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Parametric life cycle assessment of carbon footprint of electricity generation from floating offshore wind farms

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ABSTRACT

Floating offshore wind is a major opportunity for Italy to meet its 2030 renewable energy targets, as the country's deep-sea waters limit the adoption of bottom-fixed solutions. To assess how the technology can contribute to the decarbonisation of the electricity system, it is essential to evaluate its impact in terms of greenhouse gases (GHGs) emissions intensity. Whilst there are numerous studies in the literature that focus on the impact of specific plants, the present study seeks to analyse the influence that different design and site parameters can have on the final footprint. The analysis builds the Life Cycle Inventories of the main processes involved in the construction, use and disposal phases of a semi-submersible floating wind farm and develops a Life Cycle Assessment model using the CVXlab open-source Python package. Results indicate that the GHG footprint of the kWh delivered is primarily influenced by the capacity factor, the capacity of the turbine and the end-of-life treatment of the floating platform. In particular, when the platform is not recycled, other parameters also appear to become relevant, such as the material of the floating platform and the country of origin of steel.

1. Introduction

Following the adoption of the Paris Agreement in 2015, the European Union has implemented a series of programmes and legislative packages aimed at reducing greenhouse gas (GHG) emissions and accelerating the transition towards a decarbonised energy system. Among the most recent initiatives, the Fit for 55 package raised the target for renewable energy consumption from 32 % [1] to 42.5 % [2] by 2030. This ambition was further reinforced in 2022 with the adoption of the REPowerEU plan, which promoted the acceleration of authorisation procedures for renewable energy installations [3]. Offshore wind is among the most promising renewable energy technologies in this landscape, with a global installed capacity of 63 GW at the end of 2022 [4]. Half of this capacity was installed in Europe, home to the two leading global manufacturers of offshore wind turbines, Siemens Gamesa and MHI Vestas, which together accounted for 81 % of the offshore wind market between 1995 and 2018 [5].

The potential of offshore wind can be further expanded through floating technology, which enables access to wind resources at greater water depths where fixed-bottom foundations are not technically or economically viable. Although floating wind remains less mature than fixed-bottom technology, it is gaining significant traction in the energy sector owing to its estimated global potential of over 13 TW in deep waters [4]. Since the installation of the first floating wind project in Norway in 2009, Europe has established itself as the leading region in this field, with installed floating wind capacity expected to grow from 200 MW in 2022 to 18 GW by 2035 [4]. Within this context, Italy stands out as one of the countries most actively pursuing floating wind development: owing to its predominantly deep coastal waters, fixed-bottom technology is largely unsuitable, whereas Italy's technical potential for floating wind is estimated at 207.3 GW, making it the third largest prospective market for this technology [4]. This trend is reflected in the significant surge in grid connection requests recorded in recent years. At the end of 2022, the Italian transmission system operator had received requests for 103.7 GW of offshore wind projects, far exceeding the national target of 8.5 GW of wind capacity by 2030 [6]. Specifically, 80 % of these requests relate to projects located in sites with waters deeper than 100 m [6].

Nevertheless, this rapid expansion, largely driven by strong policy incentives and high expected revenues for operators, raises concerns regarding the costs borne by the public, as ancillary and system costs are ultimately reflected in electricity bills. Beyond the impressive growth prospects, it is therefore important to carefully assess the carbon footprint of floating wind projects, so as to ensure that the environmental

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benefits of deployment justify the associated economic effort. While the literature contains a growing number of LCA case studies for specific floating wind projects, analyses systematically examining how design and geographical parameters influence the life-cycle GHG emissions of the technology remain scarce. The present study aims to address this gap with the following contributions: (a) the development of a bottom-up Life Cycle Assessment (LCA) model to estimate the greenhouse gas emissions associated with the construction, operation, and decommissioning of a floating wind farm located in Italy, and (b) a systematic parametric analysis of 192 plant configurations to identify which design and geographical parameters most significantly influence the GHG footprint of the delivered electricity, providing insights to inform the plant design process.

The following sections are organised as follows: Section 2 presents a literature review of existing LCA studies on wind energy technologies, Section 3 details the methodology employed and follows two conventional steps of LCA analyses (i.e. goal and scope definition, life cycle inventory), Section 4 presents and discusses the results of the analysis, and Section 5 draws concluding remarks.

2. Literature review

The environmental impact of wind power plants has been extensively investigated in the literature, as documented in reviews by Dolan et al. [7] and, more recently, Das et al. [8], which examined the LCA publications on wind energy published before 2012 and between 2017 and 2023, respectively. From these analyses, onshore wind technology emerges as the most frequently studied configuration, reflecting its dominant share of global installed capacity (93 % of the total in 2023 [9]). As stated by Dolan et al. [7], the environmental impact of wind technology is strongly dependent on the capacity factor, which is intrinsically linked to both the geographical location and the rated capacity of the turbine. Offshore configurations benefit from higher wind speeds, enabling them to achieve a comparable life-cycle impact per kWh to that of onshore installations, despite the greater technical complexity associated with offshore installation. In their study, Raadal et al. [10] estimated a carbon intensity of 18.9 gCO_{2eq}/kWh for an offshore wind farm employing a tension-leg platform, while Bonou et al. [11] assessed two offshore turbine configurations (a direct-drive and a geared nacelle), estimating footprints of 7.8 and 10.9 gCO_{2eq}/kWh, respectively. These studies concern turbines of relatively modest rated capacity, but the average power rating of offshore wind installations has been increasing steadily and is expected to rise further with the broader deployment of floating offshore wind technology. In 2024, the mean capacity of offshore plants connected to the grid reached 10.1 MW, while the capacity of ordered plants stood at 14.8 MW [12], a substantial increase compared to the 5.5 MW recorded just six years earlier [5]. This trend is reflected in more recent LCA studies, which increasingly focus on higher-capacity turbines. Brussa et al. [13] conducted a cradle-to-grave LCA of a floating offshore wind farm located in Italy and equipped with 14.7 MW turbines, reporting a carbon intensity of 31 gCO_{2eq}/kWh. Guo et al. [14] assessed the life cycle carbon emissions of a 15 MW semi-submersible floating offshore wind system under realistic coastal conditions in China, estimating a carbon intensity in the range of 18.63–29.01 gCO_{2eq}/kWh. For fixed-bottom configurations, Smith et al. [15] assessed a 15 MW monopile-supported turbine off the coast of New Jersey, reporting a carbon intensity 13 gCO_{2eq}/kWh.

