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RESEARCH

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Scenario-based LCA for assessing the future environmental impacts of wind offshore energy: An exemplary analysis for a 9.5-MW wind turbine in Germany

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Abstract

Background Offshore wind energy (OWE) will play a significant role in achieving climate neutrality. For example, several scenarios for Germany (e.g., Kopernikus base, Kopernikus 1.5 degree, Prognos CN65, and CN60) depict substantial OWE annual installed capacity additions, especially after 2030. This tendency promotes OWE technology development as deployment expands, allowing manufacturers to gain expertise and optimize wind turbine construction. The global trend towards ever-larger components (e.g., hub height and rotor diameter) is critical to achieving higher-rated capacities. These aspects and others, such as wind quality, influence not only OWE annual electricity production but also its environmental performance. In addition, future supply chains might reduce their environmental impacts and enhance OWE climate change mitigation. In this paper, a prospective life cycle assessment (pLCA) is developed and applied exemplarily for a 9.5-MW offshore wind turbine (OWT) on the North Sea coast of Germany for the years 2030 and 2050. Considering that the current OWTs under construction in Europe have an average capacity of 10 MW, Germany plans to instal OWTs of 9.5-MW. This exemplary OWT describes the potential advances for offshore wind turbines in 2030 and 2050, considering component scale-up and learning effects. Yet, the methodology is adaptable to various installed capacities and regions. This approach allows us to analyse not only the potential future characteristics of wind turbines, but also future developments in OWE supply chains. Therefore, relevant parameters related to OWT construction and operation (e.g., rotor diameter, hub height, distance to the shore, lifetime, etc.) as well as prospective life cycle inventory data for background systems that reflect potential future developments in the broader economy are considered. In this way, scenarios (e.g., optimistic, moderate, and pessimistic) for OWE elucidate the expected environmental impacts, such as climate change, marine eutrophication, and abiotic depletion potential, in 2030 and 2050.

Results The findings describe the variability of the environmental impacts of a 9.5-MW offshore wind turbine representing the technologies expected to be available in Germany in 2030 and 2050 and show that climate change impacts could vary between 7 and 18 g CO_2-eq per kWh produced in 2030 and between 5 and 17 g CO_2-eq per kWh in 2050. However, marine eutrophication could experience a significant increase (100% increase), depending on the consideration of hydrogen as a fuel in the electricity mix, as demonstrated in the climate-neutral scenarios

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adopted for Germany. Overall, construction efficiency improvements in 2050 might reduce the required materials, leading to a 6% decrease in abiotic depletion potential compared to 2030 values.

Conclusions This paper highlights the need to consider temporal improvements in LCA studies, particularly when assessing the environmental impacts of offshore wind turbines. The complex nature and rapid growth of offshore wind technology require a comprehensive life cycle approach to deepen our understanding of its potential environmental impacts.

Keywords Prospective life cycle assessment, Offshore wind energy (OWE), Climate change, OWE future developments, Prospective life cycle inventories

Background

The offshore wind energy (OWE) global capacity could reach 560 GW in 2040, according to Li et al. [52]. China, the United Kingdom, and Germany lead OWE expansion, with each country aiming to increase its capacity from 25 GW, 13 GW, and 8 GW today to 66 GW, 50 GW, and 30 GW, respectively, by 2030 (see Fig. 1) [9, 11, 23, 42, 103]. For example, Germany committed to becoming climate neutral by the middle of the century to tackle anthropogenic climate change [72], and one of its strategies relies on renewables expansion, for instance OWE. These ambitious goals will require the installation of thousands of new offshore wind turbines (OWTs) over the next decade, which could entail significant technical diversity [7, 95]. Additionally, uncertainty could arise from different approaches to achieving government targets. For instance, German scenarios foresee different pathways for OWE deployment and suggest different paces of technological development. While scenarios from Prognos (CN65 and CN60[1]) show gradual but continuous growth over time, the Kopernikus[2] basis scenario (KP basis) allocates substantial OWE expansion after 2030 [2, 69, 71]. Similarly, in line with Prognos CN65, the Kopernikus 1.5-degree (K15) scenario expects the OWE installed capacity to nearly quadruple by 2030.[3] Therefore, OWE should expand between 2 and 4 GW per year to meet German climate targets. In addition, estimating the future environmental impact of offshore wind turbine components is challenging due to their technical complexity, diversity depending on installation sites, and uncertain technological developments, for example, in 2030 and 2050.

