5 gCO_2-eq/kWh and 46.7 gCO_2-eq/kWh for the first case with Platform A and between 16.2 gCO_2-eq/kWh and 35.2 gCO_2-eq/kWh for the second case with Platform B.

It is worth noting that the GHG emissions don’t represent the whole environmental footprint. In further research, more impact categories need to be taken into consideration. More detailed data (e.g. EPDs from companies) for the components should be created including a wide range of impact categories and accurate data. This might require looking at different types of data for stages such as transportations and O&M where only data for fuel consumptions were gathered in this research work. This availability of data may also contribute to the results which show uniformity in number and content of the considered stages. It is worth to look further at the gaps found in maintenance and installation operations and manufacturing processes.

Moreover, there is a need of a closer look at the O&M stage. Spare parts and fuel consumptions need an accurate calculation. According to the authors of study [34] the emissions from O&M are higher than the results from this investigation and the other aforementioned investigation about floating wind energy. Applying models with failure rates from the economic sector seem to be the best way of O&M evaluation.

O&M actions are mainly related to the turbine and not to the floater. Therefore, more studies can rely on current data about failures in offshore wind farms and use these data in the forthcoming studies. It is mentioned here that failure rates are meaningful in the case of wind farms but not in the case of a single turbine.

It is different to consider a wind farm than a wind turbine. Environmental footprint from export cables, inter-array cables and substation should be taken into account.

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