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Life cycle assessment of a floating offshore wind farm in Italy

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ABSTRACT

Mitigation of climate change requires consistent actions toward the reduction of emissions from the energy sector: in the last years, renewable energy technologies, such as wind power, have become a cost-effective option to pursue the transition to low emission systems for power generation. Offshore wind energy can provide access to additional wind resources, also overcoming some issues related to onshore wind deployments such as land-use competition and social acceptability. The Life Cycle Assessment (LCA) methodology can be used to gain insight into the environmental performances of different technologies, e.g. renewable energy generation technologies, along the lifecycle stages and across a number of impact categories. This paper reports the *cradle-to-grave* LCA of a floating offshore wind farm, consisting of 190 wind turbines with 14.7 MW rated power, intended to be deployed in the Mediterranean Sea. The employed technology is represented by the IEA 15 MW reference wind turbine supported by the reference semi-submersible platform. The selected functional unit is the delivery of 1 GWh of electricity to the onshore grid and the impact assessment method is the EPD (version 2018), which is usually used for the creation of Environmental Product Declarations (EPDs) and considers 8 impact categories. The results of the analysis show that the supply of raw materials, especially steel, for aerogenerators and floaters is the most significant contributor to the overall potential impacts in all the impact categories, except for abiotic depletion of elements, where power cables are the hotspot. In the perspective of decarbonisation, the estimated carbon intensity is 31 g CO_{2eq}/kWh and so it results competitive with other low emissions electricity generation technologies. To compare the estimated global warming impacts to other studies, some harmonisations efforts on capacity factor and lifetime of turbines are made. Moreover, the wind farm performance has been evaluated in terms of carbon and energy payback time, estimated in 2 and 3 years respectively, showing a substantial benefit when compared to the expected 30-year lifetime. As a conclusion, despite the number of approximations and conservative assumptions, floating offshore wind power, represented by the modelled case study, can be considered a promising technology and has been found to be already competitive with other renewable electricity generation technologies. Future research should address the uncertainty rooted to the data: repeating the analysis relying on the executive project, and therefore on a more detailed modelling, would help to get more accurate results.

1. Introduction

The deployment of renewable sources, instead of fossil fuels, for electricity generation is expected to be fundamental for reaching the goal of producing energy to fulfil the increasing global demand, while pursuing efforts to mitigate anthropogenic climate change. According to the IPCC Sixth Assessment Report (2022), following the road to electrification and decarbonisation to achieve a rapid and deep reduction of greenhouse gasses (GHG) emissions requires a major transition in the energy sector. Large contributions can be given by wind and solar energy. In particular, wind energy is identified among the increasingly cost-effective mitigation options (IPCC, 2023). Wind farms are normally characterised by relatively low environmental impacts but can show ecological effects which are significant at local level, including adverse effects on wildlife due to habitat modification and potential collision with the infrastructure (IPCC, 2023). In addition, wind farms sometimes encounter public opposition due to concerns related to noise and aesthetic impacts. Moreover, onshore wind farm deployments are

Abbreviations: CPBT, Carbon Payback Time; CED, Cumulative Energy Demand; EPBT, Energy Payback Time; EPD, Environmental Product Declaration; FU, Functional Unit; LCA, Life Cycle Assessment; OTM, Offshore Transformer Module; TLP, Tension Leg Platform.

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limited due to land availability, technical constraints as well as some social acceptability issues. Therefore, there is growing interest in the potential of offshore wind energy which can overcome such limitations. Moreover, the abundant wind resources that can be unlocked by floating installations have great potential since wind at sea has higher quality than onshore, due to higher average speed but lower turbulence and variability (IPCC, 2022).

In 10 years (2010−2020) offshore wind turbines have experienced a significant growth both in terms of rotor diameter (+44 %) and in terms of generation capacity (+150 %) (IRENA, 2020); in the same period, also for onshore aerogenerators a development has been observed: comparable in terms of size (+48 %) but much more moderate in terms of power rating (+58 %) (IPCC, 2022). According to Wiser et al. (2021) the median capacity and turbine size (in terms of rotor diameter and hub height) of offshore wind turbines in 2019 were already higher than in case of onshore turbines. Moreover, experts asked about expected evolution to 2035 depicted a more rapid growth in generation capacity for offshore turbines (+ 183 %) than onshore turbine (+120 %). Also, the rotor diameter is expected to grow more rapidly for offshore turbines than in case of onshore ones (+ 67 % and + 45 % respectively) while increase of average hub height is expected to be comparable between onshore and offshore deployments (+46–47 %).

As yet, the offshore wind energy installations are concentrated in Europe, where the technology development has been fostered, especially in countries bordering the North Sea, where high quality wind resources and relatively shallow waters can be found (IEA, 2019). Until recently, the foundations for wind turbines installed offshore used to reach the seabed and thus were called bottom-fixed. Various types of bottom-fixed designs are available but in general they are suitable for applications where the bathymetry is limited (Bhattacharya, 2019). However, it is estimated that 80 % of the world's offshore wind resources are located in waters with depth >60 m, where traditional (bottom-fixed) offshore wind installations are not economically attractive (Lee and Zhao, 2021) or technically feasible. Therefore, motivated by the interest in moving to deep water areas, floating solutions for windmills have been developed: further from shore, the better wind conditions can be exploited and environmental impacts, such as the visual impact, can be limited. *Presently,* the floating offshore technology seems promising: after the phase of demonstration and pilot projects in both Europe and Asia, the industrial-scale deployments have started recently. As of 2021, the installations of this technology are concentrated mostly in Europe, not only in the North Sea off the coasts of the UK (78 MW) and Norway (5.9 MW), but also off the coasts of Portugal (25 MW) and France (2 MW), in addition to China (5.5 MW) and Japan (5 MW) (Williams et al., 2022). There are currently four main concepts of floating foundations, represented in Fig. 1: barge, spar-buoy, semi-submersible platform and tension leg platform (TLP) (Wind Europe, 2017). In the last few years, some floating offshore wind designs have been moving from research and development phase to demonstration and operation. As stated by Wind Europe (2017), the technology readiness level (TRL) of spar and semi-submersible (semi-sub) substructures has already entered the phase with TRL > 8 (system complete and qualified, proved in operation environment) while the barge system is reaching that level and the TLP concepts are less advanced.

As of recently, the majority of the installed floating turbines rely on the spar concept (56 %) while the rest is evenly distributed between semi-sub and barge (Lee and Zhao, 2021). However, considering the projects at various development stages, the highest share of floater type is represented by the semi-submersible platform (64 %) followed by spar (13 %) and barge (10 %) but also some TLP projects (7 %) have been identified (Lee and Zhao, 2021).

In addition to the floating substructure, in order to be kept in position, the offshore wind turbines rely on mooring systems i.e. systems consisting of a mooring line and an anchor in specific mooring configurations, depending on local environmental and seabed conditions (Rhodri and Marc, 2015). Generally, the barge, semi-sub and spar systems employ looser mooring configurations e.g. catenary lines, which allow for easier installation, while the TPL concepts rely on systems maintained in high tension that achieve greater stability (Wind Europe, 2017).

