Title
An LCA Review of Current Status and Future Trends of the Offshore Wind Industry

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An LCA Review of Current Status and Future Trends of the Offshore Wind Industry

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Abstract

The offshore wind industry is constantly evolving, and this evolution is not limited to wind turbines, but extends to the production, installation, operation, maintenance, and decommissioning phases of offshore wind farm life cycles. To better understand how this evolving technology has been assessed in research, this study undertakes a systematic review of published life cycle assessment of offshore wind. The review interrogates how the life cycle phases of offshore wind farms are represented and modeled in LCA and identifies gaps between current practice in LCA and the latest technology used in the industry. Additionally, a review of siting parameters (e.g., geographic location and distance to shore), reference sources, phase assumptions, and impact categories evaluated is presented. The obtained results show the need for updated models that better reflect the industry's current practices and to conduct studies for developing markets where offshore wind has potential for growth, but comprise a small number of the previous studies conducted.

Table of Contents

List of Figures

List of Tables

1. Introduction

Climate change produced by anthropogenic activities is responsible for global temperature rise and its associated effects on oceans, the poles, glaciers, and extreme natural events. The increase in sea levels, ocean acidification and warming, the reduction of the ice sheets in the Antarctic and Arctic poles, and an increasing number of extreme natural events are all consequences of global warming produced by the increasing levels of greenhouse gases (GHG) (NASA, 2021).

In an attempt to slow global warming, the world's leading economies have made the commitment to reduce GHG emissions, which rise to 52.4 gigatonnes of equivalent carbon dioxide (GtCO2e) in 2019 (United Nations Environment Programme, 2020). Many countries have committed to reaching net-zero GHG emissions by 2050 or 2060 as part of this commitment. Electricity generation is the main sector associated with CO_2 emissions (which has a 75% share in the global greenhouse gases), followed by the transportation and the industrial sectors. Renewable energies, including solar and wind, play a major role in replacing fossil fuels and in assuring a stable and affordable energy supply (IEA, 2021) (United Nations Environment Programme, 2020).

The wind energy sector, which contributed a total power capacity of 746 GW of clean energy in 2020 with an annual installation rate of 93 GW, is estimated to require an annual deployment of 160 GW by 2025 and 280 GW by 2030 in order to meet the future net-zero emissions requirements, according to IEA Net Zero 2050 scenario (IEA, 2021). Current wind energy capacity is dominated by onshore wind. In 2019 and 2020, the offshore wind industry continued to grow, installing up to 6 GW per year, and reaching a total of 35.3 GW of installed capacity globally (GWEC, 2020a, 2021). It is estimated to reach up to 21% of the worldwide wind energy in 2025 (GWEC, 2021).

Until 2020, the UK led the world in offshore wind, with 10.2 GW of total installed capacity, followed by China with 9.9 GW, and Germany with 7.7 GW. Since 2018, China has seen rapid growth, leading the world in annual installations of offshore wind. In Europe, the countries leading annual offshore installations are the Netherlands, with 1.5 GW installed in 2020, and Belgium with 706 MW. South Korea, with 60 MW, and the US with 12 MW, were the leading countries outside of Europe (EU) and China in new installations in 2020 (GWEC, 2021).

More than 200 GW of new offshore wind capacity is expected between 2020 and 2030. The EU and Asia are expected to continue leading the industry with the introduction of a stronger US presence in 2024. At the end of 2019, the US Bureau of Ocean Energy Management (BOEM) auctioned sixteen commercial leases of offshore wind, which could produce more than 21 GW of power capacity in the US. States along the east coast have offshore wind procurement targets of 28.1 GW, of which it is estimated that 22.6 GW could be installed by 2030 (GWEC, 2020b; IEA, 2019).

1.1 Study Objectives

The objective of this study is to undertake a systematic review of published life cycle assessments (LCAs) on offshore wind energy and compare it to the latest technology and status of the offshore wind industry (OWI). This review studies the life cycle phases modeled in offshore wind LCAs, the technology considered for the different components present in an offshore wind farm (OWF), the location and siting parameters of the studies, and the impact categories considered. Additionally, it evaluates how different offshore wind markets are represented by the LCAs literature and the availability of LCAs results for developing markets with high wind energy potential.

Figure 1 shows the main concepts required to understand the modeling decisions of the OWF LCAs and the interdependence of these concepts. Each point is presented individually in this introductory section.

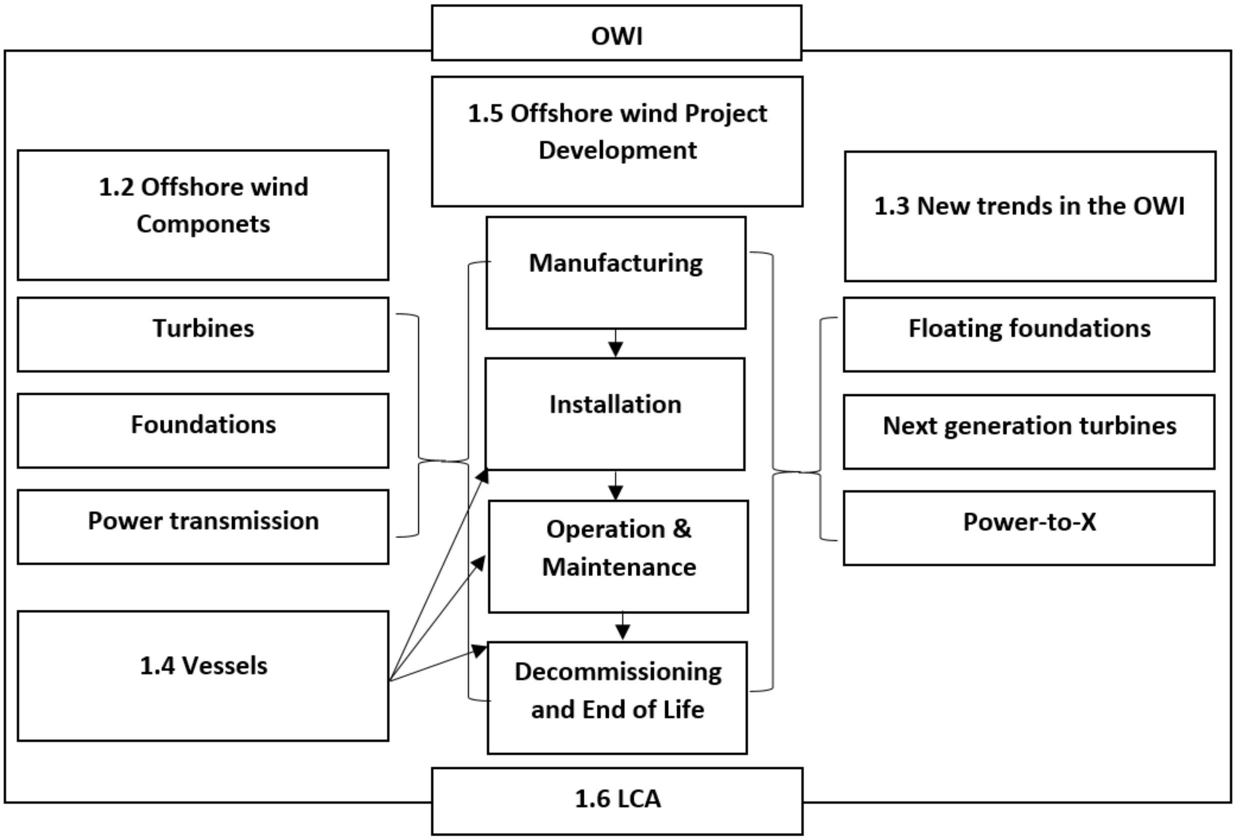

Figure 1: Concepts required for evaluating the researched LCA models.

1.2 Offshore Wind Farm Components

Offshore wind turbines (OWTs), along with their foundations and the power transmission system, are the main components of offshore wind farms (OWFs). OWTs have the same main components as onshore turbines, but are bigger than onshore turbines, and are designed to handle the aggressive environment present offshore and to require less maintenance due to its high cost in offshore environments.

1.2.1 Offshore Wind Turbine (OWT)

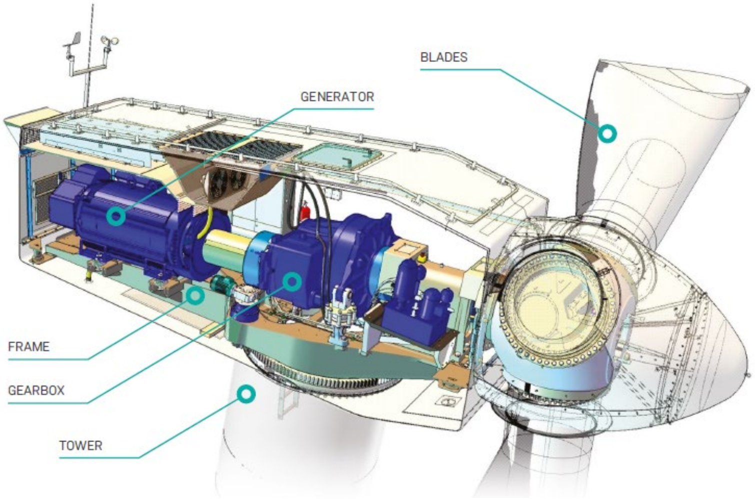

Figure 2: OWT diagram (Siemens Gamesa, 2018)

OWTs are horizontal axis wind turbines, meaning they intake wind in horizontal directions and do not work in turbulent air flows, and consist of a tower, nacelle, hub, and three blades. The tower is the cylindrical structure that allows the rest of the components to reach high wind altitude and in which the nacelle is supported. The nacelle contains the power generation system (Figure 2), which consists of a generator (transform the mechanical power into electricity), gearbox (speed up the rate of rotation, from 5 to 15 rpm to up to 1500 rpm in high-speed gearboxes), low-speed and high-speed shaft that connect these two elements and the drivetrain. Direct drive turbines do not require a gearbox but use low rotation speed generators. The blades capture the kinetic energy of the wind, transferring torque to the drivetrain. The hub connects the blades with the drivetrain (Birkeland, 2011; BVG Associates, 2019; Úna Brosnan and Andrew Thompson, 2018; Uraz, 2011).

1.2.2 Foundations

The most common OWT foundations are fixed bottom foundations (Figure 3), which can take on a number of designs including gravity base, monopile, suction bucket, tripod, jacket, and high rise pile cap (HRPC):

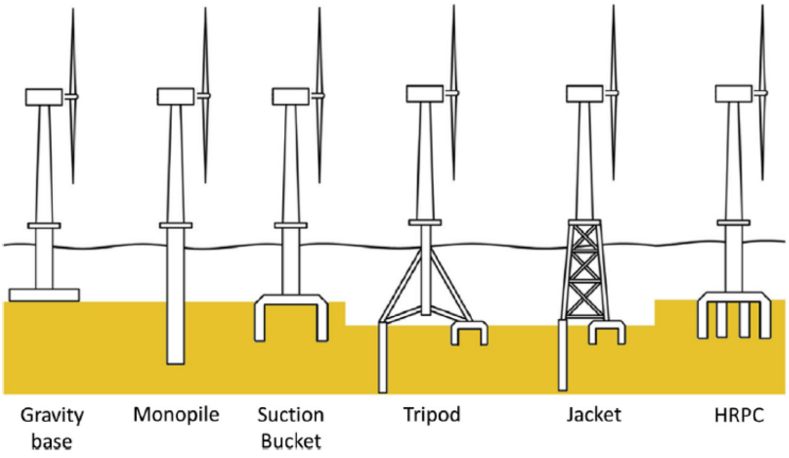

Figure 3:OWT foundations (Oh et al., 2018)

- Gravity foundation: It consist mostly of reinforced concrete with ballast. It is the first type of foundation ever used in an OWF. Its installation requires seabed preparation (Díaz & Guedes Soares, 2020; X. Wang et al., 2018).
- Monopile: It consists of a steel hollow cylinder that is inserted into the seabed to provide resistance. It requires minimum to none seabed preparation during installation, which is performed by hydraulic hammering into the seabed (Díaz & Guedes Soares, 2020; X. Wang et al., 2018).
- Suction bucket: Using an upside-down bucket and pumping out the water, the foundation sinks into the seabed due to the pressure difference between the interior and the exterior of the bucket (Díaz & Guedes Soares, 2020; X. Wang et al., 2018).

- Tripod: It is a three-legged steel jacket with a central steel column. It provides better stability and stiffness to the entire structure than monopiles and can be installed into larger water depths. However, it is a heavier foundation that requires a more complex installation hence higher cost (Díaz & Guedes Soares, 2020; X. Wang et al., 2018).

- Jacket structure: This structure is a three or four-legged pile with interconnected cross braces. The steel legs are inserted into the seabed with the support of pile sleeves (Díaz & Guedes Soares, 2020; X. Wang et al., 2018).

- High rise pile cap (HRPC): It consists of a concrete bearing platform with steel pipe piles at the bottom of it. It is widely used in Asia, but it has not been installed on any other continent (X. Wang et al., 2018).

OWTs may also use a floating foundations. The floating system consists of a floating platform plus an anchor system attached to the seabed. Floating foundations allow access to deeper waters, and therefore, better wind resources (X. Wang et al., 2018).

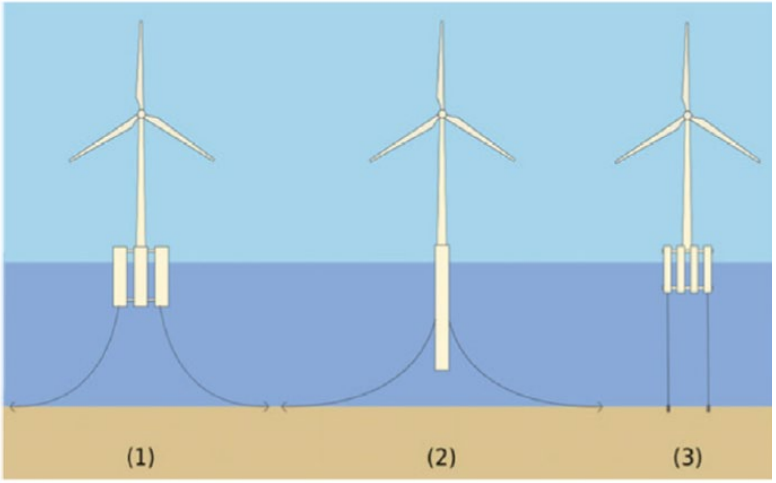

Figure 4: Floating concepts: (1) semi-submersible platform; (2) spar; and (3) tension leg platform (Wu et al., 2019)

- Semi-submersible platform: The semi-submersible platform consists of three vertical columns connected with a central one using short cylinder pontoons. The main column is connected to the tower. The waterplane area of the foundation is a key feature to achieve stability. It utilizes a catenary mooring system (Raadal, 2014; Robertson & Jonkman, 2011).
- Spar: It is basically a large cylindrical buoy, where the lower part of the structure is filled with heavier ballast to achieve a gravity center significantly lower than the buoyancy center. It utilizes a catenary mooring system consisting of three lines in a delta connection (EWEA, 2013; Robertson & Jonkman, 2011).
- Tension leg platform (TLP): This system consists of a ballasted platform. It is moored by four pairs of vertical tendons. The working principle is that the bigger design, for excess in buoyancy, assures tension in the mooring lines (EWEA, 2013; Robertson & Jonkman, 2011).

1.2.3 Power transmission

An OWT generates AC current and delivers it to an AC grid. Therefore, an AC transmission system is the most logical option to avoid the cost and transmission losses of changing from AC to DC, which requires converter stations at both ends of the system. However, the AC system requires reactive compensation to be viable for long distances, making DC a suitable alternative for those cases (Birkeland, 2011; Soares-Ramos et al., 2020).

A transformer inside each OWT elevates the voltage from the low generated voltage in the generator to up to 30 or 36 kV (Negra et al., 2006). Depending on the distance to shore and the total power capacity of the OWF, a cable, part of the array cables system, transmits the power to either an offshore substation on-site or an onshore substation. In the case of the offshore substation, the voltage is elevated again up to 130 or 150 kV to be transmitted to the onshore substation by an export cable (Birkeland, 2011). Each of these elements is described in more detail below.