The publications cited above are predominantly case-specific LCAs, as is characteristic of the broader wind energy literature. A distinct but complementary strand of research seeks to investigate how specific design or site parameters influence the overall environmental impact of a wind farm. Kouloumpis et al. [16] developed a parametric model enabling the estimation of the environmental impact of an offshore wind project from user-defined input data, including turbine model, distance from shore, and number of turbines. Tsai et al. [17] examined the influence of distance from shore and geographical location on the environmental performance of an offshore wind farm, whose type (i.e. floating/fixed) and foundations may vary depending on the location. The present study aims to contribute to this line of research by developing an LCA exercise capable of assessing how the life-cycle greenhouse gas emissions of a floating wind farm located in Italy vary as function of a set of carefully selected design and geographical parameters.

3. Methods

The environmental impact of floating offshore wind projects has been assessed by means of Life Cycle Assessment (LCA) [18], which supports the identification of opportunities to enhance the environmental performances of products, thereby providing decision-makers at all levels with valuable insights [19]. An LCA study comprises four distinct phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation [19]. The following paragraphs will first describe the model and the parameters under investigation, and will then present each of the LCA phases, with the interpretation addressed in greater detail in Section 4.

3.1. Model

The model employed in the analysis is constructed bottom-up, developed expressly for this study using the CVXlab open-source Python-based package [20], and is structured according to the typical matrices of the Supply and Use Table framework [21]:

- *Use coefficients matrix* **u**, representing the consumption of commodities by industrial activities
- *Make coefficients matrix* **d**, indicating how industrial activities supply the various commodities
- *Environmental transactions coefficients matrix* **r**, encompassing the greenhouse gas emissions (CO_2, CH_4, N_2O) associated with each industrial activity
- *Final demand matrix* **Y**, representing the demand for commodities required during the construction, use and disposal phases of the floating offshore wind farm.

These matrices, summarised in Fig. 1, are populated with the data collected for the analysis, the details of which are provided in Section 3.3.2. To calculate the indicator of interest for the present study, i.e. the GHG footprint of the kWh produced by the wind farm, the following equations are introduced into the model:

$$\mathbf{r_e} = \widehat{\mathbf{r}}\mathbf{d}(\mathbf{I} - \mathbf{ud})^{-1} \tag{1}$$

$$\mathbf{R_e} = \mathbf{r_e}\mathbf{Y} \tag{2}$$

where Eq. (1) calculates the GHG footprint of each commodity included in the analysis and Eq. (2) computes the total footprint embedded in the final demand. The resulting value of $\mathbf{R_e}$ is subsequently divided by the total electrical energy generated over the operational lifetime of the wind farm to yield the GHG footprint per unit of electricity delivered (gCO_{2eq}/kWh). Further details on the model development and on the equations utilised are provided in the Supplementary material.

3.2. Analysed configurations

The floating offshore wind farm can take on different configurations depending on the selected design and site parameters. The parameters analysed are described below.

Turbine capacity

Over the past decade, turbine size has grown considerably in terms of tip height and swept area, resulting in a steady increase in rated power output [5]. This trend is expected to continue in the coming years [12],

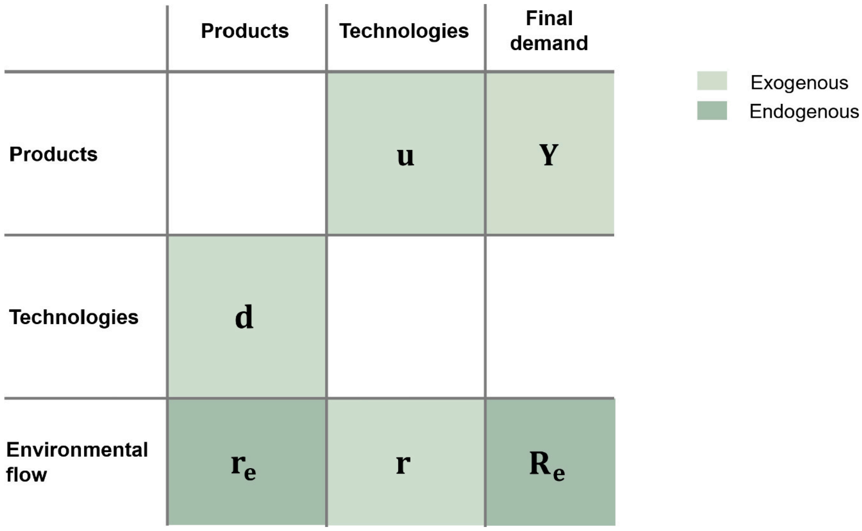

Fig. 1. Simplified representation of the Supply and Use Table (SUT) used in the model.

making turbine capacity a particularly relevant parameter for analysis. The present study considers two rated capacities (15 MW and 22 MW) corresponding to the reference floating wind turbines developed by the National Renewable Energy Laboratory (NREL) [22] and the Technical University of Denmark (DTU) [23], respectively. Both turbines, used as the basis for constructing the Life Cycle Inventory (LCI), employ a semi-submersible technology, one of the most mature floating foundation types currently available [4]. Accordingly, the analysis is restricted to the semi-submersible configuration, and the influence of foundation type on the environmental impact of the wind farm is not investigated. Once the turbine capacity is defined, the number of turbines depends on the site where the wind farm is to be installed. In this analysis, the total installed power is held constant while the number of turbines is varied. Given that the total power governs the sizing of other plant components (e.g., cables, transformers), this approach enables to evaluate whether, for the same installed capacity, deploying fewer turbines of higher rated power yields economies of scale that reduce the GHG footprint of the delivered electricity. Specifically, 66 turbines of 15 MW and 45 turbines of 22 MW are considered, both yielding a total installed capacity of 990 MW.

Floating platform material

Semi-submersible foundations are typically composed of steel. However, there is a growing interest towards the utilisation of concrete, owing to its potential to reduce fabrication costs [4]. Both materials are therefore considered in this analysis.