Notably, Italy does not present significant potential for bottom-fixed turbines, since the wind and water depth conditions are not favourable; on the contrary, floating turbines have a wider employment potential, up to 183 GW (Lee and Zhao, 2021). In fact, in 2022 the first offshore wind farm in Italy *has been connected to the grid: the plant consists of 10 turbines with 30 MW total capacity but with monopile foundations (*Del Fico, 2021*).*

The present work aims to assess the environmental performance related to the delivery of 1 GWh to the onshore Italian national grid from a floating offshore wind plant. Specifically, a Life Cycle Assessment (LCA) study has been carried out on a large wind farm off the coasts of Sicily, whose preliminary project has been submitted to the Ministry of

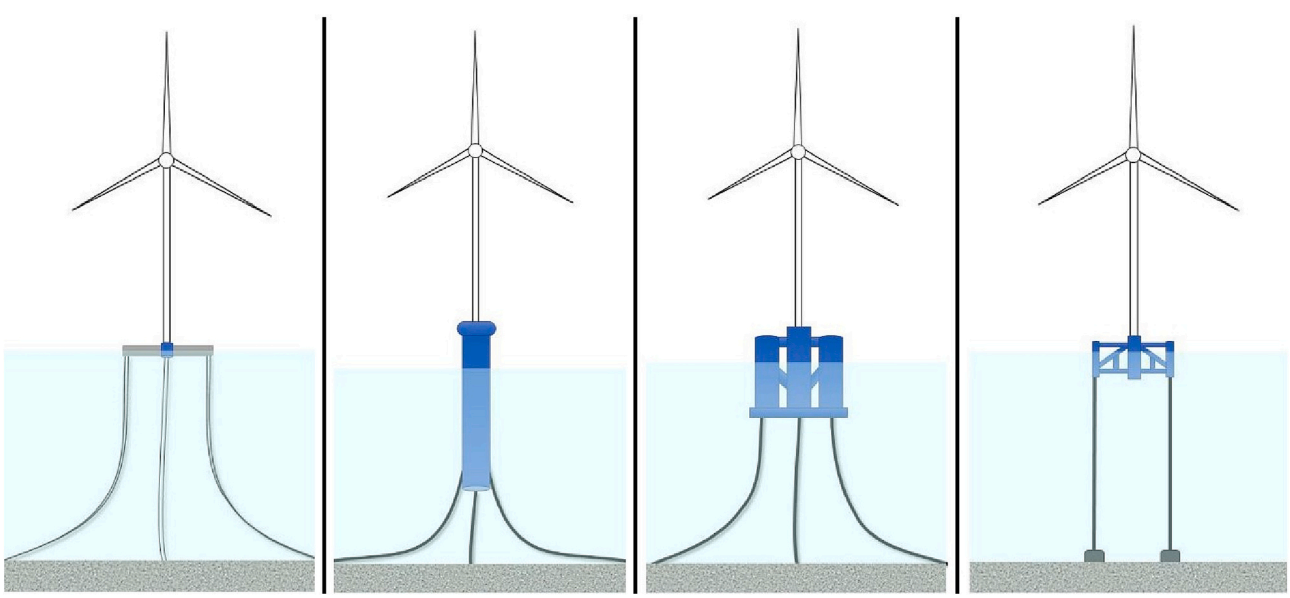

Fig. 1. Illustration of the main floater concepts (adapted from (WindEurope, 2017)). From left to right: Barge, Spar-buoy, Semi-submersible platform, Tension-leg-platform (TLP).

the Environment, according to the Environmental Impact Assessment (EIA) procedure, and is currently undergoing the permitting process (Med Wind, 2020a). The rationale behind the selection of the case study is its distinctiveness: it would be among the first offshore wind farms deployed in the Mediterranean Sea and it would stand as the largest floating one in Europe, since it accounts for almost 3 GW of installed capacity.

2. Literature review about LCA applied to wind technologies

Although wind energy is considered one of the cleanest energy sources since it is almost burden-free during its operational phase, from a life cycle perspective, any technology, despite harnessing renewable resources, results in environmental burdens associated with the consumption of resources, materials and energy. The application of the LCA methodology allows to evaluate the potential environmental impacts throughout the entire life cycle of the wind farm: by including the supply chain of components and the necessary infrastructures, the impacts of upstream and downstream processes can be taken into consideration, leading to more accurate results with respect to considering renewable energies “zero impact” technologies.

In the LCA literature, onshore wind power has been extensively covered, as highlighted in the reviews by Arvesen and Hertwich (2012) and Nugent and Sovacool (2014), which analysed about 30 and 20 LCA studies on onshore wind finding a range of potential global warming of 6–34 g CO_{2eq}/kWh and 0.4–364.8 g CO_{2eq}/kWh, respectively. Also, in more recent studies (e.g. Bonou et al., 2016; Wang et al., 2019) comparative LCAs between onshore and offshore wind turbines have been performed, focussing on GHG emissions and showing that onshore wind power performs better than offshore per kWh of energy delivered.

So far, offshore options have been researched to a minor extent: some LCA studies are available focussing on bottom-fixed offshore wind (Bonou et al., 2016; Raadal et al., 2014; Wang et al., 2019) and only few have assessed also floating designs (Garcia-Teruel et al., 2022; Raadal et al., 2014; Weinzettel et al., 2009). Also, wind turbine’s manufacturers, such as Vestas and Siemens-Gamesa, have applied LCA to analyse their own products, both for onshore (Razdan and Garrett, 2017, 2019) and offshore bottom-fixed applications (Siemens-Gamesa, n.d.; Siemens AG, n.d.), relying on primary data and making the results publicly available.

A special point of attention has been the transmission system in place in the drivetrain of the wind turbine: the traditional one uses a gearbox, whose main purpose is to couple the motion of the rotor with the speed of the generator, but more recent options, called direct-drive, rely on a permanent magnet generator (PMG) and fewer rotating elements (Carrara et al., 2020). Besides the possible technical improvements, the comparison is addressed in some LCAs studies which have concluded that direct-drive machines have a slightly lower carbon footprint compared to geared machines (Bonou et al., 2016; Guezuraga et al., 2012).

Raadal et al. (2014) assessed the environmental impacts (GHG emissions) and energy performance on a life cycle perspective of six offshore wind turbine conceptual designs, comparing five floating solutions to one bottom-fixed. The results show that the best solution, in terms on global warming (*GW*) impacts, is the MIT Tension-Leg-Barge (TLB) followed by the bottom-fixed option; instead, the highest *GW* impacts are reported for the semi-submersible design. Furthermore, Weinzettel et al. (2009) and Garcia-Teruel et al. (2022) carried out the LCA of offshore wind farms employing different floating substructures: Weinzettel et al. (2009) analysed the tension-leg-spar (SWAY) while Garcia-Teruel et al. (2022) both the spar-buoy and the semi-submersible platform. Weinzettel et al. (2009) reported the comparison to the ecoinvent dataset modelling the production of electricity from an offshore non-floating wind turbine finding that in 5 impact categories the floating solution has higher impacts, in 2 categories the results are comparable, and that the floating turbine shows better results in the global warming category. Garcia-Teruel et al. (2022), instead, found that the semi-submersible option has lower impacts in all the analysed impact categories (of the method ReCiPe Midpoint (H)) when compared to the spar concept. Among the lifecycle stages of the semi-submersible scenario, the largest contributions to the overall impacts stem either from materials and manufacturing phase or from operation and maintenance (O&M) activities, that were modelled in detail both in terms of marine operations with specialised vessels and spare parts requirements. Both the studies included in the scope of the analysis also some elements for the transmission of the generated power to the shore: either only the power cable (Garcia-Teruel et al., 2022) or an offshore transition station in addition to the submarine cables (Weinzettel et al., 2009). Both the studies revealed a significant contribution of power transmission systems to certain impact categories (e.g. ecotoxicity, human non-carcinogenic toxicity, eutrophication and abiotic resources depletion) due to the presence of copper.