- Array cables: Submarine cables that connect the turbines with the substation. The most common design is for an AC current between 30 to 36 kV, and it consists of several layers with the conductor in the center surrounded by insulation layers and external protection layers. Each cable can have up to three-core copper conductors (Birkeland, 2011; Soares-Ramos et al., 2020).
- Export Cables: These cables connect the offshore substation with the onshore substation. These cables can be either high voltage direct current (HVDC) cables or high voltage alternating current (HVAC) cables. Their basic design is similar to the cables used for the array system but for a voltage range between 110 and 320 kV. Countries including Germany mostly use HVDC 320 kV transmission, while the UK mostly uses HVAC 220 kV, and Denmark uses HVAC 150 kV (Birkeland, 2011).
- Substation: The goal of the substation is to collect and export the energy generated by the OWF and reduce electricity losses during the transmission to the coast. The step-up of voltage also reduces the number of subsea cables required. Substations are installed in the same foundations as the OWTs. The associated size and weight of the substation have a strong impact on the OWF construction cost (Úna Brosnan and Andrew Thompson, 2018).

1.3 New trends in the offshore wind industry

1.3.1 Floating foundations

With floating foundations, turbine deployment can be made further offshore, with significantly bigger water depth and greater wind exploitation. It provides many other logistic advantages like being assembled at the harbor and then towed to the site. Floating technology is starting to be a commercially competitive technology. In 2019, 11.4 MW of floating offshore wind were installed, getting to 65.7 MW of floating wind installed globally. With the UK (32 MW), Japan (19 MW), and Portugal (10.4 MW) as the main locations (GWEC, 2020a; Úna Brosnan and Andrew Thompson, 2018).

1.3.2 Next Generation Turbines

Increasing the rotor diameter and getting access to higher winds improves the turbine's capacity factor. This increases the cost of the turbine itself, but a bigger turbine with increased power capacity allows for reducing the number of total foundations and associated power transmission system in an OWF for a specific power generation target, helping reduce the levelized cost of wind energy. This trend has made companies like GE or Siemens develop OWTs that could reach up to 15 MW of power compared to the average installed turbine of 3 to 4 MW (Díaz & Guedes Soares, 2020). It is estimated that this trend will continue, reaching models of around 20 MW generation capacity by 2030 (GWEC, 2020a). Two examples of next generation OWTs are described below:

- Haliade-X 12 MW (GE): The Haliade-X 12 MW, with a rotor diameter of 220 meters and a total height of 248 meters, is the most powerful OWT in the world. Until November 2020, only one prototype was located in Rotterdam, but 109 units will be installed in the Dogger Bank OWF by 2023. Thanks to optimization done on the prototype it reached a power operation of 13 MW in October 2023, and a 14 MW optimization is currently under research (GE, 2021a, 2021b).
- The SG 14-222 DD (SIEMENS): With serial production starting in 2024, the Siemens Gamesa SG-14-222 DD OWT would be the most powerful direct-drive OWT on the market, with a nominal power of 14 MW and 222 meters of rotor diameter (SG, 2021).

1.3.3 Power-to-X

Power-to-X is an energy storage technology that is promising for intermittent renewable energy generation, especially offshore wind. Using electrolysis, the generated electricity can be used to produce hydrogen (H_2), which can be transported and stored for use in power-to-gas (production of methanol using H_2), power-to-liquid fuels (production of crude or other fuels by combining captured CO_2 with H_2), or power-to-heat (using heat pumps or electric boilers). Alternatively, this green hydrogen can also be stored and transported for industry and transportation applications (GWEC, 2020a). By converting electricity into H_2, the problem of intermittency of generation and the potential mismatch in electricity supply and demand can be addressed.

New projects and developments associated with Power-to-X are currently under study. A project in the Netherlands, NorH2, plans to generate 4 GW of green hydrogen by 2030 and 10 GW by 2040 using offshore wind. Denmark has similar projects called VindØ and Greater Copenhagen that are expected to come online by 2030. Manufacturers are also working on stand-alone systems; Siemens plans to develop an electrolysis system integrated into its SG 14-222 DD with a target demonstration by 2026 (GWEC, 2021).

1.4 Vessel Operations Related to the Offshore wind Industry

Vessels play a key role in the OWF, during the different phases of an OWF different types of vessels are required. All of them can be categorized as either construction vessels or support vessels (Douglas-Westwood, 2013).

1.4.1 Construction Vessels

- Heavy lift vessels (HLV): An HLV has at least one heavy-lift crane and potentially other smaller cranes on board. It is used to load, transport, and unload large and heavy components. Mostly used in the substations installation, heavy foundations installation, and heavier OWT components installation. They are widely used in offshore oil & gas and when not self-propelled, often called non-powered heavy crane barges (Douglas-Westwood, 2013; Úna Brosnan and Andrew Thompson, 2018).

- Jack-up Vessels: These are self-elevating vessel that can elevate above the sea surface using mechanized jack-up legs supported by the sea bed. One of the most frequent vessels used for early installation of OWFs, both for transport and lifting. It is usually equipped with smaller cranes than an HLV, but Its jack-up legs made it less sensitive to weather conditions. It can be self-propelled or not (assisted by tugs) (Douglas-Westwood, 2013; Úna Brosnan and Andrew Thompson, 2018).
- Turbine Installation Vessels (TIVs): This is the only purpose-built vessel for the OWI. It is a self-powered vessel, with at least one heavy lifting crane and 4 to 8 jack-up legs. Depending on the specific TIV, it could transport up to ten complete OWTs of up to 6 MW power (Douglas-Westwood, 2013).
- Cable-Lay Vessels (CLV): These are vessels used for the underwater cable installation. New CLVs are able to lay the cable and trench it on the sea bead (using an underwater plow). However, they are limited to deep waters. For shallowed waters, cable-lay barges are used, and rock dumping methods are implemented for the cable trenching (Douglas-Westwood, 2013; Úna Brosnan and Andrew Thompson, 2018).

1.4.2 Support Vessels:

- Tugs: These vessels are widely used during the installation and maintenance phase, from towing non-powered vessels, to trenching, escorting, and anchor handling. Different subcategories of tugs are used in the OWI depending on their capability to operate on the open sea, associated engine power, and potential articulation with a corresponding barge (Douglas-Westwood, 2013).

- Transport barges: Mostly used as a cheap feeder vessel for the OWF construction, most of these vessels are non-self-propelled and extremely sensitive to weather conditions (Douglas-Westwood, 2013).
- Survey Vessels: Used for obtaining information about the seabed. High technology vessels equip with multi-beam echo sounders, sensors, and in some cases, autonomous underwater vehicles (AUVs), which allow them to perform environmental, geophysical, and geotechnical surveys. In most cases, geotechnical work requires the assistance of other vessels equipped with drilling equipment (Douglas-Westwood, 2013).

1.5 Offshore Wind Project development

The development of an OWF has a timeline that varies from one region to another. In Europe it is takes between 4 to 5 years from the moment the developer identifies the project site until the project completion. Planning the development of an OWF requires assuring the project approval and permits, doing the site investigations and data collections, assuring the project's finance and conducting major contract awards, the manufacturing of all the components, and the corresponding installation. Once installed and in operation, it requires maintenance during its lifetime, which could include a potential life extension. Finally, at the end of the lifetime, the decommissioning of the plant is performed (Úna Brosnan and Andrew Thompson, 2018).

1.5.1 Manufacturing

The manufacturing of OWTs, substation, and foundations could require up to three years, depending on the size of the project. The manufacturing of these elements is not necessarily performed by only one company. Beatrice OWF has 84 jacket foundations fabricated by three different fabrication yards, which utilize different fabrication methods. Ronland OWF, in Denmark, has both Vestas and Siemens Gamesa OWTs. In China, Jiangsu Rudong OWF has both Siemens Gamesa and Sinoval OWTs installed in monopiles and jacket foundations. The manufacturing phase, where most of the materials and energy are consumed, aggregates a wide range of companies not only in the OWT fabrications but also in the foundations and substation fabrication (Díaz & Guedes Soares, 2020; Kaldellis & Apostolou, 2017; Úna Brosnan and Andrew Thompson, 2018).

1.5.2 Installation

Depending on the region and size of the OWF, the installation phase could take up to three years. It is possible to overlap the schedule by up to one year with the manufacturing phase (Úna Brosnan and Andrew Thompson, 2018). There is no globally accepted standard procedure for an OWF installation (Quandt et al., 2017; Rippel et al., 2019), but a general methodology would consist of: Logistics tasks on the port, foundation installation, installation of transition piece if applicable, OWT installation, cable laying operations, substation installation, and commissioning (Douglas-Westwood, 2013).

- Logistics tasks on the port: These tasks depend on the assembly strategy taken for the OWTs and the type of foundations. In the base port, the tasks can go from the storage of all components and the turbines pre-assemble onshore to just partial storage of some components (Douglas-Westwood, 2013).
- Foundation installation: Each foundation requires a different type of installation method. Depending on the foundation, some can be floated to the site, like monopiles or gravity foundations, and others must be transported on transportation vessels. Gravity-base foundations need seabed preparation for then being lifted and placed by a crane barge. Monopiles require hammering into the seabed, but no previous preparation of the seabed. Tripods and jackets have

small piles which can be installed before or after the rest of the foundation, which requires heavy lifting capacity for installation. Some foundations, like monopiles, require a transition piece before installing the OWT, which would extend the associated installation window. Most of these foundations can be installed by a wide variety of vessels. Therefore, the installation time varies significantly even for the same type of foundation (Douglas-Westwood, 2013).

- Turbine installation: The assembly strategy of the OWT would depend on the size of the turbine, the available vessels, and the site location. The main strategies are:
  - Conventional installation: Components are stored in the base port and then loaded and transported by the installation vessels. Once at the site, linear assembly is implemented: first the tower, then the nacelle, followed by the hub and the blades. Once the vessel runs out of installation sets, it returns to the base port for reloading and starting the assembly process again (Rippel et al., 2019).
  - Pre-assembly: Either a rotor-star (three blades and the hub) or a bunny-ear (two blades and the nacelle) are assembled onshore for then being transported and installed on-site. On the one hand, this strategy reduces the impact of bad weather and the complexity of offshore operations. On the other hand, it requires more loading capacity and increases the requirement for lifting cranes (Rippel et al., 2019).
  - Feeder ship concepts: Transportation vessels deliver the different components from either the base port or the manufacturer port to installation vessels that remain on site. This methodology allows reducing the storage space required in the base port and the transportation of the installation vessel from the port to the site. This methodology requires transportation vessels that can transfer the components ship-to-ship.

Additionally, a just-in-time supply chain is required for achieving an efficient performance in the installation (Rippel et al., 2019).

- Floating Technology: It has allowed both foundations and OWTs to be pre-assembled onshore, or in shallow water, and then towed to the site and moored to the seabed (Rippel et al., 2019).
- Cable laying operations: The cable-laying vessel (CLV) is required for this operation. It has a carousel where the cables are rolled and stored. On-site, the cables are unwounded, straightened, and placed. The same vessels can be used for both array cables and export cables. Export cables installation may require larger CLV with bigger carousels. To bury the cables under the seabed, operations can be done in one-stage or two-stage. In the first one, cables are laid and buried using a plow towed by the same vessel or a tug. In the second one, the burying of the cable is performed by another vessel equipped with a trenching AUV (Douglas-Westwood, 2013).
- Substation installation: Installed after the foundations and the underwater cables. The installation of the substation module requires a complex lifting maneuver, with cranes in the order of 900 tons to 3.000 tons, present only in large heavy lift vessels (Douglas-Westwood, 2013).
- Commissioning: This last step requires the use of personnel transfer vessels (PTVs) for transporting the personnel that verifies the correct installation and functionality of all OWTs systems and substation systems (Douglas-Westwood, 2013).

1.5.3 Operation and Maintenance (O&M)

OWFs are typically managed from an onshore local base relatively close to the wind farm, which helps coordinate the operation and maintenance of the wind farm. As with any power plant, an OWF could be subject to corrective, preventive, or predictive maintenance. Corrective maintenance is performed only when the failure of a component has already occurred, preventive maintenance is associated with performing scheduled maintenance based on a time cycle or operation cycle, and predictive maintenance seeks only to perform maintenance before a potential failure occurs, based on sensor measurements and analytic prediction models. The need to operate with the highest availability possible and the high cost of offshore maintenance has put significant pressure on improving predictive maintenance technology for the OWI, which has resulted in new sensors technology with higher reliability and smaller cost than previous ones, that allowed the development of a condition monitoring system (CMS) with an online diagnostic of the whole OWF. The CMS consists of several sensors located mostly in the OWT and the foundation, providing specific information about the operation conditions and components status. This has enabled digital-twin platforms which can reproduce how the OWF would react to different operations and weather conditions, improving the predictions on the failure rate of the different components (Ren et al., 2021; Sivalingam et al., 2018; Van Bussel & Zaaijer, 2001).

Once maintenance is planned, personnel need to be transported to the site and lifting operations could be required depending on the type of maintenance. Crew transportation can be done either by different types of vessels or by helicopters. The transportation alternative is strongly affected by the environmental conditions (Halvorsean-Weare et al., 2013),as helicopters are limited by visibility and wind speed (Dai et al., 2015). Even though personnel transportation is more frequent than replacing components, the latter is the main contributor to the high maintenance costs due to the use of heavy lifting cranes (Van Bussel & Zaaijer, 2001) and the main contributor to GHG emissions due to fuel consumption of the heavy lifting vessels (S. Wang et al., 2019).

1.5.4 Decommissioning and End of Life

Decommission is generally considered the inverse process of the installation, and consists of dismantling the OWT, power transmission system, and partial or total section of the foundations. The decommissioning process starts with dismantling the components offshore for transport to the base port, where further dismantling is done. Once finished, the subcomponents are transported to the recycling or waste processing facilities (Spielmann et al., 2021).

The offshore dismantling of OWT consists of the dismantling of blades, nacelle, hub, and tower. The respective onshore dismantling consists of extracting the gearbox, generator, shafts, and bearings (Spielmann et al., 2021). Since foundation structures become part of the marine ecosystem, providing shelter for different species, they could be partially removed (Krone et al., 2017; van Hal et al., 2017). Substations are removed and dismantled in a shipyard (Úna Brosnan and Andrew Thompson, 2018), where subsea cables can be left in situ only if they are buried more than 1 meter below the seabed; if not, they are removed (Topham & McMillan, 2017).

After decommissioning, the removed elements can be either reused, recycled, or disposed. Only a limited number of components in an OWF can be reused since they need to have at least 10 years of extended life at the moment of the decommissioning to be reasonable to incur in the inspection, transportation, and installation in other OWF. Recycling, which implies recovering the raw materials of the components, is more feasible. Elements such as gearbox, generators, and towers consist mostly of metals like steel, aluminum, and copper, which can be recycled. A recycling rate is the amount of raw material that can be recovered from the recycling process. Generally, any of the mentioned components would have a metal recycling rate above 80%. The amount not recovered is considered to be disposed of. Other components like blades, mostly made of polymers and glass, are more difficult to recycle and are generally disposed either by incineration, high-temperature burning, or landfill, the burial of the waste (Chen et al., 2021; Topham & McMillan, 2017).

1.6 Life Cycle Assessment (LCA)

Life cycle assessment (LCA) provides a methodology to evaluate with a systematic approach the environmental impacts of a studied system over its entire life cycle, from raw material extraction to final disposal. The LCA includes four phases; goal and scope definition, life-cycle inventory analysis, life-cycle impact assessment, and interpretation (ISO 14040, 2006).

The goal and scope define the application and purpose of the study. It describes the reasons for doing the study, the audience, and details of the methodology. The scope definition includes the description of the system boundary and the selection of the functional unit. The system boundary should include all important processes and sub-processes since they have a direct impact on the results. The functional unit is used to normalize the input and output of data, based on a unit of service of the studied system, which is also used to quantify its performance (ISO 14040, 2006).

The life-cycle inventory analysis (LCI) is the quantification of relevant input and output flows of the system through its life cycle. This data collection and calculation is essential to determine the life-cycle impact assessment (LCIA). LCIA gives meaningful indicators to describe the environmental and human health impacts of the studied system. There is more than one methodology to characterize impacts, and not all methodologies consider the same impacts. The most commonly included impact category, Global Warming, is determined by translating GHG into CO2 equivalent (CO_2e), which is based on the comparison between cumulative radiative forcing from an emissions of any well-mixed GHG to a reference gas, in this case, CO_2, over a specific time horizon, usually 100 years (EPA, 2021; ISO 14040, 2006).