Mooring chains

A mooring system comprising mooring lines and anchors is required to ensure the positional stability of the floating turbine. Mooring lines have traditionally employed steel chains, but synthetic rope fibres have gained considerable traction in the floating wind industry in recent years, owing to their corrosion resistance, high fatigue load capacity, and low failure rates [4]. Synthetic ropes are used in buoyant semi-taut configurations, which adopt a combination of chain at the top and bottom with a rope mid-section on each line [24]. To investigate whether the choice of mooring line material influences the environmental impact of the wind farm, two alternatives are considered: steel mooring chains and steel-polyester hybrid mooring chains. Drag anchors, the most common design for securing floating foundations to the seabed [4], are assumed in both cases.

Cables

Cables convey the electricity generated by the wind farm to the onshore connection point and, ultimately, to the national grid. Three cables sections are distinguished within the system boundaries shown in Fig. 1: (a) inter-array cables, (b) offshore export cables, and (c) onshore export cables. Inter-array cables transfer the electricity generated by each turbine to an offshore substation, which comprises a transformer, auxiliary systems, a housing structure to hold the components, and a fixed foundation [4]. Their length depends on the number and layout of turbines in the wind farm, and they are typically rated at 66 kV [24]. Offshore export cables are laid on the seabed and connect the offshore substation to the onshore substation, located on land. These are normally high-voltage alternate current (HVAC) cables, though high-voltage direct current (HVDC) solutions, which reduce transmission losses, are increasingly adopted for distances exceeding 80 km from shore [4]. HVAC cables rated at 275 kV [24] are assumed for this analysis, since water depths suitable for floating wind in Italy are reached within 80 km from the coast [25]. Finally, onshore export cables connect the onshore substation to the national grid and are rated at 380 kV, consistent with the voltage levels used in most extra-high-voltage lines in Italy [26]. These cables may be installed as underground or overhead lines. Whilst overhead configurations are generally preferable in terms of cost and ease of installation, underground cables may be the only viable option in certain contexts, such as densely urbanised areas [27]. Both configurations are therefore analysed to determine whether the choice of onshore cable type influences the environmental impact of the wind farm.

Capacity factor

The capacity factor of a wind farm is strictly dependent on the wind speed at its geographical location. As this analysis is not site-specific, three representative capacity factor values are considered: 15 %, 30 %, and 45 %, corresponding to the minimum, average, and maximum values observed at offshore sites in Italy [28].

End-of-life scenario for the floating platform

As floating offshore wind technology has only recently reached commercial maturity, experience with decommissioning remains limited. The prevailing trend points towards the recycling of major components, including the tower, cables, and nacelle [24]. The floating platform itself can be recycled or, as is already the case in the oil and gas industry, it can be sunk to create artificial reefs on the seabed [29]. In this study both options (recycling or sinking) are analysed for the floating platform.

Steel origin

Steel is a fundamental material in wind turbines and associated components, including platforms and cables. Although Italy is the second largest steel producer in Europe [30], approximately 90 % of its domestic steel output is derived from scrap [30] and may not meet the stringent material requirements of offshore applications, particularly for floating platform fabrication. In 2023, Acciaierie d'Italia, Italy's largest steelmaker, announced its participation in a project aimed at developing floating wind farms in the country [31], with the stated intention of supplying primary steel, i.e. produced from iron ore, for floating platforms fabrication. However, in light of the present struggles encountered by the company [32], its capacity to supply the floating offshore wind industry in the near term remains uncertain. This analysis therefore explores two options: steel produced domestically in Italy and steel imported from China. Whilst China is not Italy's primary steel import partner [33], it is the country from which Italy imports the most carbon-intensive steel. Comparing these two options thus provides an indication of the potential environmental benefit should Acciaierie d'Italia fulfil its stated ambition to supply steel to the domestic floating wind sector.

Table 1 provides a summary of all the parameters that can vary in the wind farm under analysis, yielding a total of 192 distinct configurations analysed.

3.3. LCA phases

3.3.1. Goal and scope definition

The purpose of this study is to assess the environmental impact associated with the life cycle of a floating offshore wind farm, the configuration of which varies according to a specific combination of design and geographical parameters. Whilst the environmental impact of a system can be evaluated across a broad range of impact categories, the present study focuses exclusively on climate change, quantified through the Global Warming Potential (GWP) indicator. GWP is calculated by appropriately weighting the emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The functional unit (FU) selected is the delivery of 1 kWh of electricity generated by the floating offshore wind farm to the onshore high-voltage national grid. The assessment encompasses all life cycle phases (i.e. construction, use and disposal) of a wind farm assumed to be located in Italy.

3.3.2. Life cycle inventory

Prior to data collection, the definition of system boundaries is essential for delimiting the components included in the analysis Fig. 2 provides a schematic representation of those boundaries, which include:

- Wind turbines
- Inter-array cables (66 kV)
- One offshore substation, equipped with two 66/275 kV transformers
- Submarine export cables (275 kV)
- One onshore substation, equipped with one 275/380 kV transformer
- Land cables (380 kV).

Within the defined system boundaries, primary and secondary data are collected from scientific and grey literature for the construction, use and disposal phases of the wind farm. Detailed inventory used for the analysis is available in the Supplementary material.

Construction phase. The construction phase of the wind farm encompasses the provision of all components delineated within the system boundaries shown in Fig. 2, the fuel consumed during the turbine assembly at port, and the marine transport services required for the offshore positioning of the turbines and associated components. Table 2 summarises the material and energy inputs for the construction phase for one selected configuration.

Marine transport services account for the vessels used for towing the assembled turbines from the construction port to the offshore site [24], as well as for the positioning of the offshore transformer fixed substation, mooring chains, and offshore cables. As no specific site is considered, an average distance from the coast of 30 km is adopted as a proxy, consistent with the average distance at which water depth conditions in Italy become suitable for floating turbine installation [25].