A significant element of novelty of the present work is the presence of large size wind turbines (15 MW) installed on floating foundations as the core feature of the selected case study. At the present state, not many LCA studies which analyse offshore bottom-fixed wind turbines with rated power from 5 MW up can be found in the scientific literature (Siemens-Gamesa, n.d.; Siemens AG, n.d.) but even fewer are focussed on the investigation of large turbines and floating conceptual designs (Garcia-Teruel et al., 2022; Raadal et al., 2014; Weinzettel et al., 2009). Therefore, the present research can give additional information on the lifecycle impacts of floating concepts deployments and begin to fill the knowledge gap concerning both large offshore aerogenerators, which reflect the current commercial deployments and market trends. In fact, the major world’s wind turbine suppliers have recently launched offshore models with power rating reaching up to 15 MW, that will be commercially available from 2024 (Lee and Zhao, 2021). Besides, assumptions regarding life cycle stages, e.g. installation or operation and maintenance, are generally lacking in transparency, perhaps due to data confidentiality, while in this study the assumptions are stated clearly. Furthermore, in many available LCA studies, the defined system boundaries do not consistently account for all the life cycle stages, e.g. the end-of-life stage is often partially included or even omitted. This study, instead, is intended to cover the whole life cycle, by means of modelling assumptions, and not only the wind turbines and floating structures but also the other elements of the power transmission system, which are expected to gain relevance as the distance from shore increases.

3. Methods

The environmental performance is evaluated by means of the Life Cycle Assessment (LCA) methodology, which is aimed at quantifying the potential environmental impacts throughout the entire life cycle of the object of the study, defined as *product system* i.e. the human activity or product performing one or more defined functions (ISO 14040:2006, 2018; ISO 14044:2006, 2018). The perspective tends to be as holistic as possible: the most complete approach is the *cradle-to-grave*, that means including all the life cycle stages from raw materials extraction (cradle) to management of the generated waste (grave). The general purpose of such a comprehensive approach is to avoid the so-called “burden shifting”, that means to shift impacts to other phases, geographical areas or impact categories, that might be excluded from the scope of a narrower analysis (European Commission, 2010). Besides, performing a contribution analysis of the results is useful to identify the hotspots in the life cycle, i.e. the stages or processes that contribute most to the total impacts, and consequently recommend improvement opportunities.

According to the standards (ISO 14040:2006, 2018; ISO 14044:2006, 2018), LCA is an iterative process composed of four main phases: goal and scope definition, inventory analysis, impact assessment and results interpretation; the most relevant contents are summarised in the following paragraphs (0, 3.2, 4).

3.1. Goal and scope of the study

The present study is aimed at evaluating the environmental performance of a floating offshore wind farm, selected as a case study. The performed LCA has a cradle-to-grave perspective.

The description of the case study wind farm stems from the documentation provided for the EIA scoping stage (Med Wind, 2020a). According to the available documentation, the wind farm consists of 190 wind turbines for a total capacity of 2.8 GW, installed on floating systems. The selected site is found about 60 km off the west coast of Sicily, extending on an area of 2422.5 km^2 (Med Wind, 2020a). The electrical system necessary for the transmission of the generated power consists of (Med Wind, 2020b):

- Three offshore transformer modules (OTMs), where the high voltage (HV) transformer, aimed at changing the voltage level, and the converter are located. Due to water depth, they are supposed to be installed on a floating structure, too.
- Two types of submarine cables are required for the transmission of the generated electricity, i.e. medium voltage inter-array cables (to connect the turbines to the OTMs) and the high voltage direct current (HVDC) export cables (to connect the OTMs to the shore).
- Land HVDC cables are required to connect to the onshore conversion station.

The estimated productivity of a wind plant, based on the local wind resources, is expressed by the capacity factor (CF), i.e. the ratio of the actual generated electricity produced during a period of time (typically one year) to the maximum theoretical output that would be produced if the turbine was operating without interruption at its nominal capacity over the same period of time. Table 1 reports the main characteristics of the system under study.

3.1.1. Functional unit

The selected functional unit (FU), which quantifies the function provided by the analysed product system, is "the delivery of 1 GWh of electricity produced by the offshore floating wind farm to the onshore national grid". According to this definition of the FU, the power transmission from the offshore plant to the onshore electrical grid is included, with the aim of considering the more complex electrical system which has to be put in place, in order to exploit the high wind resources further from the coast. The onshore conversion station is, instead, outside the system boundaries since it is already part of the national grid.

Table 1
Case study main characteristics and data (Med Wind, 2020a).

Characteristic	Value
Number of turbines	190
Nominal power of each wind turbine	14.7 MW
Rotor diameter, tower height	250 m, 150 m
Bathymetry	100–900 m
Number of Offshore Transformer Modules (OTMs)	3
Inter-array submarine cable length	1112 km
Export submarine HVDC cable length	690 km
Onshore cable length	75 km
Gross annual energy production [a,b]	9345.6
Annual energy production [a,c]	8804.3 GWh/year
Net equivalent hours [a]	3009 h/year
Capacity factor (CF) [a]	34.35 %
Lifetime (LT)	30 years

[a] These values are primary data, retrieved from Med Wind (2020a).
[b] The gross energy production takes into account orography and roughness length, wind velocity distribution at hub height and the provided win turbine power curve.
[c] The net energy production takes into account other efficiencies (e.g. electric efficiency, turbine performance, blades degradation, maintenance and grid availability) which altogether are equal to 89.9 %.

3.1.2. System boundaries

In the system boundaries of the analysed product system, the following life cycle stages are included:

1. Raw materials supply
2. Manufacturing and transport of components
3. Assembly and offshore installation
4. Operation and maintenance (O&M)
5. Dismantling
6. End-of-life (EoL), including transportation to the dedicated facilities for recovery or disposal.

According to the definition of the FU, these life cycle stages are referred not only to the floating wind turbines but also to the components of the electrical system.

3.1.3. End-of-life modelling

In the present work, the modelling of EoL is based on the approach illustrated in the framework of the International EPD System (International EPD ® System, 2021), which assumes that the burdens related to the "first life" of a recycled material do not affect the following uses. In case of recycling, only collection and pre-treatment activities are included in the system boundaries. Instead, for waste, which is disposed of by incineration or landfilling, not only the transportation but also the environmental burdens of the disposal shall be included in the product system. Possible benefits arising from reuse, recycling or recovery are not included as avoided impacts.

3.1.4. Analysed impact categories and characterization method

The EPD (version 2018) impact assessment method (International EPD ® System, 2021) has been selected for the analysis: this method is normally employed for the creation of Environmental Product Declarations (EPDs). The International EPD ® System (2021) has been chosen for the present study in order to directly include the results of the EPDs of some wind farm's elements i.e. mooring chains and HV transformer, for which other inventory data are not directly retrieved. According to the International EPD ® System (2021) method, the impact assessment is restricted to eight impact categories: global warming, acidification, eutrophication, photochemical oxidant formation, abiotic depletion of elements, abiotic depletion of fossil fuels, water scarcity and ozone layer depletion. Moreover, the Cumulative Energy Demand (CED) method has been applied to estimate the primary energy, both used throughout the life cycle and embodied in the plant (Frischknecht et al., 2007).