Interpretation is present in all phases of the LCA, but it is also the phase where all the findings from LCI and LCIA are considered together to generate the final conclusion of the study and potentially to provide recommendations to the targeted audience.

2. Methodology

The systematic literature review was conducted using the following journal databases: Google Scholar, Web of Science, ScienceDirect, and Scopus. A keyword search was conducted using two sets of terms. The first one consisted of: “Life Cycle Assessment'', “LCA”, “Life Cycle Assessment (LCA)", “Greenhouse gases “,“GHG", and “Carbon footprint“. The second set of terms was: “Offshore Wind Farm'', “Offshore Wind Energy“, “Offshore Wind Power“, “OWF“, and “Wind Energy“. The first set of terms was used only in combination with the second set, resulting in 30 searches. Additionally, the second set of terms was also used on its own to evaluate if potential LCAs studies were missed in the combination of keywords, getting to a total of 35 searches. Due to the scarce amount of literature about the life cycle assessment of offshore wind, all of the papers that matched the search criteria were added to the review. Reference scanning and citation tracking were also used as methods to identify potential papers.

The review began with the collection of parameters from each reviewed paper. The parameters collected in the review process were divided into four main sections as follows:

- Article information: Primary author, title, and year of publication.
- Wind farm system: location (country and continent), installed capacity of the wind farm, power capacity of the turbines, number of turbines, drive technology, type of foundation, electrical installation (types of array cables and export cables, and number of offshore substation consider), installation site (mean distance to coast, and mean depth of the water), and finally the lifetime of the wind farm main components (turbine, offshore substation, and connection cables).
- Phase consideration: For this section, the parameters analyzed were selected in relation to the different phases;

    - Transportation: Turbine production location and transport from the manufacturing location to the offshore wind farm (OWF) site.
    - Installation: Installation strategies, harbor upgrade works, installation task listed, work time calculation, foundation installation rate, turbine installation rate, type of vessels mentioned, vessel fuel consumption, and data source of the Installation section.
    - Maintenance: Maintenance services by year (using vessels, and using helicopters), and OWF components (Blades, nacelles, and gearbox) replacement over their lifetime.
    - Dismantling & End of Life (EoL): Scope of decommissioning, distance to the treatment facilities, EoL strategy (recycling, landfill, and incineration).
- Life Cycle Assessment: For this section, the functional unit, system boundary, and LCIA were identified. The life cycle impact categories evaluated were: CO2e, energy return of investment (EROI), cumulative energy demand (CED), energy payback time (EPT), abiotic depletion, ecotoxicity (aquatic), stratospheric ozone depletion, photo-oxidant formation, land use, acidification, eutrophication, ecotoxicity (terrestrial), and human toxicity. Finally, the contribution from different phases to total CO2e and EPT was also reviewed.

The resulting table from this review, Table A, is presented in the supplementary material. The results and conclusions of this study are based on the comparison of this information with the literature presented in the introduction section for the different components or aspects of the offshore wind industry.

3. Results

For the review, 19 studies (including journal articles, reports, and theses) published in English between 2004 and 2019 were selected. An overview of the impact categories evaluated by these studies is presented in Figure 5. It shows that the most frequently considered impacts are; global warming (in units of CO_2e) and Energy Payback Time (EPT), with 89.5% and 63.2%, respectively, of studies considering these impacts. The rest of the impacts are considered in 5.3% to 42.1% of the reviewed studies. One study, Jungbluth et al. (2005), does conduct an LCIA, but instead stops at the life cycle inventory stage. Even though all studies tracked flows of energy and emissions in order to calculate impact assessment indicators, only a few of them report the emissions inventories, as summarized in Figure 5.

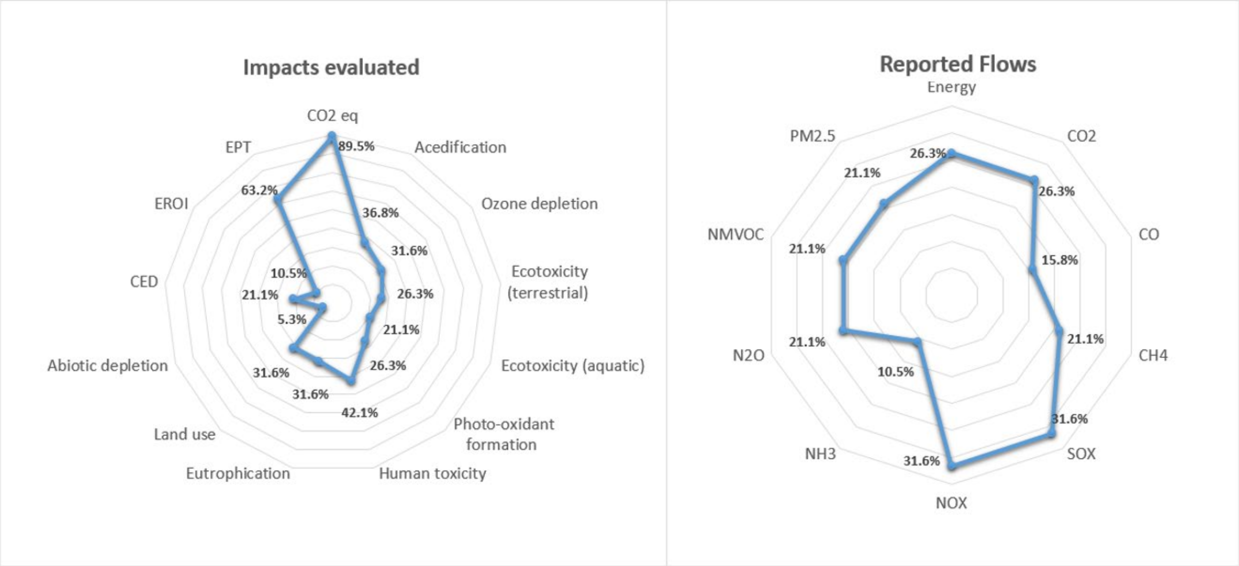

Figure 5: Percentage of studies that consider the listed impacts (left) and flows (right).

When comparing the global warming and EPT results obtained by the different LCAs reviewed, significant variability can be observed, as shown in Figure 6. The cause of these large differences and the respective analysis are presented in sections 3.3.1 and 3.3.2.

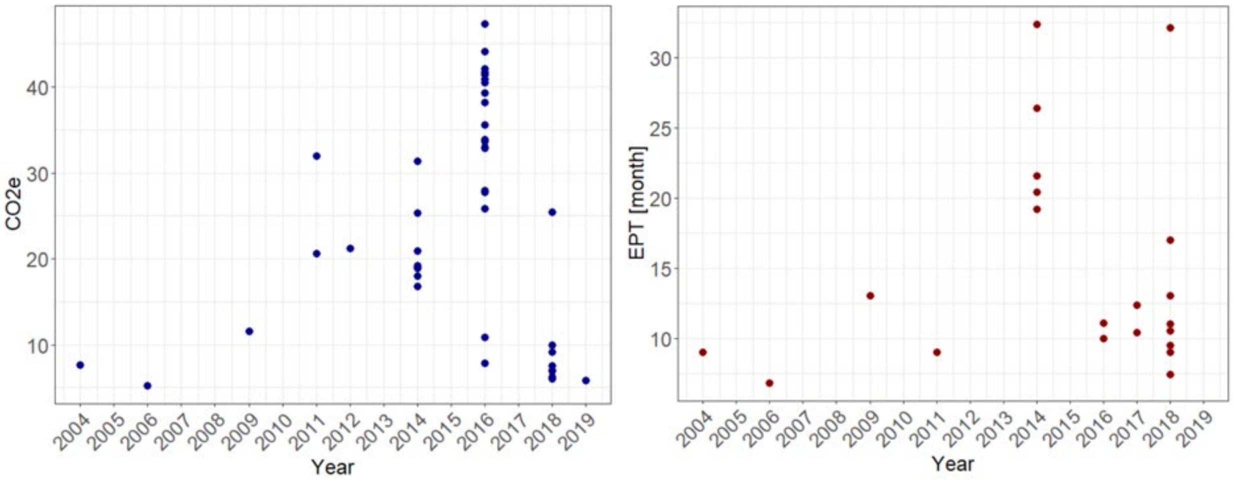

Figure 6: CO_2e & EPT of reviewed studies

To assess whether and how the existing body of LCA literature represent the current state of the OWI, a detailed evaluation of the modeling parameters and assumptions is presented in this section.

3.1 Key modeling choices and assumptions in offshore wind farm LCA studies

3.1.1 Location evaluation

Based on the reviewed studies' location selection, Europe accounts for 68% of the LCA studies. In comparison, Asia and North America account only for 10.5% each. Unspecified locations account for another 10.5%. For Europe, the LCAs are conducted assuming the OWFs are located in Germany, the United Kingdom, Denmark, Norway, or Switzerland. Previous studies for Asia are only for locations in China or Taiwan, and North American studies are only from the U.S.

3.1.2 Power installed

The reviewed LCA papers model turbine power in the range of 2 to 8 MW and OWF power between 40 to 640 MW. The 5 MW turbine is the most frequently modelled (36% of the cases), followed by the 2 MW turbine (26%), with the rest of the power values having a uniform distribution. The OWF power is mostly between 300 and 400 MW (31%), followed by 100 to 200 MW (26%). Finally, the studies using 80 turbines per OWF are the most frequent (36%).

As shown in Table 1, the European LCAs modelled OWF with higher power capacity than other locations due to both the power capacity of the turbine and the number of turbines per OWF. In addition, due to the larger contribution of European LCAs to the total number of studies, the worldwide results are highly influenced by the European results.

Table 1: Power parameters of an OWF model for different locations. Worldwide: Av.=Average; M.F.V.=Most Frequent value; F.=Frequency.

Power Parameters	**Worldwide**			**Europe**			**Asia** [a] **(Av.)** [MW]	**North America** [a] **(Av.)** [MW]	**Not Specified** [a] **(Av.)** [MW]
	Av. [MW]	**M.F.V.** [MW]	**F.**	**Av.** [MW]	**M.F.V.** [MW]	**F.**			
Turbine power	3.9	5.0	36.8%	4.4	5.0	46%	3.2	3.0	2.3
OWF power	253	300-400	31.6%	312	300-400	38%	103	151	126
Number of Turbines per OWF	63	80.0	36.8%	70	80	54%	40	51	51

Note:

[a] Only the average value is presented for each parameter since there are only two publications in each scenario.

Regarding the turbine technology itself, only one paper and two reports consider direct-drive turbines while the rest of the papers and reports consider gearbox technology. The importance and consequences of the inequitable distribution of studies from a geographical perspective and the technology assumptions are explored further in section 4.1 of the Discussion section.

3.1.3 Foundation and Site location

Table 2 shows that almost all studies consider some type of fixed foundation (89%), while only a few consider a floating foundation type (26%). As shown in Table 2, North American and European studies consider both fixed and floating alternatives for their models, and studies from Asia only consider fixed foundation technologies. Regarding the different foundation technologies, monopile foundations are the fixed foundation with the highest frequency in all locations. The high rise pile cap foundation is only modeled in Asia, and no publication considers the jacket using suction bucket (which widely used in offshore platforms and implemented in OWFs in China's Qidong and Xiangshui OWFs) (X. Wang et al., 2018).

From the floating alternatives, tension leg spar and semi-submersible are the most frequent ones (60% and 40% respectively).

Table 2: Frequency of the foundation selections in the models, for different locations.

Foundation	Locations				
	World Wide	Europe	Asia	North America	Not specified
Fixed	**89**%	**92**%	**100**%	**100**%	**50**%
Monopile	41%	31%	50%	100%	-
Gravity	18%	8%	-	50%	100%
Tripod	12%	8%	-	50%	-
Jacket (Pile)	18%	23%	-	-	-
Jacket (Suction Bucket)	0	-	-	-	-
High Rise Pile Cap	6%	-	50%	-	-
Not specified fixed foundation	24%	31%			
Floating	**26**%	**15**%	**0**	**100**%	**50**%
Tension Leg Spar	60%	100%	-	-	100%
Tension Leg Platform	20%	50%	-	-	-
Tension Leg Buoy	20%	50%	-	-	-
Semi-Submersible	40%	50%	-	50%	-
Spar-Bouy	20%	50%	-	-	-
Not specified Floating	20%	-	-	50%	-

The next table, Table 3, shows the type of foundation modeled as a function of the distance to the coast and sea depth. Notably, European LCA studies with fixed foundations consider a higher distance to shore than other locations while sharing the same average water depth. Nevertheless, it is interesting to notice, as presented in Table 4, the water depth difference for the same foundation technology in different locations. For instance, the deepest value for a monopile foundation in European locations is 12 meters, while in Asia and North America, it is around 30 meters. Moreover, the tripod technology is modeled for a water depth of 30 meters in European LCAs, and 50 meters in North American LCAs. On the other hand, for gravity foundations, the water depth seems to converge in a more specific range of values of just 15-20 meters.

Table 3: Mean modelled distance to the coast and sea depth for the different locations.

Site Parameter	World Wide	Europe	Asia	North America	Not specified
For fixed Foundation					
Mean distance to the coast [km]	35	44	10	8	30
Mean depth of the sea [m]	20	20	21	23	20
For floating Foundation					
Mean distance to the coast [km]	85	125	-	45	-
Mean depth of the sea [m]	157	200	-	115	-

Table 4: Modeled water depth for the most frequent foundations, and different locations. Results expressed as "Mean value [Minimum value: Maximum Value]" in meters.

Water depth	World Wide	Europe	Asia	North America	Not specified
Monopile	20 [10:32]	11 [10:12]	32	20 [13:30]	-
Gravity	18 [15:20]	17	-	17 [15:20]	20
Tripod	41 [30:50]	30	-	43 [35:50]	-
Jacket (Pile)	35 [25:50]	35 [25:50]	-	-	-

3.1.4 Electrical Installation

The results of the electrical connection review are presented in Table 5. Half of the LCA studies do not specify the type of array cable, nor the type of the export cable. The array cables that are modeled in the reviewed studies are in the range of 30 to 36 kV, and the export cables are in the range of 110 to 150 kV. The majority of studies (74%) model one substation per OWF, one paper considers two substations, and four other papers (21%) model no substation. In some cases this omission is simply an omission of the study's scope, but in the case of small, near shore OWFs a substation may not be required.

Table 5: Frequency of electrical installations modeled parameters (substations, array cables, and export cables) for different locations.

Electrical Installation	Locations				
	World Wide	Europe	Asia	North America	Not specified
Array Cable model					
30-36 KV	42%	54%	50%	100%	-
Not specified	58%	46%	50%	-	-
Export Cables					
110 Kv	5%	8%	-	-	-
132 Kv	11%	8%	-	50%	-
145 Kv	5%	8%	-	-	-
150 Kv	21%	23%	50%	-	-
Not specified	58%	54%	50%	50%	100%
Substation Consider					
No Substation	21%	8%	50%	50%	50%
1 Substation	74%	85%	50%	50%	50%
2 Substation	5%	8%	-	-	-

3.1.5 Turbine and supporting infrastructure Lifetime

The lifetime of the turbine and other supporting infrastructure can be influential in determining the life cycle impact intensity attributed to generated electricity. Most studies (74%) asume a turbine lifetime of 20 years, while only 21% of them selected a lifetime of 25 years. The remaining 5% considers both scenarios.

Table 6 shows that array cables are mostly modeled in the same way as the turbines, with a lifetime of 20 years (47% of the LCAs). However, the export cables and the substations, which share a very common proportion, are mostly modelde with 40 year lifetimes (32% and 33% of the studies, respectively), followed by studies using 20 year lifetime (20% to 21% of the studies, respectively). Also important to consider is that 26% to 27% of the LCAs do not specify component lifetime at all.

Table 6: Frequency of modeled lifetime for turbines, substations, array cables, and export cables, for different locations.