The environmental impacts of various stages of the technology lifecycle (e.g., material extraction, transportation, construction, operation, and disposal) can be evaluated through Life Cycle Assessment (LCA) [38]. An LCA model consists of a foreground (FG) system, collecting inventory data of the technology assessed, and background (BG) systems, comprising the supply chain and including energy and materials delivered to the FG [48]. LCA studies dealing with future developments are classified as prospective LCA (pLCA) [21], as the term prospective refers to the maturity and time position of the technology [1]. Since both parts of the LCA model (foreground and background) are subject to change, the scenario-based approach enables the alignment of the LCA model within a consistent narrative. Therefore, assessing future development from an environmental perspective requires acknowledging OWE technology diversity and its potential changes over time, accounted in the FG, and, in parallel, supply chain developments (e.g., materials, transportation, etc.) accounted in the BG [61]. Moreover, a scenario-based approach enhances result interpretation. For instance, when an LCA model depicts an exploratory scenario, the foreground and background of the LCA model align with the same narrative, and it becomes evident that the results portray a plausible view of the future, which is particularly suitable in high-uncertainty situations (e.g., when it is unknown the evolution of an input parameter) [14].

Although information about OWE is abundant, it often remains fragmented, dispersed, or inaccessible. For instance, the Open Power System Data (OPSD) contain data on OWTs for different countries (e.g., Denmark, Germany, etc.). Approximately 1050 OWTs installed in Germany from 2009 to 2019 confirm a clear trend toward enlarged nominal OWT capacity. However, OPSD [68] lacks specific details such as the generator, drivetrain and foundation types, and component weights. On the other hand, the rotor diameter is available for 550 Danish OWTs and shows a consistent increase over time (Fig. 1). Access to more detailed information requires payment or membership.

[1] CN60 and CN65: emission reduction of 60% and 65%, respectively, by 2030 in comparison with 1990 values to achieve climate neutrality.

[2] KP basis: emission reduction of 55% by 2030 and at least 95% by 2050 in comparison with 1990 values. K15 or 1.5-degree scenario estimates a per capita budget of Kyoto gases to keep rise of global temperatures at 1.5 °C.

[3] 7 GW offshore installed capacity at the end of 2021. Future targets are 25 GW and 70 GW offshore wind installed capacity by 2030 and 2050, respectively [71].