3.1.5. Payback indexes

The energy and environmental performances of renewable energies plants can be evaluated by means of payback indexes that generally indicate the time to recover an investment. Notably, the carbon payback time (CPBT) estimates the time required to compensate the greenhouse gasses (GHGs) emissions from the wind plant's life cycle; the CPBT can be calculated according to Eq. (1).

$$CPBT\ [year] = Lifecycle\ GHG\ emissions / Annual\ saved\ GHG\ emissions \quad (1)$$

The "saved" emissions are calculated assuming the annual electricity production of the case study wind plant and the emission factors associated with the electricity generation employing a non-renewable source, which is assumed as the reasonable marginal technology that is going to be replaced. In the present study natural gas in a combined cycle power plant has been assumed, considering that it is expected to be the most widespread fossil fuel-based technology in the near future.

The energy payback time (EPBT), instead, expresses the time required to recover the primary energy consumption throughout the entire life cycle of the wind farm by its own energy production, net of the yearly energy requirements for O&M; the primary energy consumption is expressed by the resulting CED for the different life cycles stages. Eq. (2) reports the EPBT expression.

$$EPBT\ [year] = \frac{(CED_{materials} + CED_{manufacturing} + CED_{transport} + CED_{installation} + CED_{EoL})}{((Energy_{annually\ generated}) - CED_{annual\ O\&M})} \tag{2}$$

3.1.6. Sensitivity analysis, benchmarking and harmonisation

Besides the assessment of the defined baseline scenario, some sensitivity analyses have been performed to test alternative assumptions i.e. the plausible future recycling of glass fibre reinforced plastic (GFRP) waste instead of the current incineration scenario and the employment of geared transmission system in the wind turbine. Moreover, based on the LCA results, the electricity produced by the modelled wind farm has been compared with the electricity taken from the Italian national grid, assuming the ecoinvent (Weidema et al., 2013) dataset representative of the Italian electricity mix[1] as of year 2018 (International Energy Agency (IEA), 2020). Indications on the energy mix are given in the *Supplementary Material* (SM.1.).

Furthermore, a certain variability with respect to the assumed CF and turbines' lifetime (LT) has been observed among other LCA studies on offshore wind power available in the literature. Since the results of an LCA are referred to the functional unit, that in most cases is defined as a unit of electricity generated by the wind farm or turbine, they prove to be strongly related to the plant productivity. Therefore, the assumption of an increase in CF or of an extended lifetime corresponds to expect more energy produced and thus reduced impacts per unit of generated electricity. In order to make the results of other LCA studies comparable with the present analysis, harmonisation has been performed: the global warming (GW) impacts (g CO_{2eq}/kWh) of the most relevant (reported in Table 7) have been adjusted according to Eq. (3), proposed in the literature (Raadal et al., 2014):

$$(gCO_{2eq}/kWh)_{harmonised} = (gCO_{2eq}/kWh) \bullet (CF_{ref}/CF) \bullet (LT_{ref}/LT) \tag{3}$$

The reference values (indicated by *ref* in the formula) are the specific lifetime and capacity factor indicated in the preliminary project documentation of the present case study (Med Wind, 2020a) and are assumed respectively equal to 30 years and 34.4 %. In particular, the declared capacity factor stems from the estimations based on the anemological characterization of the site selected for the wind farm construction and is reported in the dedicated report (Med Wind, 2020c). This kind of analysis has been performed limited to the GW category since it is the most extensively covered. Thanks to these harmonisation efforts the results of the selected studies have been reported to the specific conditions of the case study, making the comparison independent from site wind conditions and assumed lifetime.

3.2. Data collection and inventory analysis

In the absence of primary data, approximations and modelling assumptions are required to include in the analysis all the elements of the wind farm and their life cycle stages, that in the preliminary project are not defined in detail yet. The analysis has been conducted using the software SimaPro 9.3 (PRé Sustainability B.V., n.d.), which allows to create the virtual model of the product system, based on the employment of new created datasets or of processes already modelled in databases; here the ecoinvent 3.7.1 has been employed with the system model "*Allocation, cut-off by classification*" (Weidema et al., 2013).

The wind power technology assessed in this study refers to the 15 MW Reference Wind Turbine defined by the International Energy Agency (indicated as IEA 15-240-RWT), which can generally represent the offshore technology deployed in the near future (Gaertner et al., 2020). The turbine is supposed to be installed on the VolturnUS-S Semi-submersible Platform (Fig. 2) with catenary mooring, developed by the University of Maine (Allen et al., 2020).

The technical report (Allen et al., 2020) provide the main design specifications e.g. the mass of the tower and the rotor-nacelle assembly (RNA) of the IEA 15-240-RWT, that is then attributed partly to the rotor, composed of hub and blades, and partly to the nacelle and the enclosed devices, following the respective mass distribution provided in Gaertner et al. (2020). The reference semi-submersible platform is made of 4 steel columns, that are void volumes filled with ballast materials, both fixed i.e. iron ore concrete, and fluid i.e. seawater. Table 2 reports the dimensions and masses of the main components.

The mooring system has been modelled considering only the catenary chains and neglecting the anchors, due to their much lower weight. The required mass of mooring chains has been estimated assuming the

Fig. 2. Graphical representation of the UMaine VolturnUS-S reference semi-submersible platform.
Adapted from (Allen et al., 2020).

[1] Full name of dataset: Electricity, medium voltage {IT}| market for | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)

Table 2
Dimensions and masses of the main components of the reference wind turbine and floating platform, both developed in the framework of IEA Wind TCP Task 37.

	Unit	Value
IEA 15-240-RWT Reference Wind Turbine (Gaertner et al., 2020)		
Rotor diameter	m	240
Tower height	m	150
Tower mass[a]	t	1263
Rotor Nacelle Assembly (RNA) mass[a]	t	991
Nacelle mass	t	615
Rotor mass	t	376
Blades mass	t	3 × 65
Total turbine mass	t	2254
IEA VolturnUS-S Semi-submersible Platform (Allen et al., 2020)		
Structural steel mass	t	4014
Ballasting material mass	t	2540
Ballasting fluid material mass	t	11,300
Total platform mass	t	17,854
Other elements		
Mooring chains mass	t	3 × 582
HV Transformers mass	t	223

[a] The masses of tower and RNA referred to the wind turbine intended to be installed on the floating platform are reported in Allen et al. (2020) while the other components' masses are estimated based on the proportions reported in Gaertner et al. (2020).

chain specific weight and the catenary line length indicated by Allen et al. (2020) for a water depth equal to 200 m. The choice to neglect the real variability of the bathymetry in the area, as indicated in the preliminary project (Med Wind, 2020a), has been made to avoid additional uncertainty sources whereas the mooring system has not been designed yet. The potential impacts are then estimated relying on the results reported in the EPD of an R3 mooring chain (Vicinay Sestao, 2019). Also, OTMs are modelled in a simplified way, including only the HV transformer (500 MVA), whose associated impacts are extrapolated data from a real EPD (Tamini Trasformatori S.r.l., 2019) and a floating supporting structure moored to the seabed identical to the one employed for the aerogenerators. The inventory data of power cables are included by means of raw material inventories retrieved from other studies followed by the necessary extrapolations (Jorge et al., 2012; Schleisner, 2000). The rationale behind the modelling of submarine power cables is the choice to maintain the assortment of materials required for the typical multi-layer structure. Detailed data can be found in the *Supplementary Material* (SM.3.).