Modeled Lifetime	Locations				
	World Wide	Europe	Asia	North America	Not specified
Turbine					
20 years	74%	77%	50%	100%	50%
25 years	21%	15%	50%	-	50%
20 & 25 years consider	5%	8%	-	-	-
Substation					
20 years	20%	25%	-	-	-
25 years	7%	-	-	-	100%
20 & 25 years consider	7%	8%	-	-	-
35 years	7%	8%	-	-	-
40 years	33%	33%	100%	-	-
Not specified	27%	25%	-	100%	-
Array Cables					
20 years	47%	62%	50%	-	-
25 years	11%	-	50%	-	50%
20 & 25 years consider	5%	8%	-	-	-
30 years	5%	-	-	50%	-
40 years	5%	8%	-	-	-
Not specified	26%	23%	-	50%	50%
Export Cables					
20 years	21%	31%	-	-	-
25 years	5%	-	-	-	50%
20 & 25 years consider	5%	8%	-	-	-
30 years	5%	-	-	50%	-
40 years	32%	38%	50%	-	-
Not specified	32%	23%	50%	50%	50%

3.2 Life cycle phase review

The production phase has the highest impact on the LCIA outcomes. The result of this phase depends primarily on the designed parameters of the OWF, already presented, and secondly on the manufacturers' practices and study assumptions. Since this phase is also the most widely and deeply studied by the literature, this review focuses on the less examined phases; installation, operation and maintenance, and decommissioning.

3.2.1 Installation phase

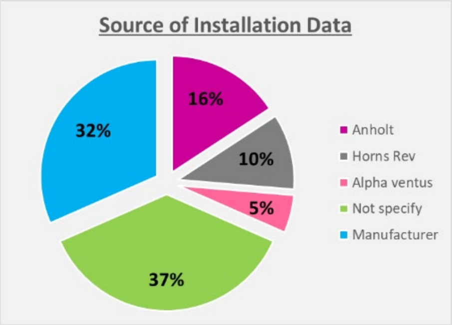

Figure 7: Data source distribution

Figure 7 summarizes the three main data sources used for modeling the installation phase; information provided by manufacturers (32%), information based on site-specific projects (31%), and unspecified data sources (37%). There are only three site-specific projects considered in the reviewed studies, some used multiple times: Anholt, Horns Rev, and Alpha Ventus, with Anholt the most frequently used of the three. Six of the reviewed LCA studies base their installation assumptions on construction and installation data from Germany's Alpha OWF, Denmark's Horns Rev OWF, and Denmark's Anholt OWF. However, only two studies model the exact characteristics of the OWFs, the rest consider just the associated performance of the project for different layouts and locations of the OWFs.

As presented in Table 7, most of the LCA studies do not specify the installation variables used. The variables evaluated for the installation phase in this review are: list of installation tasks, work time calculation, vessel fuel consumption, and installation rate for foundations and turbines. From the studies that consider these variables, the site-specific projects are the main data source used. Only Raadal (2014) includes these variables without specifying a data source. None of the papers that use the manufacturers' data sources specify these variables.

Table 7: Percentage of source for installation variables in data models.

Installation variables	Type of source used by studies considering the variables		Not consider
	Site Specific	Not specified	
List of Installation Task	16%	5%	79%
Work time calculation	11%	5%	84%
Foundation Installation Rate	21%	5%	74%
Turbine Installation Rate	21%	5%	74%
Vessel Fuel consumption	16%	11%	74%

3.2.1.1 Installation Rate

The foundation installation rate values presented in Figure 8 are based on the five studies that consider this variable, which in total evaluated 29 different scenarios. As shown in Figure 8, the floating foundations show the highest fluctuation, with one European studie at 0.65 days per foundation (dpf) and the North American studie at 7.5 dpf. Figure 8 also shows a nonlinear relationship between the installation time and the distance to the shore. The gravity foundation has the second-highest fluctuation in installation rate, between 3.85 dpf and 1.25 dpf. The monopile foundation has the smallest fluctuation (between 1 and 1.3 dpf), followed by the jacket foundation with a fluctuation between 3 and 4.3 days per foundation. The total fluctuation of the fixed foundations goes from 1 dpf to 9 dpf.

It is interesting to point out that monopile installation rates are only available in Asia and North American studies, even though they are the most frequent type of foundation used in Europe (Díaz & Guedes Soares, 2020). None of the studies considers the HRPC foundation, and the floating foundations results are based on only two papers; Raadal et al. (2014) which does not consider different installation rates between the different technologies, and Tsai et al. (2016) where no specification is given regarding the type of floating technology modeled.

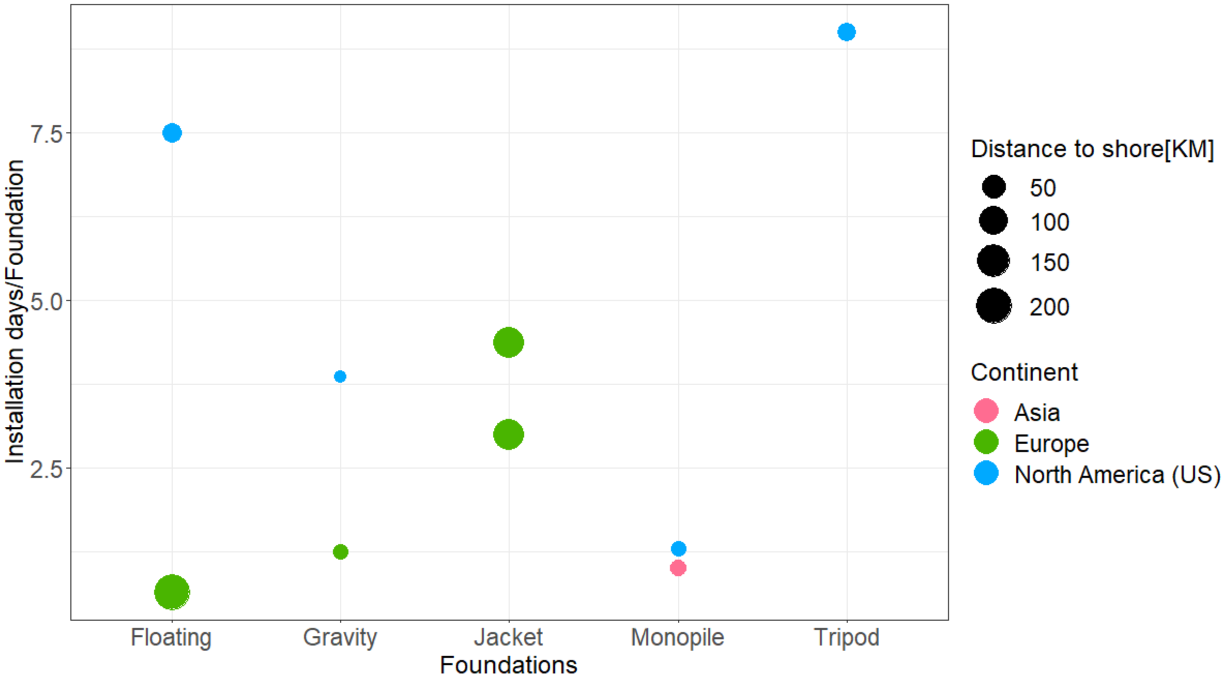

Figure 8: Foundation installation rate.

Regarding the turbine installation rate, as presented in Figure 9, the Asian and North American studies share a common installation rate of one turbine installed per day, even though they model different power capacities (2 MW and 3 MW, respectively). All the studies located in Europe share a common power capacity of 5 MW, but with an installation rate of high disparity that goes from 0.5 turbines installed per day up to 1.8 turbines installed per day. The European studies shows a seeminly random relationship between turbine installation rate and the distance to shore.

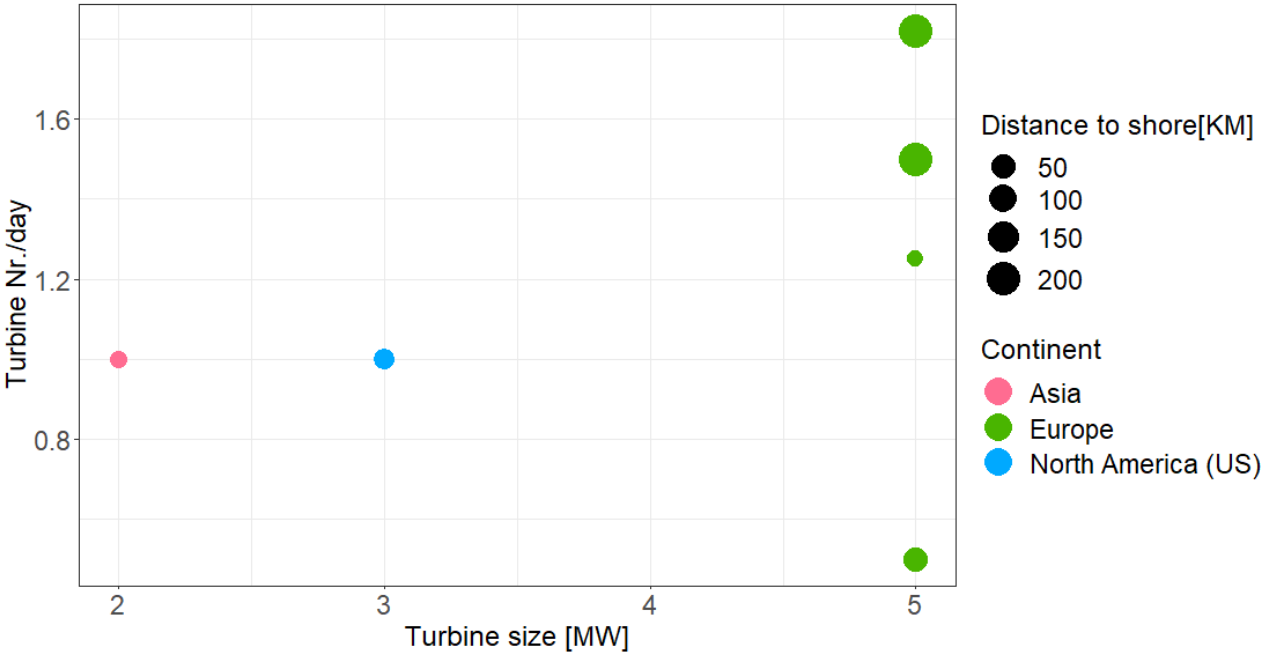

Figure 9: Turbine installation rate.

3.2.1.2 Fuel consumption of vessels

Figure 10 shows the fuel consumption of the most frequent type of vessels considered in the studies, which include crane vessels, jack-up vessels, and tug-boats. As evident in Figure 10, there is a considerable range of results across studies, with crane vessels consuming between 160 L/hr to 2,000 L/hr , jack-up vessels consuming between 87 L/hour and 2,000 L/hr, and tugboats between 320 L/hr and 1.375 L/hr. The cable lay vessel is the only one that with a tight range in values (450 L/hour to 572 L/hour). Most of the variability in vessel fuel consumption is produced by the fuel consumption modeled by Raadal et al. (2014), characterized by higher consumption. The fuel consumption of the cable lay vessel is not mentioned in this study. Lastly, it is important to point out that one jack-up vessel fuel consumption specification was discarded from this analysis by considering it out of range of this type of vessel (20,000 liter/hour, Jesuina et al. (2018)).

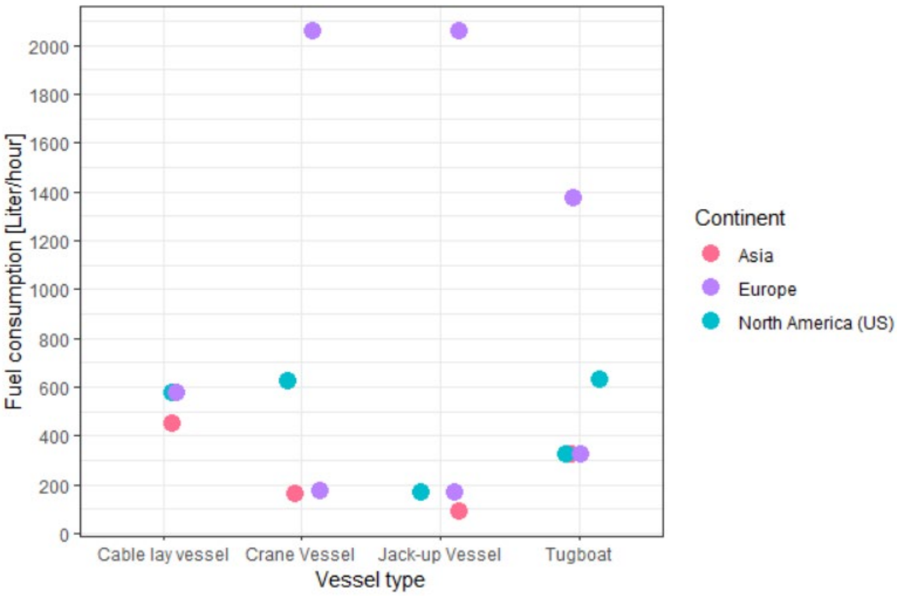

Figure 10: Vessel fuel consumption

3.2.1.3 Other Installation parameters

Other parameters may be important when modeling the installation and construction of an OWF but were not been taken into account by the reviewed papers. Some of these parameters or processes include:

- Different Installation Strategies: No paper evaluated different fuel consumption scenarios for different installation strategies. Only one paper, Jesuina et al. (2018), states a specific installation strategy without doing a sensitivity analysis concerning other strategies.

- Logistic requirements for the installation phase: Despite that OWF installation often requires adaptation or modification to the port that supports installation, no paper considers port adaptation work, port crane upgrades or civil works. One paper, Tsai et al. (2016), considers road maintenance works during the installation phase, another likely activity required for OWF installation.

- Onshore work: No paper considers the onshore work related to the operation & maintenance base construction or onshore substation construction. Only one paper, Tsai et al. (2016), considers the cable connection works onshore.

3.2.2 Operation & Maintenance

The following Operation & Maintenance modeling variables are analyzed in this section; vessel and helicopter travel to the OWF site for maintenance, and item replacement required during OWF´s lifetime. Half of the papers (57%) consider some type of maintenance service variable, and more than half (63%) consider some type of replacement.

3.2.2.1 Vessel & helicopter maintenance services

Table 8: Number of maintenance services by vessels and helicopters per year, for different locations.

Services mode	Locations					
	World Wide	Europe	Europe[a]	Asia	North America	Not specified
Vessel						
Minimum	0	0	0	1	10	0
Mean	84	137	5.5	3	10	0
Maximum	720	720	15	4	10	0
Helicopter						
Minimum	0	0	0	0	1	1
Mean	52	74	6	2	1	1
Maximum	410	410	13	4	1	1

Note:
[a] European studies' results without Reimers et al. (2014) study.

As shown in Table 8, Europe presents the studies with the highest frequency of services for both vessels (720 travels a year) and helicopters (410 travels a year) (Reimers et al. (2014)). Even if this study is excluded, the European studies remain as the ones with the highest frequency for both vessels and helicopters. However, the rate between vessel services and helicopter services changes, from a vessel services predominance to an even distribution. Asian studies also show an even distribution between helicopter and vessel services, and North American studies show a vessel services predominance.

As evident from Figure 11 there is no specific relationship between the frequency of the services and the number of turbines or the turbines' power capacity. Excluding Reimers et al. (2014) and Bikerland et al. (2011), the rest of the studies used a vessel services frequency in the range of 0 to 15 services per year per OWF and helicopter service frequency in the range of 0 to 13 services per year per OWF, regardless of the size or power of the OWF.

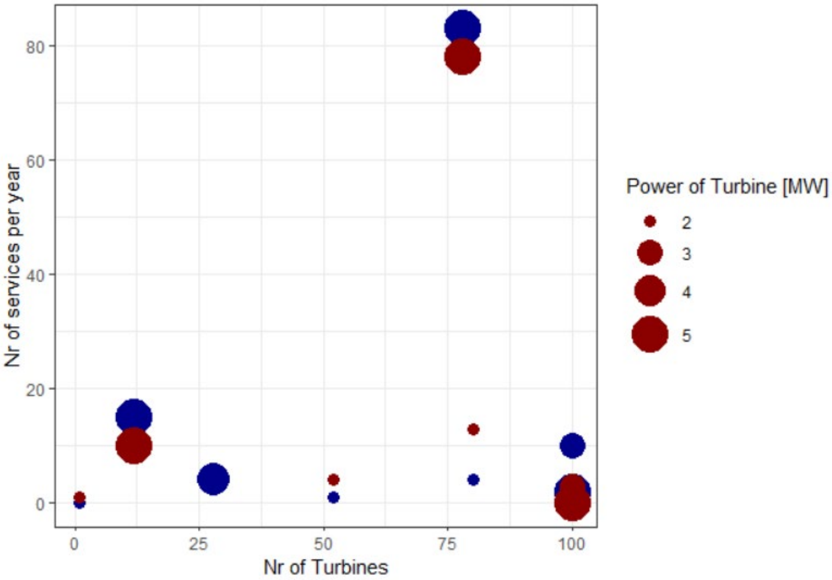

Figure 11: Vessel & helicopter maintenance services. The blue dots represent vessel services and the red dots represent helicopter services. Reimers et al. (2014) was excluded from the graph for better visualization of the rest of the results.