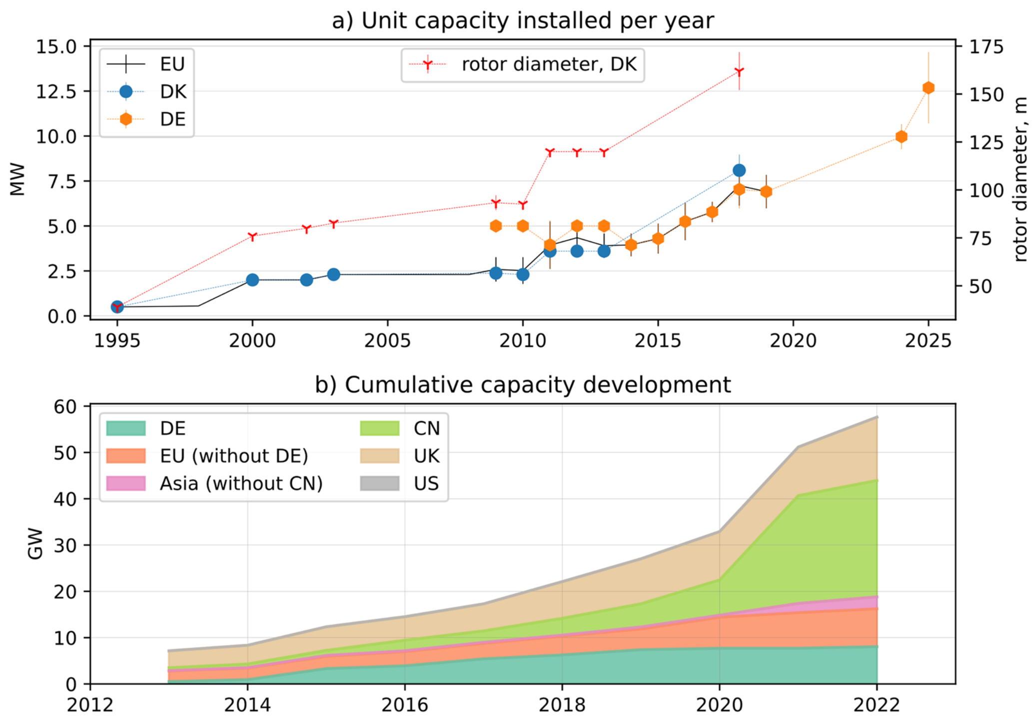

Fig. 1 Offshore wind turbine development based on [68, 70]. **a** Unit capacity installed per year represents the average nominal capacity and rotor diameters of OWT installed in Denmark, Germany, and the European Union. **b** Cumulative capacity deployments over the years. Global OWE reached 60 GW of cumulative capacity in 2022

While more than 32 LCA studies on OWE have been reported [60], only 16 have focused on OWTs above 5 MW. Hengstler et al. [40] found 56 LCAs on wind energy, only 12 of which were on turbines up to 7 MW. Incorporating these findings is challenging because of the confidentiality of the data and the lack of transparency or reproducibility of the inventory data. Therefore, previous LCA studies have described, in the FG, a current or future technology but use a historical or retrospective BG. For instance, Hengstler et al. [40] performed an LCA on OWE, matching the FG of a representative OWT of 8 MW[4] to current developments in Germany. Reimers and Kaltschmitt [76] evaluate the LCA of several wind turbines (WTs) and present a trend of future impacts over the years (e.g., from a WT of 3 MW to 24 MW in 2050). Similarly, Schreiber et al. [82] proposed a comparative LCA of direct drive (DD) and geared onshore wind turbines of 3 MW with different generator options. Moreover, few studies have considered the variabilities in relevant parameters (e.g., shore distance, water depth, hub height, rotor diameter, wind speed, etc.) and their influence on OWT power output [6, 47, 91]. Even fewer studies address prospective LCA on OWE, including improvement over time in both the FG and BG. For instance, Besseau et al. [7] draw attention to concerns related to the technical and geographical representativeness of the inventory data used to assess OWE for Denmark. In particular, they discuss the issues of using outdated inventory data from commercial databases, such as the use of the ecoinvent database [93]. Li et al. [52] focused on the future environmental impacts of OWE on a global scale. They used prospective inventory data derived from integrated assessment models (IAMs). These prospective inventories consider improvements in the supply chain over time (e.g., transportation, share of renewable energy sources, etc.). However, their geographical representation is limited. Therefore, to address this issue, this study adapts the background datasets (e.g., electricity mixes) to align with the German energy scenarios. This study employs Premise,[5] a tool that aligns ecoinvent life cycle inventories with data from IAMs, and the Superstructure approach [88]. The latter allows the generation of prospective background databases for pLCA [80, 88]. To our knowledge, there are no pLCA studies focused on OWE in Germany. Therefore, our case

[4] OWT: 8 MW and rotor diameter of 167 m and a hub height of 99 m.

[5] [79] *Premise User guide* [Online]. Available: https://premise.readthedocs.io/en/latest/extract.html#current-iam-scenarios [Accessed 28 May 2023].

study of a 9.5-MW OWT illustrates a scenario-based prospective LCA in Germany as a basis for evaluating the future environmental impacts of OWTs. Finally, this study aims to address the question of how large the magnitude of potential environmental impacts of a 9.5-MW OWT could be in 2030 and 2050.

Expected developments of offshore wind turbines in Germany

The expansion plans for OWE indicate that further technological progress can be expected. The following section discusses the current state of OWTs, their technological developments, and plans for Germany, which serve as an example case study. In Germany, 12 GW of OWE projects were approved, with units ranging from 9.5 to 15 MW [95]. The expansion of OWE will locate wind farms further from the shore (e.g., 40 and 100 km at water depths between 30 and 40 m, respectively). The hub height depends on the project characteristics and should be at least half the rotor diameter, ranging between 90 and 150 m.