The assumptions needed to include in the analysis the main life cycle stages of the wind farm's components are reported in the following sections (1 – 3.2.6); details on the inventory can be found in the *Supplementary Material* (SM.6.).

3.2.1. Material acquisition

The supply of raw materials is modelled by employing the *market* datasets provided in the ecoinvent database, in order to include both the material acquisition and their transport to Europe. The collected data for the inventory, in terms of raw materials requirements, originate from other LCA studies both for the tower (Raadal et al., 2014) and for the rotor (Wang et al., 2019). The tower is mainly made of low-alloyed steel, besides other materials for cables, such as copper and aluminium, electronic devices and lubricant oil. The rotor, instead, is made of fiberglass reinforced plastic, constituting the blades, cast iron and chromium steel, employed for the supporting structure and the hub. Furthermore, two different types of nacelles, differentiated by the drivetrain, have been modelled: both the direct-drive option and the one with gearbox. Although the most common transmission system still relies on the gearbox, in the baseline scenario analysed in the LCA study, the direct-drive option is selected since it is described in the technical report of the 15 MW Reference Wind Turbine (Gaertner et al., 2020) and the specific masses per material are indicated. While the material assortment for the geared system is retrieved from Wang et al. (2019) and the required masses for the 15 MW turbine are estimated by scaling up the data of the modelled 2 MW turbine. Details on the inventory of the aerogenerators are found in the *Supplementary Material* (SM.2.).

3.2.2. Material processing and transport of the components

The manufacturing phase is approximated including only the material processing necessary for the production of the main components, relying on the *processing* datasets already present in ecoinvent 3.7.1, similarly to Wang et al. (2019) and Weinzettel et al. (2009). Also, the transportation from the manufacturing site to the selected port is accounted for in this life cycle stage. The transport distances for the single components of the wind turbines, differentiated between lorry and ship transport, are assumed from Razdan and Garrett (2019), which estimated them for a general European manufacturing location. The additional distances, estimated using *SeaRates* and reported in Table 3, are assumed to reach a plausible port on the west coast of Sicily where the assembly might occur.

Taking into account the weight of components, according to Table 2, and distance assumptions in Razdan and Garrett (2019) and Table 3, transportation to the assembly port is estimated and expressed in tonne-kilometre (t•km), that is the unit of measure of freight transport.

3.2.3. Assembly and installation

The components of the turbine are transported separately to the selected harbour and then assembled on site using building machines e. g. cranes, operated by diesel or electricity. For the turbine assembly i.e. the erection of the tower and the positioning of the nacelle and the rotor on its top, the diesel consumptions for crane works are estimated based on potential energy (Burger and Bauer, 2007). The consumption of electricity, at medium voltage, for the assembly of individual parts i.e. turbines, floating platforms (total mass, including ballasting materials) mooring systems and OTMs, is estimated assuming 0.5 $kWh/kg_{material}$ (Burger and Bauer, 2007).

After the onshore assembly, the offshore installation of floating platforms requires marine operations and specialised vessels; the advantage of semi-submersible designs is that they can be totally assembled in harbours presenting a dry-dock and then towed to the offshore site. Thus, semi-submersible designs require less specialised vessels than other floating systems, such as spar-buoy and TLP, which need crane vessels for the installation of the wind turbine once the floater is already in position on the offshore site (Jiang, 2021; Rhodri and Marc, 2015). The modelling of the installation stage is based on assuming the number and type of the employed vessels, the correspondent daily fuel consumption and the estimated installation time. Several different assumptions can be found in the literature with regard to the marine vessel operations during installation of wind turbines Garcia-Teruel et al., 2022; Sanden and Vold, 2010; Arvesen et al., 2013). Table 4 reports those for the present study.

Table 3
Assumptions on transport distances of the different components of the wind farm.

Mean of transport	Unit	Wind farm's component to be transported			
		Wind turbine[a]	Floating platform	Mooring chains	HV Transformer
Lorry	km	120	120	100	150
Ship	km	4000	4000	3200	800

[a] Additional distance to reach Sicily (from a plausible European manufacturer location) assumed for the whole wind turbine structure; meant to be added to Razdan and Garrett (2019) assumptions.

Table 4
Modelling assumptions on offshore installation of a wind turbine or an Offshore Transformer Module (OTM).

Wind farm's element to be installed		Vessel type	Number of vessels	Workdays	Heavy fuel oil consumption (t/d)[b]
OTM	Wind turbine	Tugboats	2	1	18.5
		AHTS[a]	1	1	37.5
		PSV[a]	1	1	18.5
		Fast supply vessel	1	1	9
		Crane vessel	1	11	4

[a] AHTS = Anchor Handling Tug Supply vessel. PSV = Platform Supply Vessel.
[b] The conversion from (L/h) to (kg/h) has been made assuming Heavy Fuel Oil (HFO) density equal to 0.983 kg/L as in (Arvesen et al., 2013).

3.2.4. Operation and maintenance

The operational lifetime of the wind farm is expected to be 30 years. Besides the transformation and occupation of the seabed, the impacts of this stage are mainly due to spare parts required for scheduled maintenance and repairs in case of failures. The transport of personnel for maintenance activities has been excluded from the analysis. Due to the lack of details, but with the aim of including a first approximation of the necessary components for maintenance, the additional production of 5 % complete wind turbine structures, without floating platforms, is assumed (Weinzettel et al., 2009). Moreover, lubricant oil (present in the inventories of tower and nacelle with gearbox) is assumed to be replaced two times per year, averaging the assumptions retrieved in the literature (Garcia-Teruel et al., 2022; Wang et al., 2019). These assumptions give a rough approximation of the required spare parts; nevertheless, there are studies in the literature that examine more in detail the O&M phase of floating wind farms (Arvesen et al., 2013; Garcia-Teruel et al., 2022).

3.2.5. Dismantling

The dismantling stage includes the marine operations to bring the floating turbines back to the shore and the energy consumption needed for disassembling; this stage is modelled exactly as the assembly and installation phase.

3.2.6. End-of-life

The End-of-life stage in the wind power LCAs available in literature results to be covered to a limited extent: due to the long lifetime of the plants, both temporal and technological uncertainties are associated to it. Therefore, a number of assumptions are needed in order to represent the future management of the different materials wste streams; Table 5 reports the analysed EoL scenarios, based on the indications found in literature (Bonou et al., 2016; Raadal et al., 2014; Razdan and Garrett, 2019). Notably, a sensitivity analysis has been performed focussing on Glass Fibre Reinforced Plastics (GFRP), which is composed of ca. 60 % reinforcing glass fibres and ca. 40 % resin (Fonte and Xydis, 2021), and that is currently incinerated; a future scenario is tested since recycling options are under development (Beauson et al., 2022; Fonte and Xydis, 2021).

Table 5
End-of-life scenarios under analysis.