3.2.2.2 Items replacements

The main replaced items considered in the papers' models are blades, nacelles, and gearboxes. As shown in Table 9, the highest replacement frequency for gearboxes is presented by a North American study (2.22 replacements over the lifetime of the turbine), followed closely by a European study (2.18). The mean value of frequency replacement fluctuates between 0.17 and 0.211 depending on the location. The European studies have the highest nacelle replacement frequency (1 replacement over the lifetime of the turbine). The mean value fluctuates between 0.12 and 0.5 depending on the location. The blades' replacement frequency is shared by European and Asian studies (0.33). The corresponding mean value fluctuates between 0 and 0.33 replacements over the lifetime of the turbine.

Table 9: Replacement frequency over the turbine lifetime of the main turbine components, for different locations.

Main components	Locations				
	World Wide	Europe	Asia	North America	Not specified
Gearbox					
Minimum	0	0.05	0	2	0.70
Mean	0.92	0.79	0.17	2.11	0.85
Maximum	2.22	2.18	0.33	2.22	1
Nacell					
Minimum	0	0	0	0	0
Mean	0.27	0.27	0.17	0.12	0.5
Maximum	1	1	0.33	0.24	1
Blades					
Minimum	0	0%	0.32	0	0
Mean	0.13	0.9	0.33	0	0.17
Maximum	0.33	0.33	0.33	0	0.33

Figure 12 (left) shows no specific relationship between component replacement frequency over the lifetime of the turbine and the locations of the study or the turbines' power capacity. Figure 12 (right) might indicate that the first studies, prior to 2011, tended to consider lower replacement rates for gearboxes.

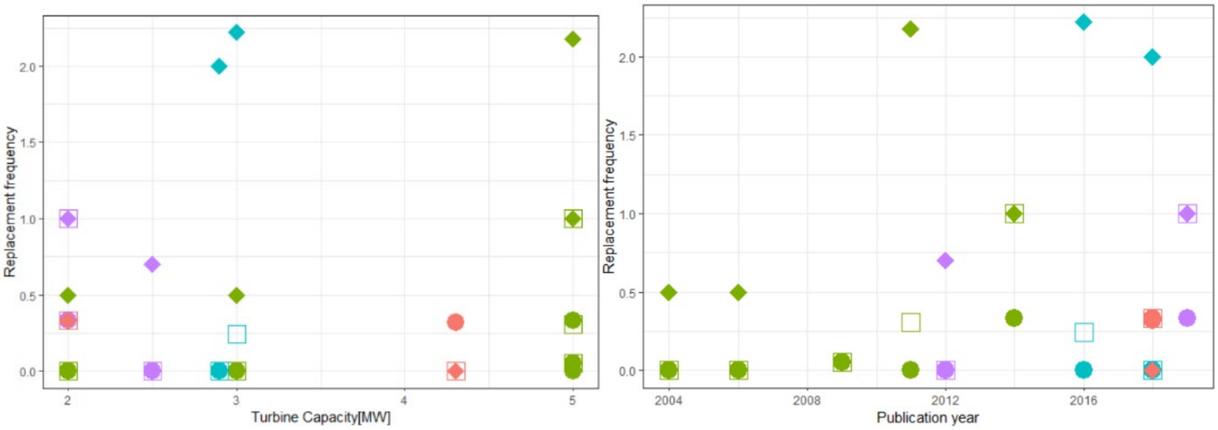

Figure 12: Main components replacement frequency over the turbine lifetime by different turbines power capacity (left) and by year of study (right) for different locations. Round dots= Blades, Empty square dots=Nacelles, Diamond dots=Gearbox. Pink dots= Asia studies, Green dots= European studies. Blue dots= North American studies. Violet dots=Location Not specified studies.

3.2.3 Decommissioning and EoL Strategies

3.2.3.1 Decommissioning

The majority of the reviewed studies do not specify the scope of decommissioning that they asume (full decommissioning versus partial), nor provide detail about the corresponding tasks, as shown in Table 10. Interestingly, half of the studies do specify sending the decommissioned OWF to a treatment facility. However, the studies fail to specify the associated distance or fuel consumption of transporting the elements to that treatment facility.

Table 10: Decommissioned strategy

Decommissioned Strategy	**Locations**				
	World Wide	**Europe**	**Asia**	**North America**	**Not Specified**
Scope					
Full decommissioning	11%	0%	100%	0%	0%
Partial (scour protection unremoved)	5%	0%	0%	100%	0%
Not specified	84%	81%	0%	6%	13%
Tasks					
Consider Inverse as assembly	21%	50%	25%	0%	25%
Not specified	79%	73%	7%	13%	7%
Transportation					
Location					
To a treatment facility	53%	80%	0%	10%	10%
Not specified	42%	63%	25%	0%	13%
Not consider	5%	0%	0%	100%	0%
Distance or Fuel consumption					
Known	44%	50%	13%	13%	25%
Not specified	56%	90%	10%	0%	0%

3.2.3.2 EoL

From the reviewed studies, 57% consider some EoL strategy. Table 11, Table 12, and Table 13 are based only on those studies. Table 11 presents the frequency of recycling as an EoL strategy for different materials, and is considered by 100% of the papers that consider some EoL activity.

Table 12 reports the incineration strategy, and Table 13 the landfill strategy, which are considered by 55% and 81% of the studies, respectively. Most of the reviewed papers model specific materials (82% in recycling strategy, 45% in incineration strategy, and 73% in landfill strategy). A few studies also consider the fate of generic components of the turbine (36% for the recycling strategy, 18% for the incineration strategy, and 9% for the landfill strategy).

Table 11: Percentage of studies that included the following materials and recycling rates in their models (Recycling Strategy).

Materials	Pct. of studies that included these materials	Pct. of studies assuming given recycling rates									No. of studies for the different locations
		1	0.95	0.9	0.85	0.75	0.66	0.55	0.5	0.2	
Steel	73%	0	0	73%	0	0	0	0	0	0	Asia (2), NA(2), Europe (4)
Iron	55%	0	0	55%	0	0	0	0	0	0	Asia (2), NA(2), Europe (2)
Copper	73%	0	9%	64%	0	0	0	0	0	0	Asia (2), NA(2), Europe (4)
Aluminum	55%	0	0	45%	0	0	0	9%	0	0	Asia (1), NA(2), Europe (3)
lead	36%	0	0	36%	0	0	0	0	0	0	Asia (1), NA(1), Europe (2)
Concrete	18%	0	0	0	9%	0	0	0	9%	0	Europe (2)
Gravel	9%	0	0	0	0	9%	0	0	0	0	Europe (1)
Glass reinforced plastic	9%	9%	0	0	0	0	0	0	0	0	Europe (1)
Generic Components											
Tower	9%	0	0	9%	0	0	0	0	0	0	NS (1)
Nacelle	9%	0	0	0	0	0	0	0	9%	0	NS (1)
Rotor Blades	18%	0	0	0	0	0	0	0	9%	9%	NS (2)
Foundation	9%	0	0	0	0	0	0	0	9%	0	Europe (1)
Cables	18%	0	0	0	0	0	9%	0	9%	0	Europe (2)

Table 12: Percentage of studies that included the following materials and incineration rates in their models (Incineration Strategy).

Materials	Pct. of studies that included these materials	Pct. of studies assuming given incineration rates		No. of studies for the different locations
		1	0.5	
Rubber	27%	27%	0	Europe(1), NA(1), Asia(1)
Glass fiber	18%	18%	0	Europe(1), NA(1)
Generic Plastics	27%	27%	0	Europe(2), NA(1)
Plastics except PVC	9%	9%	0	Asia(1)
PVC	9%	9%	0	Europe(1)
Generic Components				
Blades	18%	9%	9%	NS(1), Europe(1)
Nacelle	9%	0	9%	NS(1)

Table 13: Percentage of studies that included the following materials and landfill rates in their models (Landfill Strategy).

Materials	Pct. of studies that included these materials	Pct. of studies assuming given landfill rates			No. of studies for the different locations
		1	0.15	0.1	
Steel	27%	0	0	27%	Europe (2), NA(1)
Iron	18%	0	0	18%	Europe(1), NA(1)
Copper	27%	0	0	27%	Europe (2), NA(1)
Aluminum	27%	0	0	27%	Europe (2), NA(1)
Lead	18%	0	0	18%	Europe(1), NA(1)
Glass fiber	27%	27%	0	0	Europe(1), NA(1), Asia(1)
Silica sand	9%	9%	0	0	NA(1)
Gravel	9%	9%	0	0	NA(1)
Concrete	36%	27%	9%	0	Europe(1), NA(2), NS(1)
PVC	27%	27%	0	0	Europe(1), NA(1), Asia(1)
Generic Components					
Blades	9%	9%	0	0	Europe(1)

As shown in Table 11, recycled metallic materials are the most frequently recycled materials, with a 36% to 76% frequency, depending on the specific metal. Steel is the most frequent metal modelled (76%) with a 0.9 recycling rate. Only two metals are modelled with an alternative rate besides the 0.9 rate; copper and aluminum are mostly modelled with a 0.9 recycling rate, but one paper considered a 0.95 recycling rate for copper, and another considers an aluminum recycling rateo of 0.55. The non-metallic materials present more variable recycling rates. For instance, concrete is assumed to be recycled in two papers that consider recycling rates of 0.85 and 0.5; however, the mechanisms and rationale for these recycling rates are unclear. For the incineration strategy, Table 12, the blade, shows a significant disparity in the results; one paper consider a total incineration while the other considers a partial one (0.5 rate). For the landfill strategy, Table 13, a similar result is evident for the landfilling of concrete.

Figure 13 presents a different view of EoL strategies, considering how assumption about EoL strategies have changed over the years. Recycling shows a consistent assumption of a rate of 0.9 for metals over the years, and in 2012 the first study that considers generic component recycling (for blades or cables) was published. Incineration, when included for a particular material or component, is often assumed to be at a rate of 1. The landfill strategy shows 100% disposal of non-metals and generic components, and 10% for metals and nonmetals, with no change evidente over time.

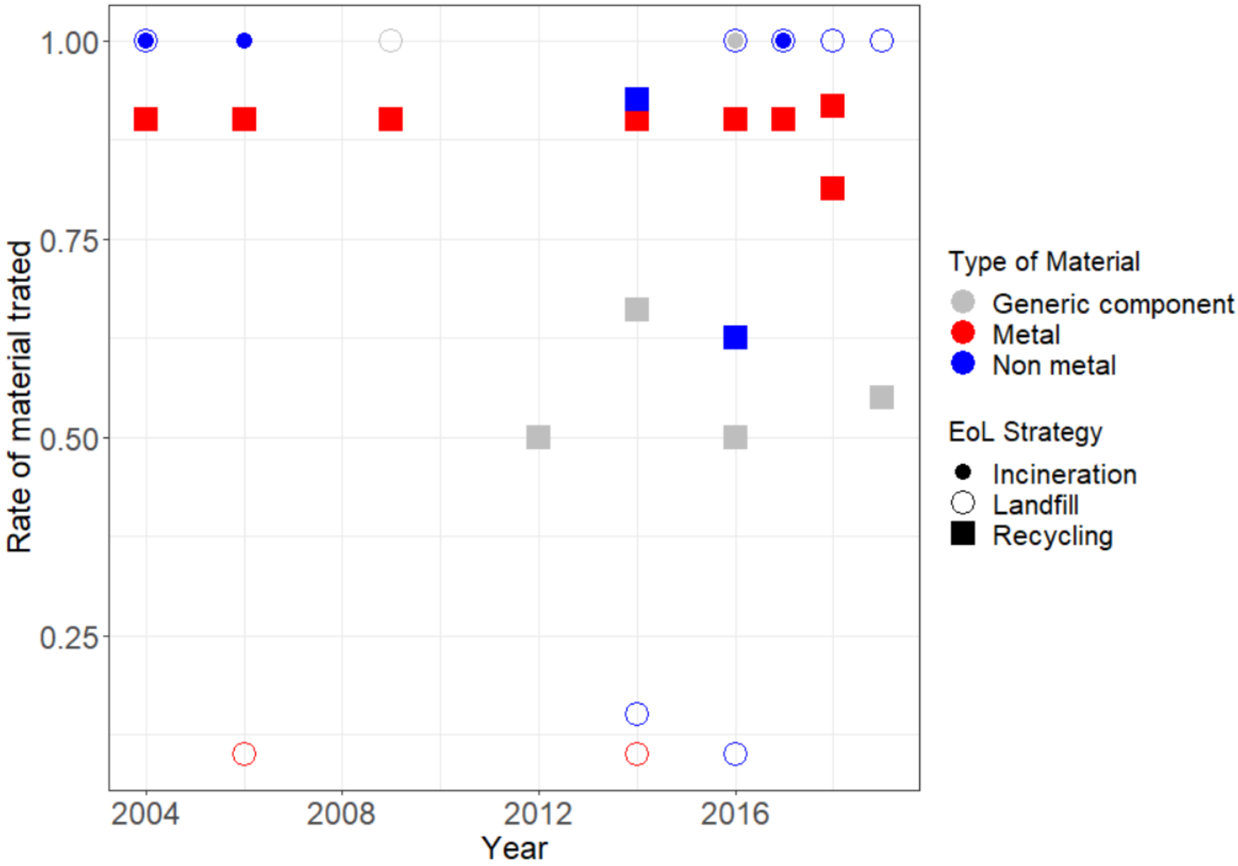

Figure 13: Percentage of recycling, landfill and incineration for metals, nonmetals, and generic elements .

The potential causes and lack of explanation for the wide variety of assumptions for EoL strategies evident across the reviewed studies is explored further in the discussion section.

3.3 Impact consideration

As shown in Figure 5 the most frequently considered impact categories are global warming (in units of CO_2e) at 89.5% of studies, and energy payback time with a modeled frequency of 63.2%. This section shows the impact of the different modeling decisions and phases assumptions over the two most frequent impact categories, CO_2e and EPT.

3.3.1 Impact consideration: CO_2e

The range of results for CO_2e impacts is 5.2 g CO_2e /kWh to 47.4 g CO_2e /kWh with a mean value of 24 g CO_2e /kWh. As shown in Figure 14, up to 2009, there had only been three OWF studies corresponding with CO_2e values lower than 11.5 g/kWh. The highest CO2e values correspond to the Tsai et al. (2016) study, which considers different scenarios located in North America, and presented results from 25.8 up to 47.4 g CO_2e /kWh. Most recently published studies, from 2018 up to now, also present CO_2e values equal or lower to 10 g CO_2e /kWh.

Different values from this range can be observed for different turbine modeling parameters in Figure 15. Interestingly, low power turbines of 2 MW or relatively high power turbines of more than 6 MW only present low values of CO_2e , while those in between are higher. Additionally, the few studies that consider direct-drive turbines are associated with low values of CO_2e. The different types of foundations and the total installation capacity can be observed for either low or high CO_2e values. Site modeling parameters and study location seem to present the same lack of strong relationship with the impact results.

Figure 16 shows the contribution of the different life cycle phases to CO_2e. It is clear that the production phase is most significant, with a mean contribution of 75% of the results and a low dispersion of results between the different studies. However, this is not the case of the installation phase with a mean contribution of 11.5% and a range of values from 5% up to 15.5%, or the maintenance phase with a mean value of 11.8% and a range from 1.85% to 24%.