Concerning the offshore transformer fixed substation, a "jacket" configuration is considered. A single substation equipped with two 275/380 kV transformers and connected to the shore by four offshore export cables is considered. Export cables are dimensioned on the basis of the electrical current produced by the plant. The cross-section of offshore inter-array cables varies according to the circulating current, which increases as each cable connects a greater number of turbines. Three cross-section sizes (small, medium, large) are therefore considered. For both export and inter-array cables, a submarine XLPE three-core configuration with copper conductor is assumed, rated at 100–300 kV and 10–90 kV, respectively [34].

Unlike the offshore substation, the onshore infrastructure is excluded from the analysis; only the onshore transformer is considered, sized according to the total apparent power of the wind farm. The onshore cables departing from this substation may be either overhead or underground. In both cases, an initial section comprising four underground cables over an average distance of 40 km is assumed. Beyond this initial section, the cables connect to either two underground cables or nine overhead cables. The length of this second section is assumed to be 80 km, which is expected to be sufficient to reach an existing high-voltage grid connection point. Underground cables are modelled as CU/XLPE/LEAD/PE cables rated at 380 kV [35], while overhead lines are modelled as aluminium-conductor steel-reinforced cables [36].

Each product included in Table 2 is the output of upstream industrial activities, which in turn depend on further upstream processes. As the inventories were developed bottom-up, it was not always possible to determine the electricity consumption associated with the manufacturing of all products. The following approach was therefore adopted to estimate the total electricity consumption of the supply chain:

1. Estimation of electricity consumption for welding

A portion of the electricity consumption is plausibly associated with the welding process, assumed to be a Submerged Arc Welding (SAW) process, involved in the fabrication of the turbine tower and the steel floating platform. This consumption is estimated on the basis of the welding length of both components, as determined by their geometry. The tower is modelled as a cylinder composed of multiple welded cylindrical segments [37], while the platform geometry is taken from the NREL [22] and DTU [23] reference studies. The specific electricity consumption of the SAW process is derived from Ivanov et al. [38] and Singh [39].

2. Estimation of remaining electricity consumption

Considering the electricity consumption from welding and other energy inputs along the supply chain, the Energy Payback Time (EPBT) is calculated. For a floating offshore wind farm, the EPBT typically ranges between 1.6 and 2.7 years [10]. As the EPBT value obtained by considering welding electricity alone falls below this reference range, an additional energy consumption, assumed to be entirely electricity, is introduced to bring the EPBT value within the range reported in the literature. This is the value indicated as consumption of electricity by grid in Table 2.

Table 1
Parameters selected for the definition of wind farm configurations.

Capacity	Platform	Mooring chains	Land cables	Capacity factor	End-of-life of the platform	Steel origin
15 MW or 22 MW	Steel or Concrete	Steel or Mixed (steel-polyester)	Underground or Overhead	Low or Medium or High	Recycling or Sinking	Italy or China

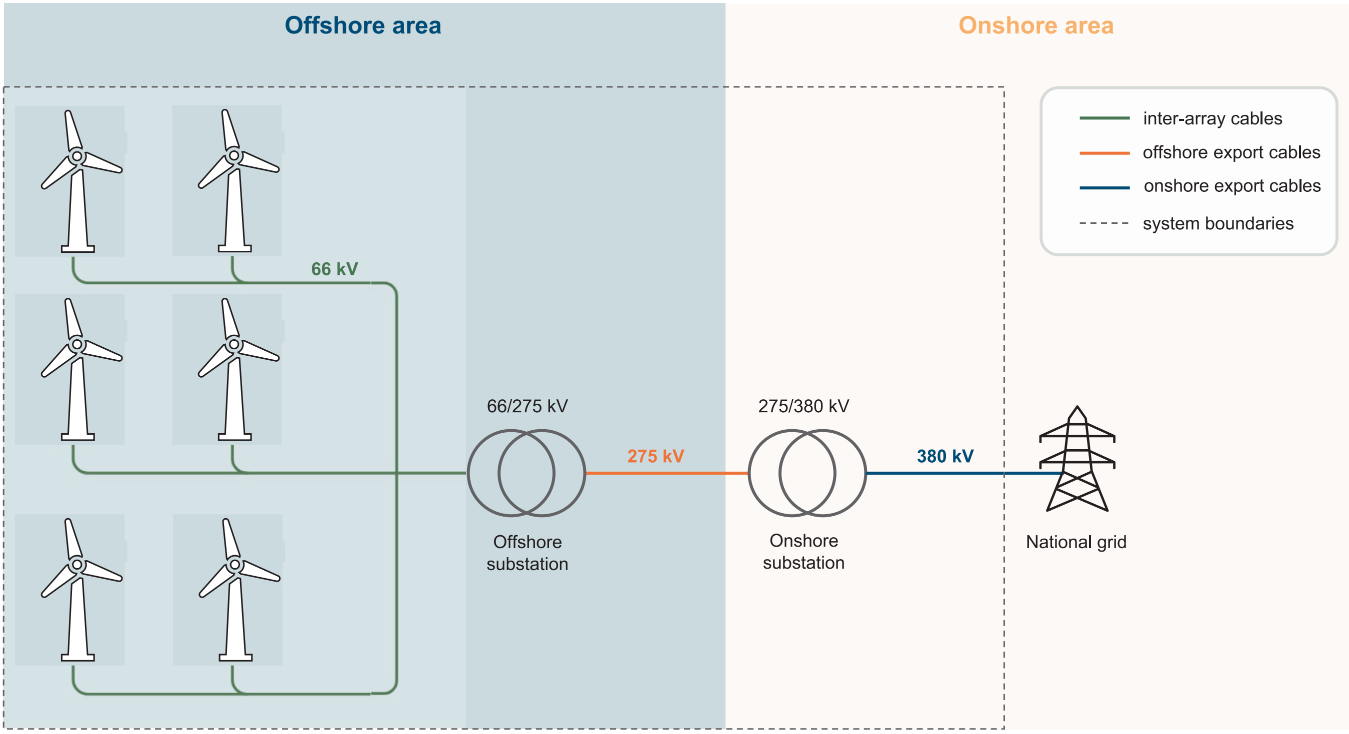

Fig. 2. Schematic representation of the wind farm with system boundaries.

Table 2
Products consumed during the construction phase of the 15 MW-wind farm with steel floating platform, steel mooring chains, and underground land cables (consumption of products during the construction phase is not influenced by the choice of the capacity factor, the end-of-life treatment, and the origin of steel).