Waste material	Assumed end of life scenario	
	Baseline scenario	*Alternative scenario*
Metals: Steel, Aluminium, Copper, Iron	90 % recycling + 10 % landfill (scraps)	
Polyethylene	100 % incineration	
Glass Fibre Reinforced Plastics (GFRP)	incineration of 60 % glass + 40 % plastic, mixture	100 % recycling
Waste from Electrical and Electronic Equipment (WEEE)	100 % treatment and disposal	
Cables	100 % sorting treatment and recycling	
Lubricant oil	100 % incineration hazardous waste	

Further information on EoL modelling is given in the in the *Supplementary Material* (SM.4.)*,* together with the detailed inventory analysis (SM.6.).

4. Impact assessment results and discussion

The total impacts of the functional unit for the impact categories included in the EPD and CED characterization methods are reported in Table 6; details, in terms of contributions to the total score of single components and lifecycle stages, are included in the *Supplementary Material* (SM.5.).

4.1. Contribution analysis

The contribution analysis, aimed at the identification of the hotspots, is represented graphically in Fig. 3: the results are reported both for the impact categories included in the International EPD ® System (2021) and for the CED method. Note that the first life cycle stage, i.e. raw materials acquisition (indicated by "supply"), can be further subdivided among the main components of the wind turbines and other offshore wind farm's elements (such as cables, offshore transformer module), in order to emphasize the contributions of the different components. The following life cycle stages, i.e. components' manufacturing and transport, assembly and installation, operation and maintenance (O&M), dismantling and end-of-life (EoL) are, instead, referred to the entire offshore wind plant. Note also that in the *photochemical oxidant formation* and the *ozone layer depletion* categories the HV transformer is not included, due to inconsistency of EPD results with the required impact assessment methods. Also, the impacts of the mooring chains and of the HV transformers are not included in the CED results, since the consulted EPDs do not provide the corresponding assessment.

Clearly, it appears that the hotspot of the life cycle is the materials' supply stage: in particular, either the floating system or the wind turbine structure is the most impacting element. In five (*global warming, photochemical oxidant formation, abiotic depletion of fossil fuels, water scarcity and ozone layer depletion*) out of the eight selected impact categories, the supply of the floating system i.e. semi-submersible platform and mooring chains, is the most contributing element: in these categories, it ranges altogether between 26 % to *water scarcity* and 32 % to *photochemical oxidant formation*. The other impact categories are mostly impacted by the supply of the wind turbines (reported as sum of tower, rotor and nacelle): its contribution ranges between 22 % to *acidification* and 36 % to *abiotic depletion of elements*. The only exception, displaying a different ranking of contributions, is the category of *abiotic depletion of elements,* to which the cables are the main hotspot, contributing more than half of the total impacts (52 %), followed by the turbine's structure (36 %). Focussing on the life cycle stages following the supply of raw materials, i.e. from manufacturing to end-of-life, the estimated impacts result to be at maximum the third most critical contributor to the overall burden for whichever impact category: the assembly stage shows significant impacts to *global warming* (11 %), *abiotic depletion of fossil fuels* (12 %) and *water scarcity* (16 %). O&M is the third impacting process to *photochemical oxidant formation*, accounting for 11 % of the total impacts, and dismantling accounts at maximum for 16 % of the overall impacts (*ozone layer depletion*).

Focussing on the semi-submersible platform, the low-alloyed steel supply and the mooring chains are the most impacting elements: the steel production activity shows the largest environmental burdens to the rest of the impact categories, with a contribution ranging between 35 % to *acidification* and 44 % to *photochemical oxidant formation*.

Going into detail on the components of the turbine (tower, rotor and nacelle), the contribution of the tower is the most relevant in several impact categories: *global warming* (9 %), *photochemical oxidant formation*

Table 6
Total impact assessment results expressed per functional unit (1 GWh).

AC	EU	GW	POF	ADP $_{elements}$	EDP $_{fossil\ fuels}$	WS	OLD	CED
kg $SO_{2\ eq}$	kg $PO_{4\ eq}^{3-}$	t CO_{2eq}	kg NMVOC	g Sb $_{eq}$	GJ	m^3 $_{eq}$	g CFC-11$_{eq}$	GJ
184	68	31	131	1713	363	1.6×10^4	3	410

AC = Acidification, EU = Eutrophication, GW = Global Warming, POF=Photochemical Oxidant Formation, AD el = Abiotic Depletion of elements, AD ff = Abiotic Depletion of fossil fuels, WS=Water Scarcity, OD=Ozone Layer Depletion; CED = Cumulative Energy Demand.

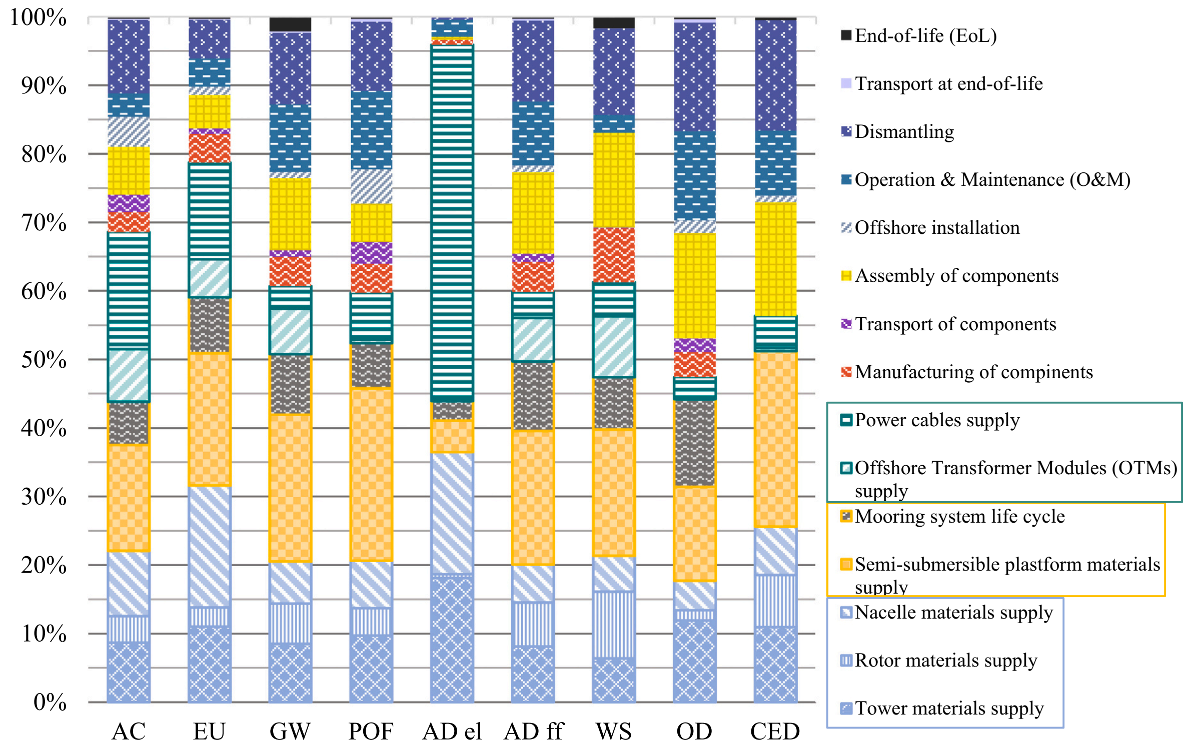

Fig. 3. Contribution analysis of the potential environmental impacts of 1 GWh of electricity delivered by the offshore wind farm to the onshore national grid, in the baseline scenario (turbines with direct-drive transmission system). Abbreviations meaning is included in the footnote to Table 6.
Note that in the results of the CED the contribution of the mooring chains and the HV transformer are not included.
The boxes in the *legend* are used to highlight groups of components; from bottom to top:
wind turbine structure, floating system, power transmission.