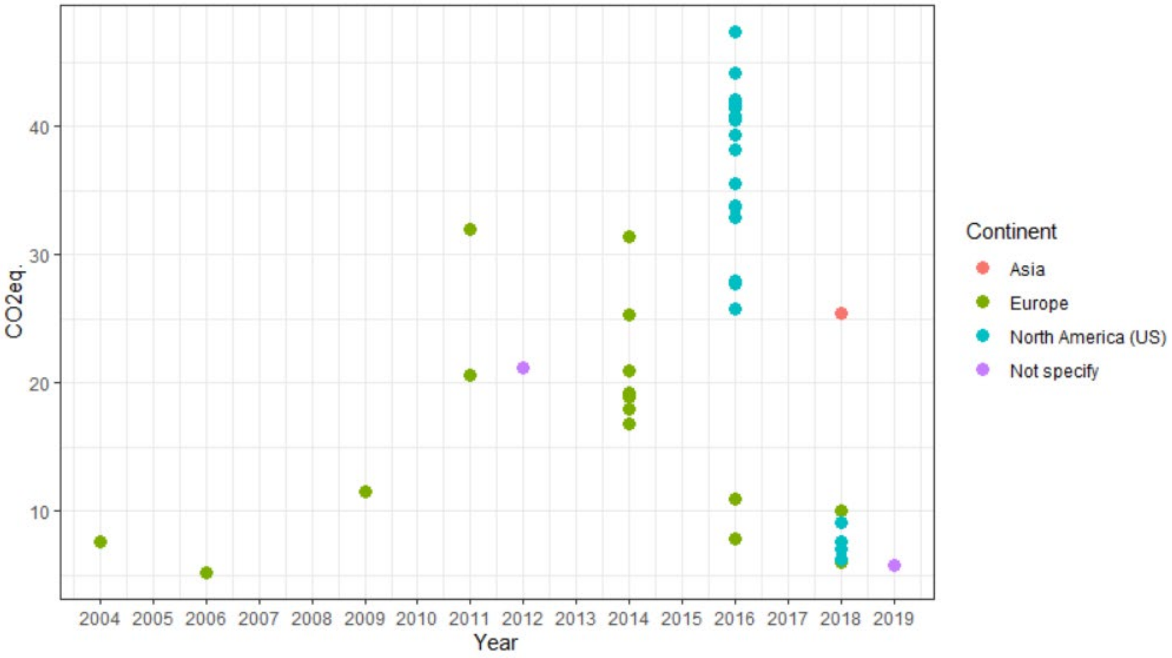

Figure 14: CO_2e models results vs publication years.

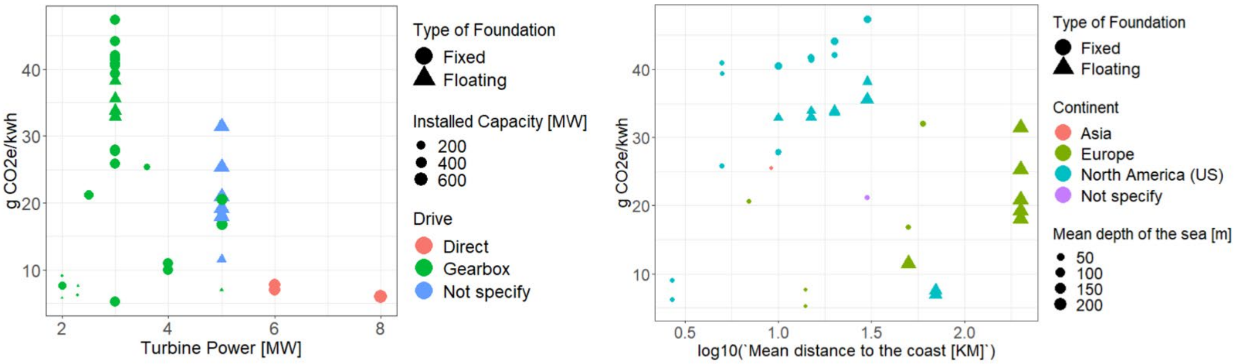

Figure 15: CO_2e results vs. turbine modeling parameters (left) and vs. different site modeling parameters (right).

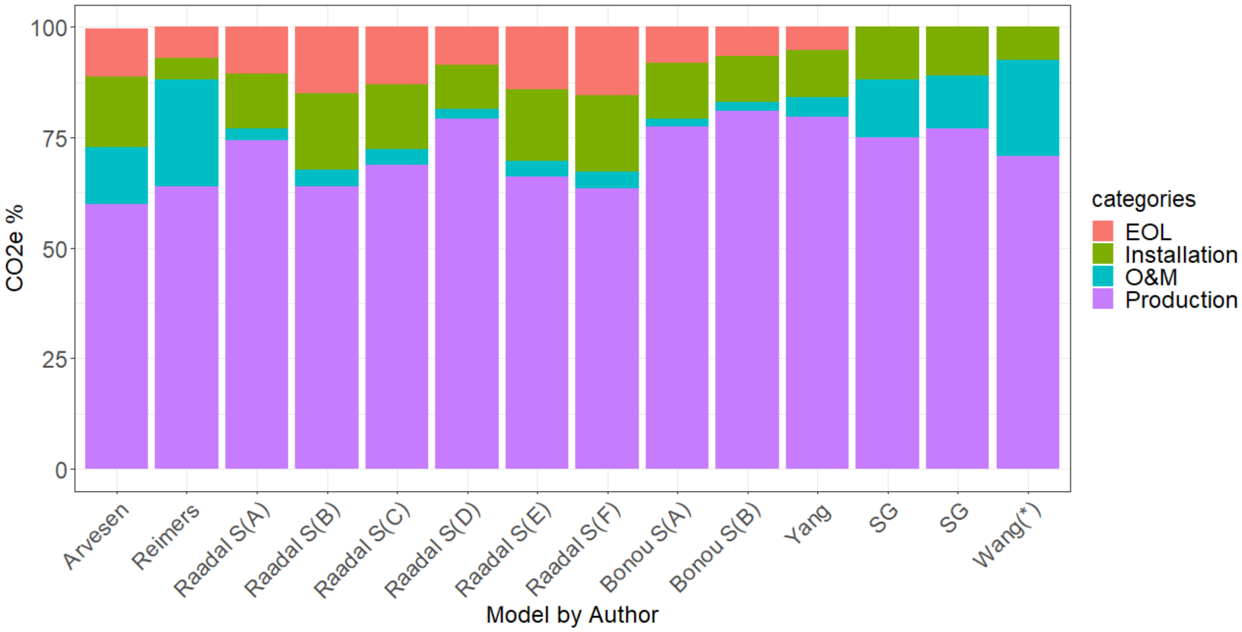

Figure 16: Distribution of CO_2e results by the life cycle phase for reviewed studies, SG= Siemens Gamesa. The production phase in Wang's model includes a net EoL credit meaning that dismantling and recycling credits are embedded in the production phase.

Table 14 summarizes the model scope and CO_2e by phase for the reviewed studies. It can be observed that all the studies that identify their vessel fuel consumption, present CO_2e installation proportion over the mean value of the general proportion of this phase (12.9%). Regarding the Operation & Maintenance phase, the two studies that consider the highest nacelle replacement rate are the studies with the highest CO_2e O&M proportion. Only one of the three studies that considered high gearbox replacement is associated with a high CO_2e O&M proportion. Interestingly studies that disaggregate by life cycle phase only appear after 2011, with Arvesen et al. (2012).

The site modeling parameters, mean distance to the coast and mean depth of the sea, were compared with the CO_2e installation and O&M proportions, and no relevant relationship was observed.

Table 14: Main phases modeling parameters and CO$_{2e}$ results. Data Source: SS= Site Specific; M= Manufacturer; N/S= Not specified.

Paper	Installation			Maintenance		Identify a Specific EoL Strategy (Y/N)	g CO$_{2e}$/kWh	CO$_{2e}$ phase distribution (*Percentages corresponding to CED distribution.)			
	(Data Source)	Installed MW/day	Identify Vessel Fuel consumption (Y/N)	Identification of Service Rate (Y/N)	Identify Item replacement (Y/N)			Production [%]	Installation [%]	O&M [%]	EoL [%]
Elsam	SS	N/S	N	Y	Y	Y	7.6	-	-	-	-
Jungbluth	N/S	N/S	N	N	N	N	N/S	-	-	-	-
Vestas	N/S	N/S	N	Y	Y	Y	5.2	-	-	-	-
NEEDS	SS	N/S	N	N	N	N	N/S	-	-	-	-
Weinzettel	M	N/S	N	Y	Y	Y	11.5	-	-	-	-
Wagner	M	N/S	N	Y	Y	N	32	-	-	-	-
Birkeland	SS	6.25	Y	**Y**[d]	**Y**[e]	N	20.6	-	-	-	-
Arvesen	N/S	N/S	N	N	Y	Y	21.2	60	15.5	12.9	11
Reimers	SS	2.5	N	Y	**Y**[f]	N	16.8	64	5	24	7
Raadal	N/S	8.3	**Y**[b]	**Y**[c]	N	Y	22.3 [18 - 31.4]	67	14.63	3.26	12.77
Tsai	SS	3	Y	Y	**Y**[e]	Y	36.6 [25.8-47. 38]	*50.75	*14.75	*22.25	*12.75
Bonou	M	N/S	N	N	N	Y	9.4 [7.8 - 10.9]	79.25	11.6	1.85	7.3
Huang	SS	2	Y	Y	Y	Y	N/S	*48.5	*25.5	*12.5	*13.5
Yang	N/S	N/S	N	Y	Y	Y	25.4	79.61	10.59	4.46	5.34
SG (1)	M	N/S	N	N	N	N	10	73	14	13	-
SG (2)	M	N/S	N	N	N	N	7	75	12	13	-
SG (3)	M	N/S	N	N	N	N	6	77	11	12	-
Jesuina	N/S	N/S	**Y**[a]	N	**Y**[e]	Y	7.5 [6.23 -9.11][g]	-	-	-	-
Wang	N/S	N/S	N	Y	**Y**[f]	Y	5.8	122.88	7.38	21.85	-52.1

Notes:

[a] Highest study regarding vessel fuel consumption.

[b] Second-highest study regarding vessel fuel consumption.

[c] Highest study regarding maintenance services by vessels and helicopters.

[d] Second-highest study regarding maintenance services by vessels and helicopters.

[e] Studies considering gearbox replacement frequency of 2 or greater.

[f] Studies considering nacells replacement frequency of 1 or greater.

[g] Phase contribution of this study not considered due to inconsistency in the results.

3.3.2 Impact consideration: EPT

The energy payback time (EPT) results go from 6.8 months up to 32.4 months, with a mean value of 15.5 months. On the one hand, Figure 17 shows that EPT presents similar highlights as CO_2e , regarding its results versus the turbine modeling parameters, specifically the turbine power and the direct drive technology. On the other hand, EPT may present a more linear relationship with the coast's distance than CO_2e. However, this apparent linear relationship could be caused by two reasons; one, the values corresponding to the 200 km coastal distance come from the same study, second, many studies that have high values of CO2e for low coastal distances do not specify their EPT, which is commonly linear with CO2e impact.

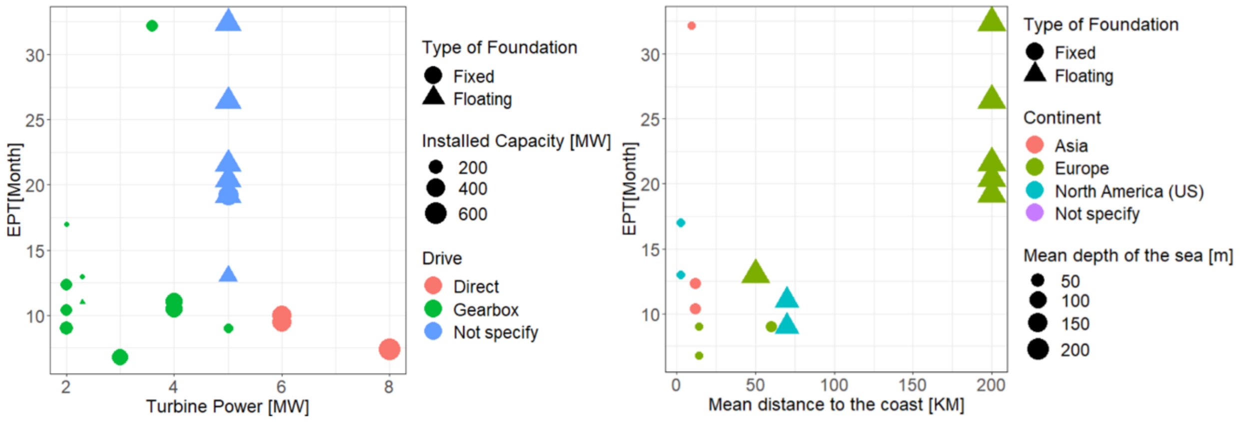

Figure 17: EPT results by turbine modeling parameters (left) and by different site modeling parameters (right).

4. Discussion

This section compares the results obtained with the latest offshore wind technology and state-of-the-art practices in the installation, O&M, and decommissioning of OWF. An evaluation of current studies and valuable information for the future markets is also addressed in this section.

4.1 Offshore Wind Farm Modeling in LCA Studies

4.1.1 Location evaluation

Commissioned projects are well-represented on a continental level, when comparing the LCA model selected locations with the world OWF installation (Díaz & Guedes Soares 2020). However, this may not be the case if we consider projects under construction, as represented in Figure 18. Given that Europe represents a mature market and Asia a developing one, perhaps it is not suprising that the LCA literature has been strongly focused on the European market, but fails to represent the developing ones. This seems to extend to developing markets for OWF beyond Asia. For instance, the regions of Central America, South America and South Africa (Figure 19) have sufficient capacity factors for developing OWF in the near future. Nevertheless, there are no available LCA studies in those regions. It seems that LCAs have been focused not on prospective assessments of potential markets, but instead on assessments where OWFs are already in place.

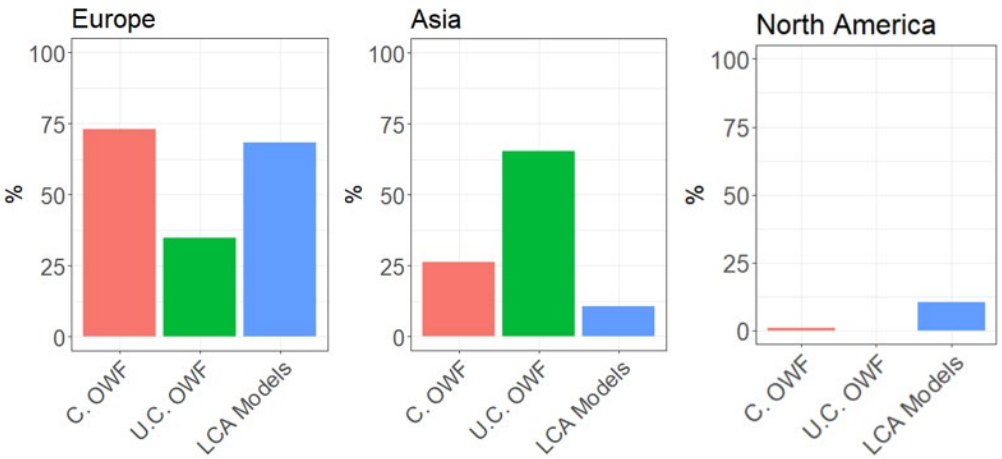

Figure 18: Continent location evaluation. Categories: C.OWF= Commissioned offshore wind farm, U.C.OWF= Under construction OWF, LCA Models= Life cycle assessment models. [based on Table A and data from Díaz & Guedes Soares, (2020)]

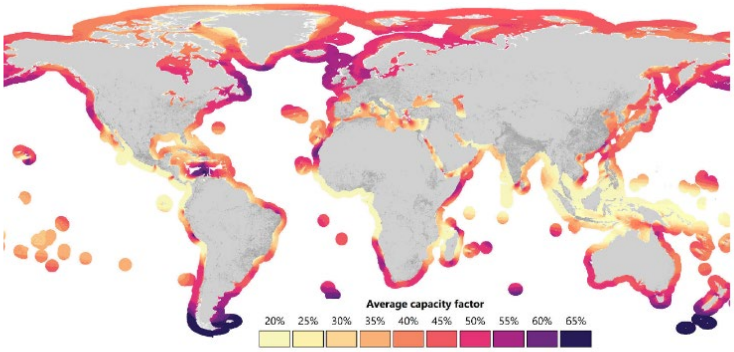

Figure 19: Global wind average capacity factor (IEA, 2019)

The top five locations for total power installed until 2019 based on the Global Offshore Wind Report 2020 are the UK (33%), Germany (26%), China (24%), Denmark (6%), and Belgium (5%). Table 15 shows the location of both commissioned and under construction OWFs in the world based on Diaz & Guedes Soares (2020) and the location of the different LCA models.