Product name	Unit	Value
Floating turbine (15 MW)	unit	66
Marine transport service, ICEV, Marine gas oil	tkm	16′468′256
Offshore transformer fixed substation	unit	1
Offshore inter-array cables (66 kV, AC) | Small section	km	85
Offshore inter-array cables (66 kV, AC) | Medium section	km	40
Offshore inter-array cables (66 kV, AC) | Large section	km	55
Onshore transformer (275/380 kV)	MVA	1′042
Onshore cables (380 kV, AC) | Initial section	km	40
Onshore cables (380 kV, AC) | Underground lines	km	80
Electricity by grid	TWh	1.26

The electricity consumed is assumed to be supplied by the Italian grid generation mix of 2023 [40]. Natural gas required for gas-fired electricity generation is supplied according to the Italian mix of natural gas and liquefied natural gas imports and domestic production for 2022 [41–43]. Similarly, oil consumed by oil-fired power plants is supplied in accordance with the Italian mix of imports and domestic production for 2022 [44].

Use phase. During the operational phase, the wind farm is subject to preventive maintenance activities to ensure its continued operational integrity [24]. Accordingly, the use accounts for the consumption of marine transport services for the transfer of maintenance technicians from port to the wind farm site. Three annual and two biennial interventions are assumed, carried out by an average of ten operators per visit over the 30-year operational lifetime of the plant. The distance travelled by the vessels corresponds to the previously assumed offshore distance of 30 km, covered on both the outward and return journeys.

Disposal phase. At the end of its 30-year operational lifetime, the plant is expected to be fully decommissioned. The decommissioning phase encompasses the dismantling of the wind farm and the management of the resulting materials, which may undergo recycling, landfill disposal, or incineration. Table 3 summarises the inputs required by the disposal phase for one selected configuration.

The consumption of maritime transport services during decommissioning is assumed to be equivalent to that of the construction phase, while electricity consumption is assumed to correspond to that required for the welding process alone. Road transport services, necessary to convey dismantled materials to their respective end-of-life treatment facilities, are estimated assuming an average distance of 800 km.

Table 4 presents the allocation of recycling, landfill, and incineration for the various materials in the turbines and other components. The treatment of the end-of-life stage in LCA is not standardised and is highly dependent on the specific system under study. The present analysis adopts the so-called ‘avoided burden approach’, which incentivises end-of-life recycling [45], a practice that is becoming increasingly prevalent within the wind energy industry. Whilst Table 4 indicates that all steel and concrete in “Other components” are fully recycled, the end-of-life treatment of the floating platform is configuration-dependent. In configurations where the platform is recycled, both steel and concrete are fully recovered. Conversely, in configurations where the platform is sunk to form an artificial reef, neither the concrete nor the steel

Table 3
Products consumed during the disposal phase of the 15 MW-wind farm with steel floating platform, steel mooring chains, and underground land cables with recycling of the platform material.

Product name	Unit	Value
Electricity by grid	TWh	0.08
Marine transport service, ICEV, Marine gas oil	tkm	16′468′256
Road transport service – heavy, ICEV, Diesel oil	tkm	439′153′505
Incinerated waste	ton	95
Recycled concrete	ton	0
Recycled copper	ton	1′341
Recycled permanent magnet	ton	1′717
Recycled steel	ton	504′195

Table 4
End-of-life treatment of materials in turbines and other components (data for "Turbine" from [46]; data for "Other components" are based on assumptions).

	Turbine			Other components		
	Recycling	Landfill	Incineration	Recycling	Landfill	Incineration
Aluminium	92 %	8 %	–			
Concrete				100 %	–	–
Copper	92 %	8 %	–			
Magnet	100 %	–	–			
Polyester				100 %	–	–
Polymers	–	50 %	50 %			
Steel	92 %	8 %	–	100 %	–	–

incorporated within the floating platform undergoes recycling.

3.3.3. Life cycle impact assessment

The goal of the analysis is to quantify the greenhouse gas emissions embedded in the electricity produced by the wind farm. As such, climate change is the sole impact category considered in this study. The GHG emissions inventoried in the LCI are therefore weighted in terms of their Global Warming Potential (GWP) to obtain their impact intensity relative to carbon dioxide in units of grams of CO_2 equivalent. Specifically, the GWP over a 100-year time horizon is adopted [47].

3.4. Sensitivity analysis

Within the inventory, some data are either based on assumptions (e.g. distance from shore, onshore cable length) or selected from a wide range of plausible values (e.g. electricity consumption of the SAW process). Consequently, a sensitivity analysis is performed to assess the influence of these inputs on the final results. Three sensitivity scenarios are defined ('Maximum', 'Minimum' and 'Average') corresponding to the combinations of input values expected to yield the highest, lowest, and intermediate GHG footprint per kWh, respectively. This approach is preferred over more sophisticated methods, such as Monte Carlo simulation, as the probability distributions of the input data are unknown, precluding the assignment of meaningful probabilities to their potential values. Among the inputs examined, electricity consumption exhibits the widest range between the 'Minimum' and 'Maximum' scenarios and is identified as the most uncertain parameter. Further details on the inputs subjected to sensitivity analysis are provided in the Supplementary material.

4. Results

4.1. GHG footprint of floating offshore wind electricity

Under the medium capacity factor and 'Average' sensitivity scenario, the GHG footprint of the analysed configurations ranges from 6.0 to 25.1 gCO_{2eq}/kWh. These values are well below the carbon intensities of fossil-based technologies, including pulverised coal and natural gas, both in conventional configurations (1023 and 434 gCO_{2eq}/kWh, respectively) and in systems equipped with carbon capture and storage (369 and 128 gCO_{2eq}/kWh, respectively) [48]. The results also compare favourably with certain renewable technologies, falling below the footprint of polycrystalline silicon photovoltaics (36.7–37.2 gCO_{2eq}/kWh) [48]. On average, however, they exceed the carbon intensities of onshore wind (12.4 gCO_{2eq}/kWh), bottom-fixed offshore wind (14.2 gCO_{2eq}/kWh), and hydropower (10.7 gCO_{2eq}/kWh) [48].