(10 %), *abiotic depletion of elements (18 %) and of fossil fuels* (8 %) and *ozone layer depletion* (12 %). The rotor is the most impacting component only in *water scarcity* category, to which it represents 10 % of the total impacts. To *acidification* and *eutrophication,* the most relevant component is the nacelle, accounting for 10 % and 18 %. respectively.

The power cables are a significant element to all the impact categories; notably, to *acidification* (17 %) and *eutrophication* (14 %) they represent the third most contributing element. Among the different types of cables, the HVDC submarine cable (500 kV) is the one with the largest environmental burdens to all the considered impact categories. The reason for the high impacts can be reasonably attributed to the required length of cable and the higher specific weight, due to the different layers required to prevent water ingress and withstand possible damages. In more detail, the supply chain of copper is the main hotspot to all the impact categories. However, the resulting impacts are certainly influenced by the assumptions made to compile their inventory. Also, the relevance of the offshore transformer modules is not identified as hotspot to any impact category; nevertheless, its assessment has been limited by the simplification of their structure and due to the employment of the available EPD for the transformer.

4.2. *Payback indexes*

Considering that wind power, like other renewable energies, is fundamental to achieve the decarbonisation of the electricity sector and to fight climate change, a special attention is given to the potential impacts on global warming: the potential emissions of greenhouse gases amount to 31.3 t CO_{2eq}/GWh and, under the assumptions made, the CPBT would be about 2 years with respect to a 30-year wind plant's lifetime. On the other hand, the EPBT is found to be slightly over 3 years: the majority of the studies found in the literature for bottom-fixed offshore solutions show EPBTs below one year (Siemens-Gamesa, n.d.; Siemens AG, n.d.), while in case of floating installations (Garcia-Teruel et al., 2022; Raadal et al., 2014; Weinzettel et al., 2009) the results range between 0.4 and 4.3 years, depending on the floater design: this results confirm that floating deployments cause higher energy requirements (e.g. steel production is highly energy-intensive).

4.3. *Sensitivity analyses*

It is assumed that variations in the results of the sensitivity analyses are considered significant when they are ±10 %. When testing the different end-of-life assumptions, i.e. comparing the current disposal scenario of glass fibre reinforced plastic with the future possible recycling, the observed variations in the results, referred to the functional unit, are lower than ±1 % for all the impact categories. This is due to the limited relevance of the EoL stage to the overall impacts; although, the results of the end-of-life stage of the turbine, assessed separately, show an improvement (i.e. impacts reduction) between −14 % (*abiotic depletion of fossil fuels)* and − 52 % (*global warming*).

The sensitivity analysis on the transmission systems does not result in a clear preference between the two alternatives: the geared system shows impacts reduction in 5 out of 8 impact categories, but significantly only for *eutrophication* (−15 %) and *abiotic depletion of elements* (−13 %). On the contrary, for the rest of the impact categories the geared system is almost equivalent to the direct-drive one.

4.4. Comparison with the literature and benchmarking

Fig. 4 represents the comparison made between 1 GWh (FU) either produced by the modelled floating offshore wind farm, considered its whole life cycle based on the LCA results, or taken from the Italian national grid. The impacts of 1 GWh taken from the Italian grid, assuming the ecoinvent dataset "Electricity, medium voltage {IT}| market for | Cut-off, U" and calculated with the International EPD ® System (2021) method.

The electricity generated by the offshore wind farm has a significantly better environmental performance in all the assessed impact categories (between −83 % for *eutrophication* and −95 % for *ozone layer depletion*), except for the *abiotic depletion of elements,* where the modelled offshore wind farm provides an environmental burden almost twofold (+95 %) the impact of the electricity mix.

Also, it is useful to compare the results of the present study with those available in the LCA literature. As a general remark, from the literature review emerges that there are some particularly significant assumptions, which influence profoundly the estimated environmental performance of wind power systems: foremost the capacity factor and the lifetime of wind turbines. Moreover, the choice to model the electricity transmission system and other modelling assumptions i.e. functional unit, system boundaries and end-of-life scenarios and modelling approach, can lead to different conclusions. Since different life cycle impact assessment (LCIA) methods have been employed across the selected LCAs studies on wind power (as reported in Table 7), the comparison with other results will be focussed on global warming (GW). The resulting GW impacts, harmonised with respect to capacity factor and lifetime, as presented in Section 3.1.6, are reported in Table 7, together with the characteristic features of the studies selected for comparison purposes.

It can be observed that the two available studies assuming a semi-submersible floating system (Garcia-Teruel et al., 2022; Raadal et al., 2014) show harmonised results similar to the case study. On the contrary, bottom-fixed turbines display, in general, lower global warming impacts. Once again, it is found that offshore plants show overall higher impacts than onshore ones and that, in a life cycle perspective, floating systems seem to be more impacting than bottom-fixed structures. These results can be attributed mainly to larger requirements of high-impact materials and to more complex infrastructure. However, the higher environmental burdens of a floating wind farm can be compensated if sites with good wind conditions are selected for the installation. Since the impacts of the functional unit are inversely proportional the amount of electricity produced but the energy production is not directly related to any burden (Weinzettel et al., 2009), having higher capacity factors (or extended lifetime) reduces the FU impacts. Floating foundations make accessible locations further from shore or with greater water depth, that were unsuitable for bottom-fixed turbines. Moreover, the capacity factor offshore is generally higher than onshore (the global weighted-average in 2020 was 40 % and 36 %, respectively) (IRENA, 2020) and is expected to improve further and surpass 50 % (Garcia-Teruel et al., 2022).

Nevertheless, the estimated GHG emission intensity (31 gCO_{2eq}/kWh) is comparable with the range indicated in the literature for wind power, as well as competitive with other low emission electricity generation technologies, such as nuclear and photovoltaic (Edenhofer et al., 2011; IPCC, 2014; Turconi et al., 2013). As expected, the GHG intensity of wind power is very small in relation to the emission factors from fossil electricity generation technologies, which are determined principally by direct emissions that renewable energies do not present.

5. Conclusions and recommendations

The present work and the selection of the case study are highly motivated by the growing interest in renewable energy coming from wind and especially on the deployment of floating offshore wind farms. A key point is that there is currently a knowledge gap in LCA studies focussing on offshore wind that represents the current market trends i.e. turbines with rated power much >5 MW and floating conceptual designs. Moreover, this study attempts to be more comprehensive in terms of assessed environmental burdens, by focussing not only on GHG emissions and cumulative energy demand (Raadal et al., 2014; Siemens-Gamesa, n.d.; Siemens AG, n.d.), but on a wider set of impact categories as provided by the EPD method.