Asian countries including South Korea, Vietnam, and Japan already have commissioned OWF, but no published LCA study was found. This could be a bias of the method for identification of relevant LCA studies since only English language databases were searched. Continental European countries are clearly the best represented by LCA. Even though the UK is the leading country regarding commissioned OWF projects, there is only one available LCA study. Norway and Switzerland are modeled but without any project commissioned or under construction.

Table 15: Location of current OWF in the world and the reviewed studies [based on Table A and data from Díaz & Guedes Soares, (2020)]

Countries	**Continent**	**Commissioned**	**Under Construction**	**LCA models**
UK	EU	26%	12%	5%
China	Asia	18%	52%	5%
Germany	EU	17%	15%	11%
Denmark	EU	11%	4%	16%
Belgium	EU	8%	4%	0%
Netherlands	EU	5%	0%	0%
Japan	Asia	3%	0%	0%
Sweden	EU	3%	0%	0%
Finland	EU	2%	0%	0%
South Korea	Asia	2%	2%	0%
Vietnam	Asia	2%	10%	0%
Ireland	EU	1%	0%	0%
Taiwan	Asia	1%	2%	5%
United States	N. A.	1%	0%	11%
Norway	EU	0%	0%	11%
Switzerland	EU	0%	0%	5%
Number of Projects		**115**	**52**	**19**

Considering only 2019 OWF installations, the top five countries are the same as total installation, but in a different order: China (39%), the UK (29%), Germany (18%), Denmark (6%), and Belgium (6%). Interestingly, the country with the highest total power installation (the UK), and the country with the highest 2019 power installation (China), are both modeled only once, and Belgium, one of the top five countries, has no LCA studies (GWEC, 2020a, 2021).

4.1.2 Power Capacity

The total power capacity modeled in LCAs seems to reflect the largest OWF installed up to 2018, as represented by Figure 20. However, when we consider the under-construction projects in 2019, we can identify projects such as Hornsea I and II, located in the UK, both with total capacities of more than 1 GW

(Díaz & Guedes Soares, 2020). In addition, we can also identify a project like Northwester 2 in Belgium using a Vestas V164 turbine of 9.5 MW. These projects exceed both the highest total power capacity modeled by LCAs (640 MW) and the highest turbine power capacity (8 MW).

The average rated capacity of turbines installed in Europe in 2019 was 7.8 MW, and the average wind farm size was 621 MW. Even though a few LCAs represent these averages, there is not one that represents the leading under-construction projects. With an average annual increase of 1 MW of turbine power capacity installed in the EU and more than 22% of average total power increase over the past decade, there is a clear need for studies that help us predict the impact of the power generated by these new projects. Moreover, the next generation of offshore wind turbines, Halaide X by GE or SG14-222 DD by Siemens Gamesa, with a power capacity of 12 MW and 15 MW, respectively, could radically change the validity of existing LCA studies (GWEC, 2020a, 2021).

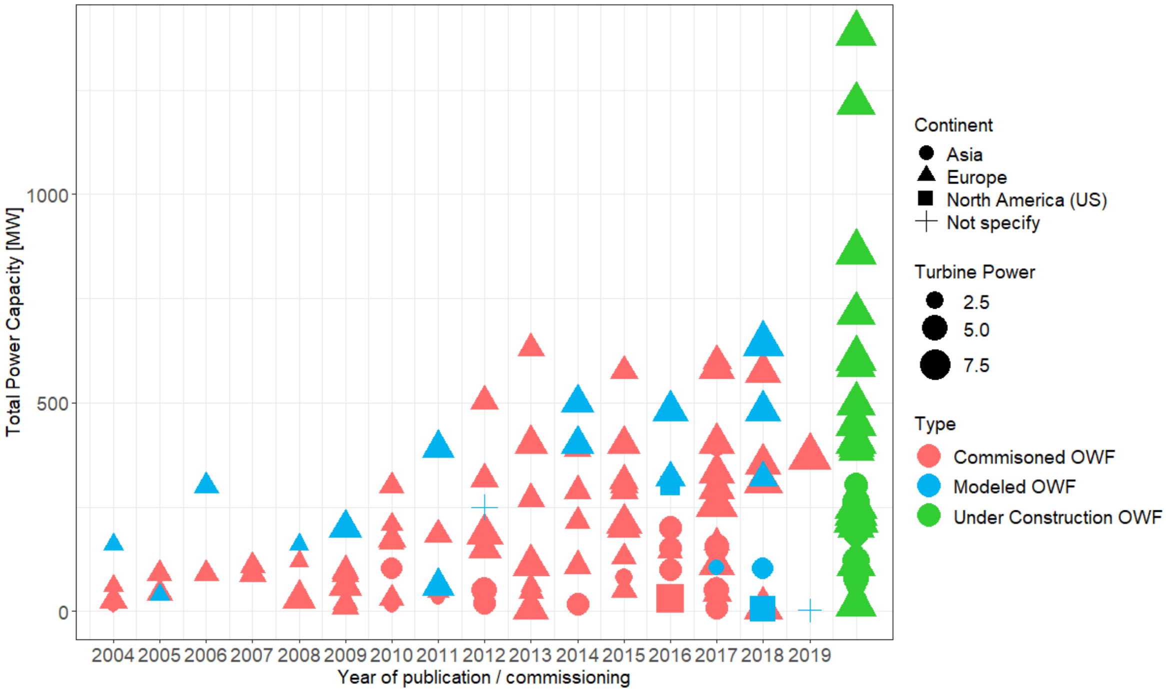

Figure 20: Power capacity of installed OWF and modelled capacity in LCA studies for different continents and years [based on Table A and data from Díaz & Guedes Soares, (2020)]

4.1.3 Site Location and Foundations

The modeled location within each LCA study defines the distance to shore and water depth of the OWF, which are the main variables for selecting the type of foundation to use. As described in the results section, fixed foundations and especially monopile are the most frequent modeled foundations. Similar to previous points, this follows the current status of the EU market, where more than 70% of the foundations installed are monopiles. Other types of foundations are also modeled such as gravity, tripod, and jacket. However, foundations like HRPC are only modeled by one paper, despite representing 40% of the foundations installed in Asia (Díaz & Guedes Soares, 2020).

Floating foundations, despite being a new technology, which until 2019 represented less than 0.3% of the total offshore wind power installed, were considered in 26% of the studies. Unlike the next generation of OWTs or other new technologies, the floating foundation is a new trend that seems to be well-represented in LCAs despite its low rate of adoption (GWEC, 2020a, 2021).

Differences were observed when comparing the foundations' water depth of real projects with those used in the studies. As shown in Figure 21, gravity, tripod, and monopile foundations are modeled for water depth exceeding the water depth used in real OWF. These studies do not present any specific consideration for modeling a foundation exceeding real tested water depth.

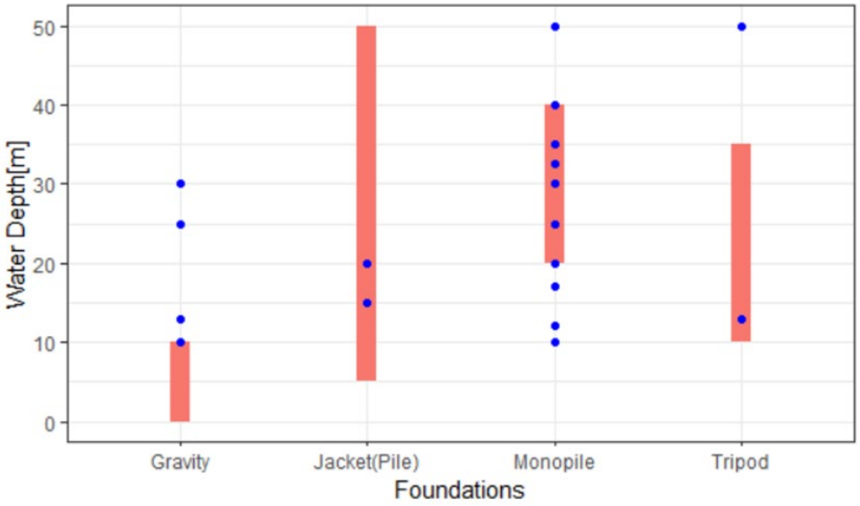

Figure 21: Foundations and water depth specifications. The blue dots represent the water depth specification for the different foundations and the red lines represent the range of water depth for which these foundations are applied in real projects [based on Table A and data from Díaz & Guedes Soares, (2020)].

4.1.4 Electrical Installation

The necessity and number of offshore substations required for an OWF depend on the power capacity and the distance to the shore of the farm. For a total installed capacity greater than 120 MW, at least one substation is required regardless of the distance to shore, and for capacities greater than 250 to 400 MW, more than one substation is required. As evident from Figure 22, at least four LCA models have a number of substations below these requirements. Only one study, Bikerland (2011), considers more than one substation even though the total power capacity of the respective OWF is under 400 MW (Douglas-Westwood, 2013; Huang et al., 2017).

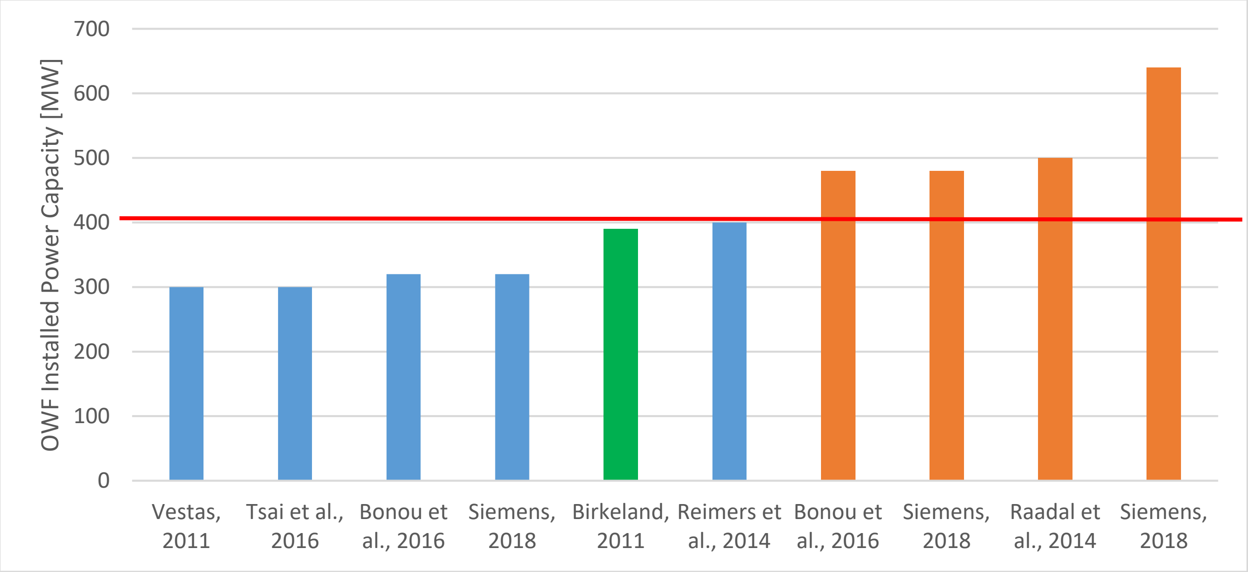

Figure 22: Substation evaluation. Top 10 studies with the highest installed power capacity. In blue studies with 1 substation under 400 MW, in green study with 2 substations, and in orange studies with 1 substation and more than 400 MW.

The internal array system most frequently used is the 33 kV voltage cable. As shown in the results section, less than half of the studies specify this parameter, and those studies consider a voltage range of 30 to 36 kV. However, new projects like Atlantic in Portugal are already installing 66 kV cable systems, which are not considered in any of the studies (Soares-Ramos et al., 2020; Wind Europe, 2019).

The UK and Germany, leading countries in total power capacity installed, have a main transmission system based on HVAC of 220 kV and HVDC of 320 kV, respectively. None of the reviewed studies consider these alternatives (Soares-Ramos et al., 2020).

4.1.5 Lifetime

As seen in the results section, turbines are modeled for 20 or 25 years of operation, and substations, array cables, and export cables are modeled in the range of 20 to 40 years. None of the studies explicitly state the lifetime consideration for the foundations. Foundations could last up to 100 years depending on the type and load, and substations and transmission cables could last 35 to 40 years (Pakenham et al., 2021; Topham & McMillan, 2017). Therefore, OWF lifetime extensions are being implemented and repower alternatives considered. Currently, Siemens offers a ten-year-lifetime extension using new O&M monitoring technology (Pakenham et al., 2021; Siemens Gamesa, 2018). A twenty-year extension of the OWF lifetime could be possible by replacing the turbine, while reusing the foundation and supporting infrastructure. However, installing a new turbine in a twenty-year-old foundation with 20-year-old power transmission, could face many challenges, cost being one of them (Pakenham et al., 2021). No reviewed LCA models evaluated any alternative similar to these.

4.2 Phases Consideration

4.2.1 Installation Phase

The installation phase of an OWF could represent almost 20% to 30% of the overall cost of a project (Paterson et al., 2018; Rippel et al., 2019; Tekle Muhabie et al., 2018). However, only four studies, 16% of the reviewed LCAs, provide details about which tasks are considered. Most of the reviewed tasks in the background section are considered by these studies, with exception of the pre-installation task of dredging and surveying, which is not considered by any of the studies. Different assembly strategies are not evaluated by any of the reviewed studies, even though the assembly strategy is considered one of the key activities in reducing the installation time and increasing performance (Lacal-Arántegui et al., 2018; Paterson et al., 2018). Three studies specify transportation assumptions based on a fixed distance from the manufacturer's location to the installation harbor and from the harbor to the OWF location. It could be inferred that a conventional assembly strategy is modeled. Still, a base-port feeder ship strategy or a port pre-assembly strategy could also be possible in some of these cases.

The foundation installation task clearly depends on the type of foundations adopted for the OWF. This decision depends on the location, water depth, and soil conditions (Douglas-Westwood, 2013; Lacal-Arántegui et al., 2018). The foundation installation rate is only provided by five studies, 26% of the reviewed LCAs, which all consider some type of bottom fixed foundations. Interestingly, as shown in Figure

23, most fixed bottom foundations (gravity base, monopile, and jacket) have an installation rate performance greater than any real project. Lacal-Arantegui et al. (2018) showed that monopiles, the most common type of foundation currently being installed, achieved a 56% improvement in installation time from 2002 to 2012, getting to almost 2 days per foundation in 2018. However, LCAs, published in 2016 and 2018, modeled 1.3 days per foundation and 1 day per foundation, respectively. The tripod is the only foundation modeled with longer installation rates than those achieved by real projects.

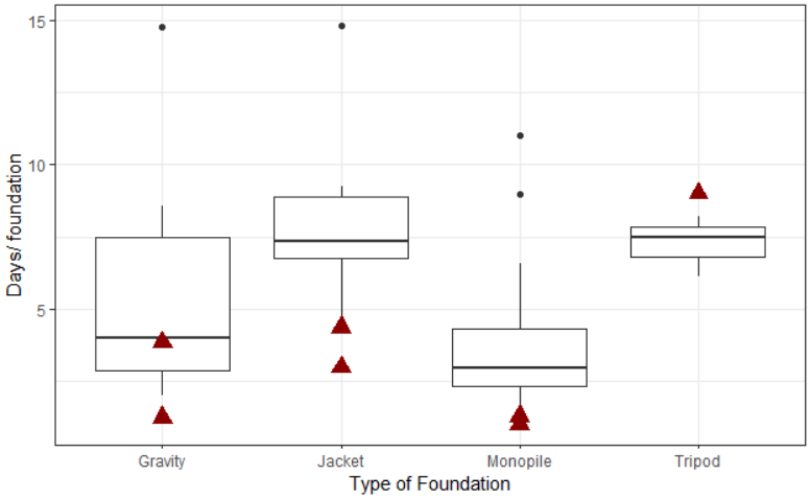

Figure 23: Foundation installation rate modeled vs real projects. The red triangles represent the foundation installation rate modeled in LCAs and the boxplots represent the rate of installation of real projects. [based on Table A and data from Lacal-Arántegui et al., (2018)].