Under the 'Minimum' sensitivity scenario, the results range from 4.5 to 23.9 gCO_{2eq}/kWh, whilst under the 'Maximum' sensitivity they range from 15.5 to 48.6 gCO_{2eq}/kWh. The highest values in both sensitivity scenarios and the lowest in the 'Maximum' scenario correspond to the same configurations as those identified at the boundaries of the 'Average' range.

4.2. Influence of selected parameters on the GHG footprint

Fig. 3 illustrates the results for all configurations analysed, with the aim of identifying the parameters that most significantly influence the GHG footprint of the delivered kWh.

The close resemblance between graphs (a) and (b) in Fig. 3 suggests that the choice of onshore cable type has no discernible influence on the climate impact of the electricity produced. In contrast, the capacity factor exerts a substantial influence on the results: configurations characterised by a low capacity factor (red) display a markedly higher footprint than those with a medium (blue) or high (green) capacity factor. This is expected, as a higher capacity factor enables the same plant to distribute its embodied emissions over a greater quantity of generated electricity. For equivalent installed power, it appears that large turbine capacity is associated with a higher total GHG footprint. Consequently, the 22 MW configurations do not yield a lower overall impact than the 15 MW ones despite deploying fewer turbines, owing primarily to the increased material requirements. The end-of-life management of the floating platform has a marked influence on the results: all configurations in which the platform is sunk (right-hand side of each subplot) exhibit a higher footprint than their recycling counterparts (left-hand side). This outcome is closely linked to the 'avoided burden approach' adopted to model end-of-life recycling: while recycling the material does incur carbon emissions associated with material collection and processing, it also generates carbon credits by displacing the production of virgin materials. Since the net impact of recycling configurations is lower than that of sinking configurations, the burden associated with recycling activities is more than offset by the credits generated.

The choice of platform material has a notable influence when the platform is sunk at the end of life: concrete platforms exhibit a lower carbon footprint than steel platforms. Sinking precludes the generation of credits from recycling, which are considerably more significant in the case of steel platforms, given that primary steel production carries a substantially higher environmental burden than concrete production. Similarly, the origin of steel influences results only in sinking configurations, where Chinese steel (filled symbols) penalises environmental performance relative to Italian steel (hatched symbols). In recycling configurations, the steel-producing country has no effect on the results, as the positive emissions from steel production during the construction phase are offset by the negative emissions from steel recycling in the disposal phase. By the same logic, the choice of mooring chain material influences results only in sinking configurations, where steel mooring chains exhibit a slightly higher impact than steel-polyester hybrid chains. This difference is particularly pronounced for 22 MW turbines, owing to the larger mooring diameters required and the consequent increase in material demand.

Overall, the parameters that most significantly influence the GHG footprint of the delivered electricity are the capacity factor, the end-of-life treatment of the floating platform, and the turbine capacity. In configurations where the platform is sunk, the platform material and the country of origin of steel also exert a considerable effect.

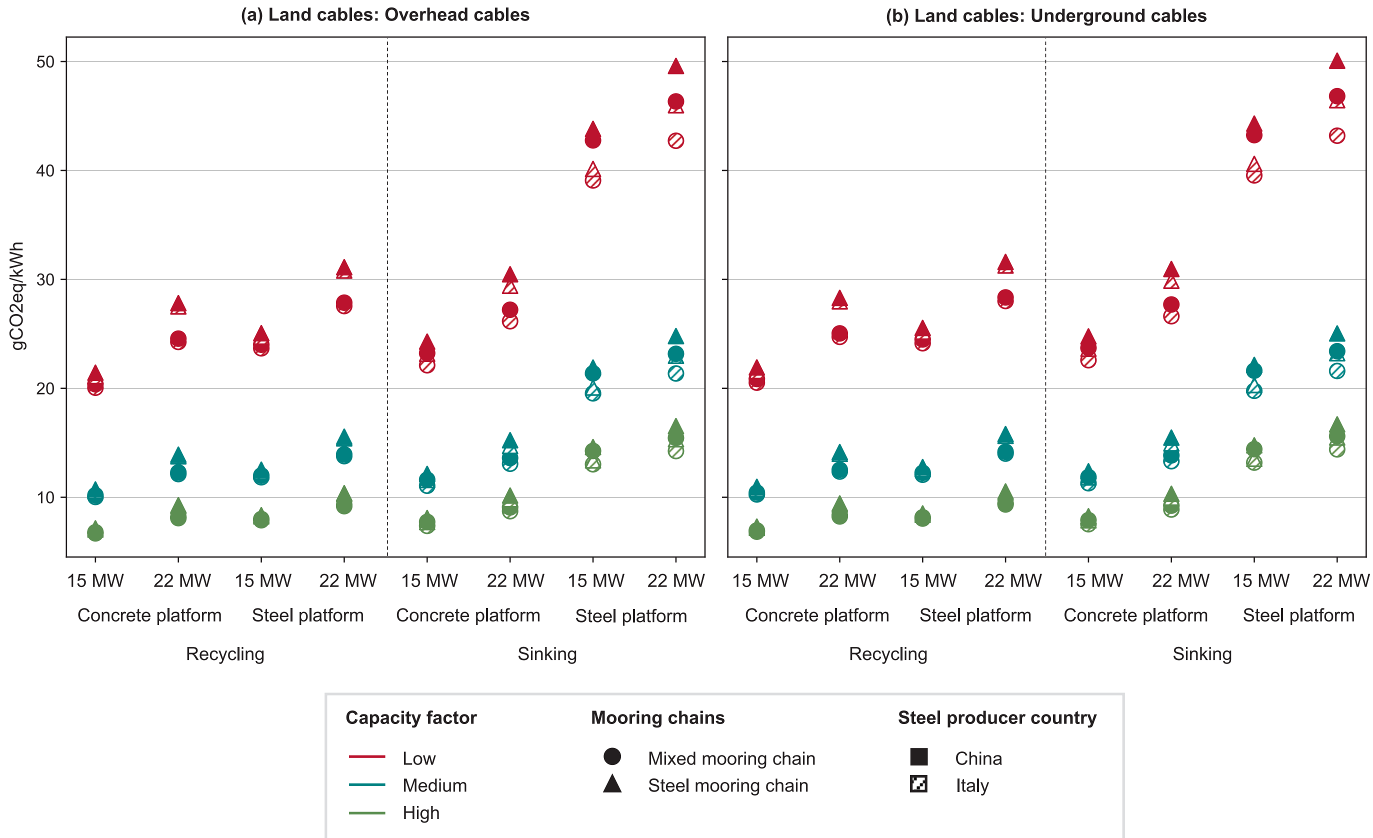

Fig. 3. GHG footprint of all configurations with (a) overhead and (b) underground land cables by end-of-life, platform material and turbine capacity. Colours indicate the capacity factor, while symbols specify the material of the mooring chains. Filled and hatched symbols refer to configurations with Chinese and Italian steel, respectively.