One major conclusion is that in almost all the impact categories, the

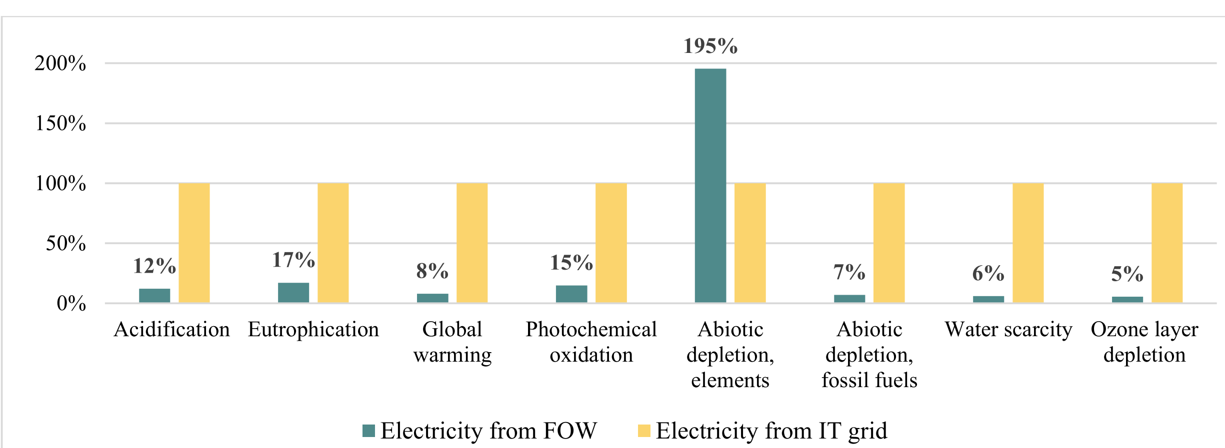

Fig. 4. Percentage relative comparison on potential environmental impacts, assessed with International EPD ® System (2021) method, for the provision of 1 GWh of electricity either by the modelled floating offshore wind (FOW) farm or taken from the Italian national grid (with 2018 electricity mix). The impacts of 1 GWh taken from the IT grid are reported as equal to 100 % in order to ease the comparison.

Table 7
Main characteristics and global warming (GW) impact, both estimated and harmonised, of case studies from LCA literature about offshore wind turbines or plants.

Power rating (MW)	Offshore foundation design	CF (%)	LT (year)	EPBT (year)	GW impact (gCO_{2eq}/kWh)	Harmonised GW impact (gCO_{2eq}/kWh)	LCIA method	Ref.
4	Bottom-fixed	52 % [a]	20	0.88	10	10	EPD	Siemens, n.d.
4	Bottom-fixed, G	59 %	20	0.9	10.9	12	Recipe	Bonou et al., 2016
5	Bottom-fixed	46 %	20	1.6	18.9	17	Only GWP	Raadal et al., 2014
6	Bottom-fixed, DD	59 %	20	0.8	7.8	9	Recipe	Bonou et al., 2016
6	Bottom-fixed	50 % [a]	25	0.79	7	11	EPD	Siemens, n.d.
8	Bottom-fixed	61 % [a]	25	0.62	6	9	EPD	Siemens-Gamesa, n. d.
5	Sway (Tension Leg Spar)	53 %	20	0.43	11.5	12	CML 2 baseline 2000 V2.03	Weinzettel et al., 2009
5	Sway (Tension Leg Spar)	46 %	20	1.8	20.9	19	Only GWP	Raadal et al., 2014
5	TLB (Tension Leg Barge)	46 %	20	1.6	18	16		
5	TLP (Tension Leg Platform)	46 %	20	1.7	19.2	17		
5	Spar buoy	46 %	20	2.2	25.3	23		
5	Semi-submersible platform	46 %	20	2.7	31.4	28		
6	Spar buoy	50 %	25	3.3–4.3	39.3	48	ReCiPe Midpoint (H) 2016,	Garcia-Teruel et al., 2022
9.5	Semi-submersible platform	40 %	25	2.8–3.7	33.9	33		
15	Semi-submersible platform	34.4 %	30	3	31		EPD (version 2018)	This study

CF = capacity factor; LT = lifetime; EPBT = Energy Payback Time; GW = Global Warming; G = geared, DD = direct drive.
[a] The CP has been estimated based on the reported "Estimated energy production" of the plant during its lifetime.

highest contributions to the overall impacts are given by the supply of the floating system. i.e. the semi-submersible platform and the mooring chains, or by the wind turbine's supply. Among the materials needed for both, steel is the most impacting. However, each floater design requires different amounts of steel and other raw materials e.g. for the ballast, which would result in diverse environmental burdens; therefore, it would be beneficial to choose floating solutions that allow to limit the overall weight, for instance the tension-leg-platform shows a lower structural mass (Rhodri and Marc, 2015). In addition to the efforts on limiting steel requirements and their related environmental burdens, e. g. increasing recycled steel content, further research should be focussed on other aspect of the significance of this material: the potential improvement of steel industry should be investigated, as well as the representativeness of the ecoinvent dataset of steel production[2] should be verified.

Comparing the results of the modelled wind farm with the electricity currently taken from the Italian national grid, it is evident that wind energy has a significantly better environmental performance in all the assessed impact categories except the *abiotic depletion of elements*; once again, it is highlighted that the material requirements are the main hotspot of the floating wind farm's life cycle.

Having estimated the carbon and energy payback time of the modelled wind plant, equal to about 2 and 3 years, respectively, in view of an expected 30-year lifetime, it can be concluded that the development of big offshore wind farms is convenient from the environmental point of view, although there are additional materials and infrastructure requirements which are responsible for the life cycle impacts. Nevertheless, the development of floating offshore technologies unlocks the possibility to exploit better wind resources, thus increasing the energy production and reducing the demand for land-based installations.

A point still open is the end-of-life stage, which is fundamental to include in the analysis according to a LCA perspective. In fact, the related scenarios are strongly influenced by technological and temporal uncertainties and modelling choices, e.g. EPD approach or avoided burden method, that can lead to profoundly different results. The selected EPD approach, on one hand, simplifies the modelling, but on the other hand it does not give insights on the possible impacts and benefits of the recycling phase.

As a conclusion, despite the number of approximations and conservative assumptions, floating offshore wind power, represented by the modelled case study, can be considered a promising technology and has been found to be already competitive with other electricity generation technologies. However, in general terms, it is important to note that the results of the present work are affected by several limitations since the lack of primary data had to be handled. In fact, since the LCA was carried out only based on the preliminary documentation submitted for the EIA scoping phase, the data employed for the study are mainly secondary and tertiary data, which stem from literature and databases. Also, with the aim of including all the life cycle stages from cradle to grave, it has been necessary to make several assumptions not completely supported by the case study documentation: assembly and installation as well as operation and maintenance phase have been included on the basis of simplified assumptions and therefore only a first rough assessment of their impacts is provided. To further improve the analysis, it would be necessary to model these lifecycle stages in greater detail, also considering site specific aspects. Moreover, the choice to rely on the EPD results of mooring chains and HV transformer constrained the selection of the impact assessment method; however, this has allowed to include these elements with a greater level of detail, compared to the database options or the estimations limited to material requirements.

Future research should address the uncertainty rooted to the data: repeating the analysis relying on the executive project, and therefore on a more detailed modelling, would help to get more accurate results.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[2] Full name of employed dataset "Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, U".

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.05.006.

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