The turbine installation task clearly depends on the assembly strategy adopted, as described previously. Similar to the foundation installation rate, only 26% of the studies state the turbine installation rate. Figure 24 shows a general comparison between the model turbine installation rate and real projects' turbine installation time. Clearly, the modeled turbine installation performance is greater than any real project, for any turbine power capacity. Additionally, it is not clear in the reviewed LCA models whether the transition piece required for monopile foundations is considered in the installation time of the turbine or the foundation (Paterson et al., 2018). A more valuable comparison would have been comparing each study with real projects using the same installation method, but as stated, that information is not provided in the LCA models.

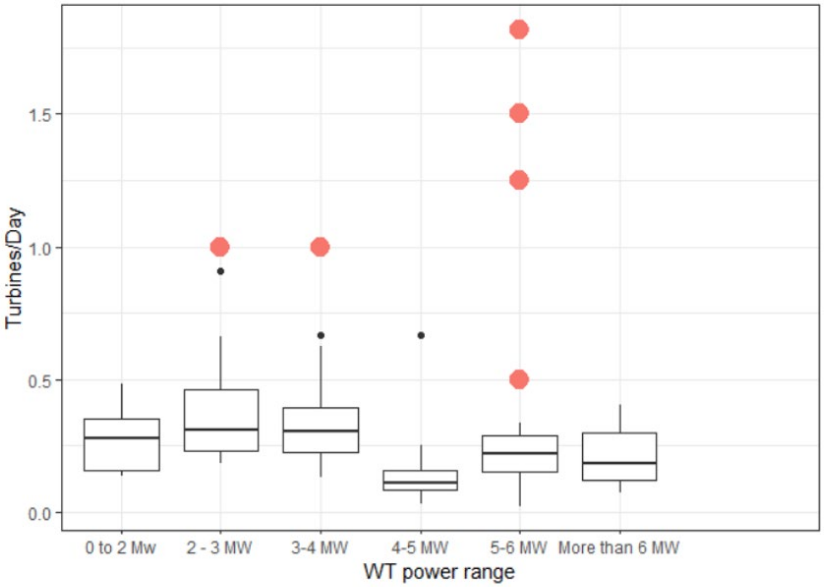

Figure 24: Turbine Installation rate modeled vs real projects. The red dots represent the turbine installation rate modeled and the boxplots represent the rate of installation of real projects. [based on Table A and data from Lacal-Arántegui et al., (2018)]

One probable reason for the difference in both the foundation installation rate and the turbine installation rate is the weather conditions and the subsequent consideration of weather windows. Weather conditions could be responsible up to 50% of the time lost in an OWF installation (Paterson et al., 2018; Scholz-Reiter et al., 2011). A valid consideration might be that the time spent as a stand-by time of vessels at the ports, with minimum impact on the LCA study, is not considered. However, since it is not uncommon that vessels have to return to port due to weather conditions, incurring fuel consumption associated with incomplete tasks from transit to site to partial loading of material, it would be interesting to understand better what the most accurate installation performance of both foundations and turbines are to reflect the fuel consumption of vessels more accurately.

Vessel characteristics are another key parameter that could affect the OWF installation performance (Lacal-Arántegui et al., 2018; Paterson et al., 2018). Vessels that could reduce the number of trips to the harbor for material loading could potentially reduce the total installation time since they allowed a reduced window of operation that could be affected by weather conditions (Paterson et al., 2018).

The vessels' fuel consumption assumptions, reported by 37% of the studies, introduce a notable uncertainty in LCA models due to the high variability among studies and different vessels. For instance, the Brave tern, a Turbine Installation Vessel (TIV), can have a fuel consumption of 2,156 L/hour in transit, while only a 335 L/hour consumption when already elevated and actively working (Fred.Olsen Wincarrier, 2013). However, the JILL, a self-propelled jack-up vessel, has a fuel consumption of only 504 L/hour in transit and 283 L/hour when actively working (Fred. Olsen Windcarrier, 2021). This also shows the potential value of considering the transition time lost due to weather conditions since the relevant fuel consumption during the vessel transit to the site. It also shows that the fuel consumption associated to vessels not only depend on the type and number of the vessels, but also on which specific vessels will perform the assembly operations.

OWF installation requires both processes onshore and offshore, but most studies simplify onshore tasks or exclude them from their system boundaries. Lastly, none of the reviewed studies considers any scenario with foreign transportation of imported turbines in their OWF construction.

4.2.2 Maintenance

As shown in the results section, only a reduced number of studies provide a detailed description of the modeling decisions for the maintenance phase. Additionally, there is high variability in the modeled variables between the different LCAs that do describe the maintenance phase more specifically. The impact of this activity may not have a strong influence on the associated environmental impacts, but it is crucial to assure the operation of the OWF during the whole lifetime and with the associated capacity factor. Relatively new maintenance strategies, like condition-based maintenance, allow reducing the frequency of services by using a condition monitoring system (CMS). The introduction of other technologies like digital-twins, which uses Artificial Intelligence (AI) combined with CMS, will likely reduce the frequency further.

However, none of the reviewed studies associated the service frequency with a corresponding maintenance strategy, nor did any perform a sensitivity analysis for different maintenance strategies, that would provide insights into trade-offs between reliability, vessel fuel consumption, and monitoring systems and sensors (Ren et al., 2021).

Element replacement is a crucial point in the maintenance phase since it affects the inventory of materials required for the OWF and has a significant impact on impacts associated with the use of specialized vessels for the replacement process (Ren et al., 2021). Nonetheless, more than 36% of studies do not provide a description or mention any element replacement. The most frequent reason for the failure of an OWT is due to either the gearbox or the blades (Kabir et al., 2015). These are the most frequently modeled in addition to the nacelle unit as a whole. However, similar to the service frequency, there is a large range in the corresponding replacement assumptions. Even though the failure rate should be dependent on the location of the OWF due to weather conditions or the type of foundation (Ren et al., 2021), the variability for a gearbox replacement ranges from no replacement to more than 2 replacements over the lifetime of the turbine. Additionally, most of the studies do not clearly describe the logistics required for the replacement. Crane vessels and jack-up vessels are two commonly used vessels for these service activities (Bussel & Henderson, 2001; Ren et al., 2021), yet they are only clearly mentioned in two of the studies that consider element replacement. Furthermore, as shown previously, the same type of vessel can have significantly different fuel consumption, and the final consumption of the whole element replacement operation could also be affected by the weather conditions.

Lastly, direct-drive turbines, which have the same failure rate as indirect-drive turbines without the need to consider a gearbox replacement, are only modeled by three LCAs, but none of them consider or detail element replacement (Ren et al., 2021).

4.2.3 Decommissioning and EoL Management

The decommissioning of an OWF is the least understood phase (Spielmann et al., 2021). Up to 2019, only five OWF had been decommissioned. Due to advances in offshore wind technology in the past 20 years, these cases are not the best measure of the amount of work that would be required during the decommissioning of a newly installed OWF (Spielmann et al., 2021). As seen in the results section, none of the studies provide a detailed description of the decommissioning task. Only three studies clearly state the inslusion of either full or partial decommissioning, with the rest of the studies prodiving little detail about this phase besides that it was considered. No sensitivity analysis was performed regarding different decommissioning scopes, and only two of the five decommissioning strategies presented in the introduction section were modeled by the reviewed LCAs.

Associated onshore logistics of decommissioning could have a significant contribution to GHG emissions (Spielmann et al., 2021). However, only four studies clearly state that the transportation logistics to a treatment facility are considered and provide the distance to the respective plants or the required fuel consumption. Further detail to evaluate if these assumptions represent the real logistics that would be required for the location of the OWF are not provided in any of the studies.

With the increasing installation of offshore wind energy and the outlook for the coming years, waste management and recycling will be a central point associated with the decommissioning of OWF (Chen et al., 2021). Even though metals which are the main element in key components like towers, nacelles, generators, and gearboxes, have high recycling rates (Chen et al., 2021), the non-metallic elements present a challenge due to the lack of proper recycling techniques that could allow effective recycling.

Blades, a component with a high replacement rate and mostly made of polymers and glass (Chen et al., 2021), are one of the main components associated with the nonmetallic elements. The ongoing research into 100% recyclable blades reflects the market interest in increasing the resource and energy efficiency of the wind energy market (4 C Offshore, 2020).

4.3 Discussion of impact assessment results

4.3.1 Potential impact of new technologies in the impact assessment

OWT with higher power capacity and extended lifetime will most probably be associated with a reduction in their corresponding impacts. Bigger OWT require more time for installation, but due to advances in installation methods and vessels, the installation time per turbine remains mostly constant. The power installed by day has been reducing at a similar rate as the turbines get bigger (Lacal-Arántegui et al., 2018). This trend is difficult to validate in the reviewed material due to the lack of significant studies considering high power turbines.

Advancement in the array cable system using 66Kv cables will potentially allow a reduction in the number of substations required for a given OWF potential (Úna Brosnan and Andrew Thompson, 2018). This is another trend that cannot be observed in the results section due to the lack of studies that consider this system. Power-to-X technology, a leading-edge storage alternative (Wind Europe, 2019), cannot be evaluated for the same reason.

It is clear that more updated LCA models are needed to understand better the impact that these and other new technologies may have on the impact assessment of an OWF.

4.3.2 Trends and Considerations for Future Offshore Wind Markets

The production phase has been the main focus of most OWF LCA due to its major contribution to many environmental impacts (Arvesen & Hertwich, 2012; Kaldellis & Apostolou, 2017). CO_{2e}, as shown in the results section, is mostly affected by the production phase. However, other parameters besides the turbine production may be of significant interest, in part because OWF projects may have limited potential to reduce impacts from production, but could have some control over reducing the impacts of other life cycle phases.

Vessel selection and availability are essential during the whole lifetime of an OWF, from its installation, operation and maintenance, and decommissioning (Paterson et al., 2018; Spielmann et al., 2021). Interestingly projects that describe their assumption regarding vessels have a contribution of installation phase plus O&M phase greater than any other project that does not clarify this, suggesting that future studies should ensure that vessel selection and use is carefully included within the análisis scope.

Different assembly strategies for the installation phase and maintenance strategies have not been considered by the reviewed studies. Both phases have a strong dependency on vessel considerations and weather conditions. Weather conditions will limit the tasks performed in these phases depending on the vessel characteristics, and vessel selection will be made considering the most frequent weather conditions in the location.

Future markets that may consider their first project with imported OWT from bordering countries will most probably phase projects with significant transportation contributions. The construction of these potential OWFs will require an assembly strategy that is not independent of the production of the turbine (Úna Brosnan and Andrew Thompson, 2018) and may define the vessel requirements. In addition, vessel availability is a significant logistic topic (Rippel et al., 2019) that may lead to the use of no optimal vessel or even limit the scope of the OWF that could be constructed. Understanding how all these considerations are related in a systematic approach may help future markets understand how the impact assessment would look like in their offshore wind roadmap.

5. Conclusion

This review of the existing body of literature on LCAs of OWT and OWF revealed a high degree of variability among study results, and due to a lack of detail and inconsistent scopes, it is difficult to determine the source of variability. Equally important is the mismatch between the previous studies and the likely future of OWF development on the basis of geography, power capacity, and even new technologies. There is a clear need for updated LCAs studies that better reflect current practices of the installation, O&M, and decommissioning phases of the OWF, that includes the latest technology, and considers the developing and future markets.

Except for the OWT production, the rest of the phases of an OWF project are strongly related to the selection, availability, and characteristics of the vessel fleet considered for an OWF project. It has been shown in this work that vessels' fuel consumption may have a significant impact on the environmental performance of an OWF. Additionally, maintenance strategies like CMS or digital-twin have the potential to reduce item replacement during the OWF lifetime, and recyclable blades could completely change the recyclable rate of OWFs' non-metallic materials. Both of these changes could have a significant impact on the environmental performance of an OWF.

Emerging technologies such as new generation turbines, power-to-x, lifetime extension, and new power transmission systems are game-changers in the performance of an OWF project in any dimension. These new technologies will demand a rethinking of current OWF layouts, demand more specialized vessels, and enable new possibilities for an OWF project. This will completely change the scope and results of future LCAs.

The current status of the OWI demands an updated understanding of the life cycle assessment of offshore wind energy produced in countries like China, which has led the OWI in power installed per year since 2018. In less than ten years, Asia has gone from its first MW installed to be the second region in the OWI, with a strong predominance of China, but also with the current development of countries like Taiwan, Japan, South Korea, and Vietnam (GWEC, 2020a).

LCA should help provide a better understanding of environmental performance for OWF new potential markets. Brazil, one of the most suitable countries in South America for developing an OWI, lacks any LCA study for the construction and operation of OWF. With a 1688 GW of gross offshore wind potential and 320 GW of technical, environmental, and social potential (Vinhoza & Schaeffer, 2021), understanding what the different environmental and social impact indicators would look like in their roadmap to construct this industry is essential for the development of offshore wind energy policy, not only for Brazil, but also for the rest of the countries in the region.

The future net-zero emissions scenario requires that all these new technologies become fully incorporated in the industry, and all potential markets worldwide start developing their OWI. New LCAs studies are needed to reflect the current and future changes in this industry, if a sustainable and net-zero emission OWI in the future are to be attained.

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7. Supplementary material

Table A: Summary of reviewed studies. Article information and OWFs' location are presented here. This is a partial representation of the complete dataset.

Paper ID	Scenario Nr	Primary Author	Year	Continent	Country	Ref
1	**1**	Yu-Fong Huang	2017	Asia	Taiwan	(Huang et al., 2017)
1	**2**	Yu-Fong Huang	2017	Asia	Taiwan	(Huang et al., 2017
2	**3**	Jan Weinzettel	2009	Europe	Norway	(Weinzettel et al., 2009)
3	**4**	Hermann-Josef Wagner	2011	Europe	Germany	(Wagner et al., 2011)
4	**5**	Juhua Yang	2018	Asia	China	(Yang et al., 2018)
5	**6**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**7**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**8**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**9**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**10**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**11**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**12**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**13**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**14**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**15**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**16**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**17**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**18**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**19**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**20**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**21**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**22**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**23**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
5	**24**	Liang Tsai	2016	North America (US)	US	(Tsai et al., 2016)
6	**25**	Britta Reimers	2014	Europe	Germany	(Reimers et al., 2014)
7	**26**	Anders Arvesen	2012	Not specify	Not specify	(Arvesen & Hertwich, 2012)
8	**27**	Hanne Lerche Raadal	2014	Europe	United Kingdom	(Raadal, 2014)
8	**28**	Hanne Lerche Raadal	2014	Europe	United Kingdom	(Raadal, 2014)
8	**29**	Hanne Lerche Raadal	2014	Europe	United Kingdom	(Raadal, 2014)
8	**30**	Hanne Lerche Raadal	2014	Europe	United Kingdom	(Raadal, 2014)
8	**31**	Hanne Lerche Raadal	2014	Europe	United Kingdom	(Raadal, 2014)
8	**32**	Hanne Lerche Raadal	2014	Europe	United Kingdom	(Raadal, 2014)
9	**33**	Alexandra Bonou	2016	Europe	Not specify	(Bonou et al., 2016)
9	**34**	Alexandra Bonou	2016	Europe	Not specify	(Bonou et al., 2016)
10	**35**	SIEMENS GAMESA	2018	Europe	Not specify	(SIEMENS, 2018)
11	**36**	SIEMENS GAMESA	2018	Europe	Not specify	(SIEMENS, 2018)
12	**37**	SIEMENS GAMESA	2018	Europe	Not specify	(SIEMENS, 2018)
13	**38**	NEEDS	2008	Europe	Denmark	(NEEDS, 2008)
14	**39**	Vestas /Elsam	2004	Europe	Denmark	(Vestas, 2004)
15	**40**	Vestas	2006	Europe	Denmark	(VESTAS, 2006)
16	**41**	Niels Jungbluth	2005	Europe	Switzerland	(Jungbluth et al., 2005)
17	**42**	Christine Birkeland	2011	Europe	Norway	(Birkeland, 2011)
18	**43**	Jesuina Chipindula	2018	North America (US)	US	(Chipindula et al., 2018)
18	**44**	Jesuina Chipindula	2018	North America (US)	US	(Chipindula et al., 2018)
18	**45**	Jesuina Chipindula	2018	North America (US)	US	(Chipindula et al., 2018)
18	**46**	Jesuina Chipindula	2018	North America (US)	US	(Chipindula et al., 2018)
19	**47**	Shifeng Wang	2019	Not specify	Not specify	(S. Wang et al., 2019)