4.3. Contributions by phase and technology

The GHG footprint can be disaggregated by life cycle phase (construction, use, and disposal) or by technology to highlight their respective contributions to the overall result. Phase contributions are presented in Fig. 4, which shows results for configurations with hybrid mooring chains and underground cables, two parameters found to have a negligible influence on the final footprint. The capacity factor is fixed at its average value for ease of presentation, but the full results across all capacity factor values can be found in the Supplementary Material.

The use phase contributes negligibly to the overall footprint, as emissions during the operational stage of a renewable energy plant are

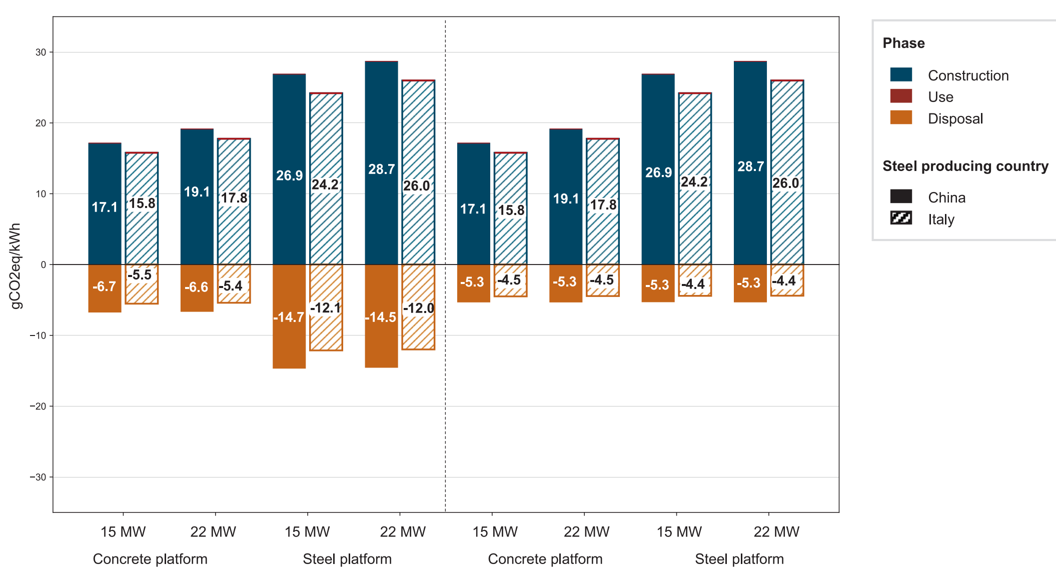

Fig. 4. GHG footprint of configurations (mixed mooring chains, underground cables, medium Cp) by *end-of-life*, *platform material* and *turbine capacity*, with contributions by phase. Filled and hatched bars refer to configurations with Chinese and Italian steel, respectively.

attributable solely to maintenance activities. Regarding the construction phase, steel platform configurations yield a higher carbon intensity than concrete ones. The difference is, however, less pronounced than a direct comparison of the carbon footprints of steel and concrete (2.5 and 0.1 tonCO_{2eq}/ton on average, respectively) might suggest, for two primary reasons: the considerably greater mass of concrete platforms relative to steel platforms, and the substantial steel content in the armour of concrete structures. Configurations using domestically produced steel exhibit a reduced construction phase contribution, primarily owing to lower steel transportation requirements. As expected, the choice of end-of-life treatment does not affect the construction phase contribution, since it pertains exclusively to the disposal phase. Consistent with the findings of Fig. 3, net emissions from the disposal phase are negative across all configurations, indicating that recycling credits outweigh the associated recycling burdens. Recycling configurations generate more credits than sinking configurations, and consequently their (negative) disposal phase contribution is greater, offsetting the construction phase impact more effectively and yielding a lower overall footprint.

Fig. 5 illustrates the contributions of upstream activities during the construction and disposal phases. The dominant contributors to the GHG footprint during construction are steel production, electricity generation and the manufacture of other materials (e.g. aluminium and copper).

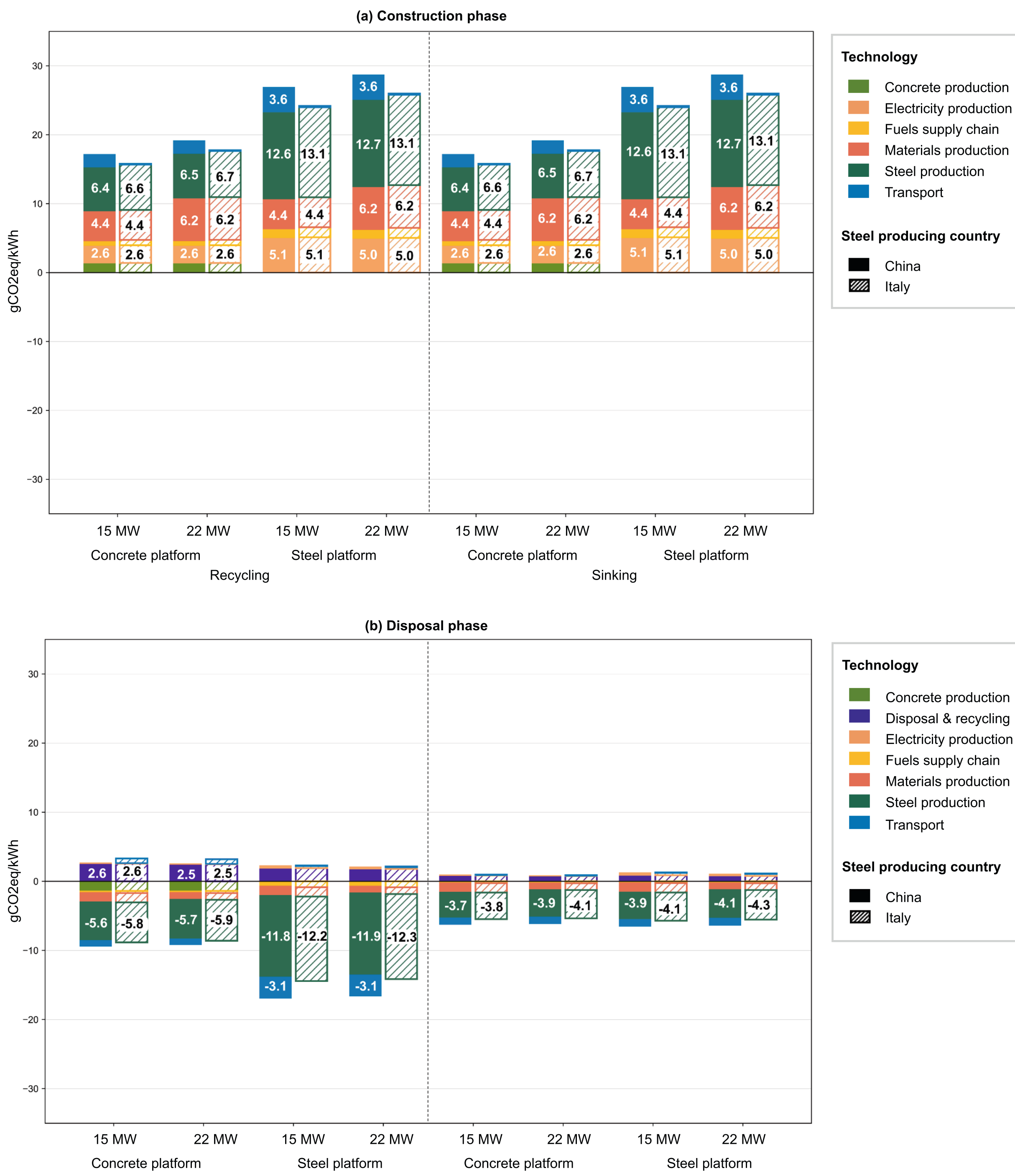

Fig. 5. GHG footprint of configurations (mixed mooring chains, underground cables, medium Cp) by *end-of-life*, *platform material* and *turbine capacity*, with contributions by technology, for the (a) construction and (b) disposal phases. Filled and hatched bars refer to configurations with Chinese and Italian steel, respectively.

Notably, steel production remains a significant contributor even in concrete platform configurations, owing to the steel reinforcement and the substantial overall mass of these platforms. The production of concrete alone, by contrast, exerts a negligible effect on the overall carbon footprint. In configurations where steel is imported from China, the transport contribution becomes significant, as it is attributable almost entirely to steel transportation. In contrast, the contribution from materials production is unaffected by the steel-producing country, as it relates to non-steel materials. The fuels supply chain (i.e. extraction and refining) exhibits a broadly comparable contribution across all configurations, while electricity production carries a greater impact in steel platform configurations due to the welding involved in platform fabrication. Finally, with regard to the disposal phase, the majority of credits (negative values) arise from the avoided production of primary steel and, in configurations with imported steel, from the avoided transportation of that steel.

5. Conclusions

In light of the growing interest among European countries, and Italy in particular, in floating offshore wind, a comprehensive assessment of its life-cycle greenhouse gas emissions is of considerable importance. While the literature contains numerous studies determining the carbon intensity of electricity produced by specific, well-defined wind projects, analyses examining the influence of design and geographical parameters on the environmental performance of the technology remain scarce. This aspect is however of relevance for floating wind, given the relative immaturity of the technology and the wide range of design options available.

The present study addresses this research gap by analysing 192 configurations, each defined by a specific combination of design parameters (turbine capacity, platform material, mooring chains material, and onshore cable type), geographical parameters (capacity factor), and other additional parameters (end-of-life treatment of the platform and country of origin of steel employed). The findings indicate that the capacity factor, the end-of-life treatment of the floating platform, and the turbine capacity are the parameters exerting the greatest influence on the GHG footprint of the kWh delivered by the floating wind farm. In configurations where the floating platform is sunk at the end of life, the platform material and the provenance of steel also become relevant. Specifically, the marked influence of the end-of-life treatment is directly attributable to the ‘avoided burden approach’ adopted to model recycling: configurations involving platform recycling consistently outperform those involving platform sinking. Furthermore, in sinking configurations, the absence of steel recycling credits renders steel platform configurations environmentally more burdensome than their concrete counterparts.

Nevertheless, even under the least favourable combination of parameters, the environmental impact of floating offshore wind remains substantially lower than that of any fossil fuel technology, confirming its value as a component of energy transition strategies. In comparison with onshore and bottom-fixed offshore wind, floating wind exhibits a higher carbon intensity, albeit to a relatively modest extent, indicating that the possibility of accessing sites with higher capacity factors can partially offset the additional emissions associated with the greater complexity of floating installations. In this regard, the results could be refined through a more detailed modelling the operational phase, particularly with respect to extraordinary maintenance interventions and the potential replacement of plant components, which may be necessary due to the challenging conditions in which the turbines operate.

Several directions for future work development can be identified. First, extending the analysis to platform types other than the semi-submersible configuration considered here would broaden the findings. Second, incorporating additional environmental impact categories beyond GWP, such as marine eutrophication, resource depletion, or land use, would provide a more comprehensive picture of the environmental implications of the design choices analysed. Finally, complementing the present environmental assessment with an economic analysis would offer a more complete evaluation of the trade-offs involved in the design and planning of floating wind installations.

CRediT authorship contribution statement

Debora Ghezzi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Matteo Vincenzo Rocco:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2026.105063.

Data availability

All data used in the study can be found in a Zenodo folder linked in the Supplementary Material file

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