While the North Sea is known for its shallow water with an average depth of 80 m, the water depth in the German Bight varies from 30 m to a maximum of 50 m [55]. Therefore, monopiles are the predominant foundation type [20, 65]. In the German market, monopile foundations may remain dominant because of their simple design [51], even at water depths of 44 m [97]. Manufacturers (e.g., Steelwind Nordenham GmbH) already offer ultra-large XL monopiles with diameters of up to 10-m-long and 120-m-long pipes [29, 67]. These components are manufactured from S355-M steel, which is more ductile than structural steel [43]. Soares-Ramos et al. [84] evaluated 11 wind farms authorized for construction. The authors noted that in the majority of OWTs, water depths exceeded 30 m, with a range of 40 to 53 m. This trend has led to growing interest in floating foundations, which today represent 0.2% of global installations [36]. Floating foundations are suitable for water depths greater than 50 m [36, 101]. This study assumes that, in Germany, monopile foundations and tubular steel towers will remain dominant. According to Kallehave et al. [46], monopiles still have optimization potential. For example, weight savings between 10% and 25% are reasonable. Monopiles with a maximum diameter of 10 m are designed for installation at water depths of up to 60 m [46]. However, they are costly to build and transport. Most towers consist of conical tubular steel structures. To reduce weight and, foremost, to address corrosion, Zee et al. [102] investigated glass fibre-reinforced polymer (GFRP) towers. Additionally, experimental prototypes of hybrid structures that combine concrete and steel exist [37]. Hybrid structures can withstand higher loads, but their fabrication is complex and time-consuming [19]. However, to our knowledge, LCAs for hybrid structures for offshore wind applications are still lacking [40]. Therefore, information is insufficient to estimate hybrid structures' environmental impacts or to compare them with steel towers.

The nacelle, made of fibreglass, holds the wind turbine's drivetrain (e.g., geared, or direct drive units), yaw, and electric systems. Today, geared generators dominate the market despite drawbacks such as higher maintenance requirements, and greater mechanical losses. In OWE application, geared permanent magnet synchronous generators (G-PMSG) hold 12% of the global market share, while a direct drive permanent magnet synchronous generators (DD-PMSG) and direct drive electrically excited synchronous generators (DD-EESG) account for 5% and 2%, respectively, of the total installed capacity [51]. Despite the scarcity of rare earth elements needed for permanent magnets, there is a preference for PMSGs, and new developments lean toward high-temperature superconductor generators (HTSs) [54]. Nevertheless, uncertainty persists as both geared and direct drive wind turbines are in close competition and may remain valid options [41, 51, 62, 66]. Direct-drive wind turbines are attractive for OWE applications due to their efficiency, high energy yield and low maintenance requirements [56, 66]. In Germany, less than 2 GW of recently granted OWE projects specify generator, drive train and rotor types. Of these, 45% were G-PMSG and 55% were DD-PMSG [65, 75, 97]. After 2030, the dominant nacelle-technology remains uncertain. Figure 2 illustrates the wide range of technologies used in offshore wind turbines.

Depending on local wind conditions (e.g., wind speed, long-term extreme gusts, and turbulence), as defined by the International Electrotechnical Commission (IEC), wind classes influence rotor blade design, impacting dimensions, mass, and materials. For instance, OWT Class II is suitable for lower wind speeds (e.g., 8.5 m/s), while OWT Class I is suitable for wind speeds of 10 m/s. Consequently, OWT II requires longer blades than OWT Class I to generate equivalent energy outputs. Despite identical rotor diameters, Class III blades endure more turbulence than Class II blades, making Class III blades more massive. The majority of rotor blades are made of GFRP, with a spar cap made of composite materials such as GFRP, carbon fibre-reinforced polymer (CFRP), or biological fibres and resin [51]. According to Ennis et al. [32], 55% of rotor blades longer than 70 m have carbon fibre spar caps. In Europe, a total of 29% of rotors installed between 2005 and 2015 contained CFRP [86]. Carbon fibre spar caps can reduce blade weight by 20% without compromising strength [32]. Depending on

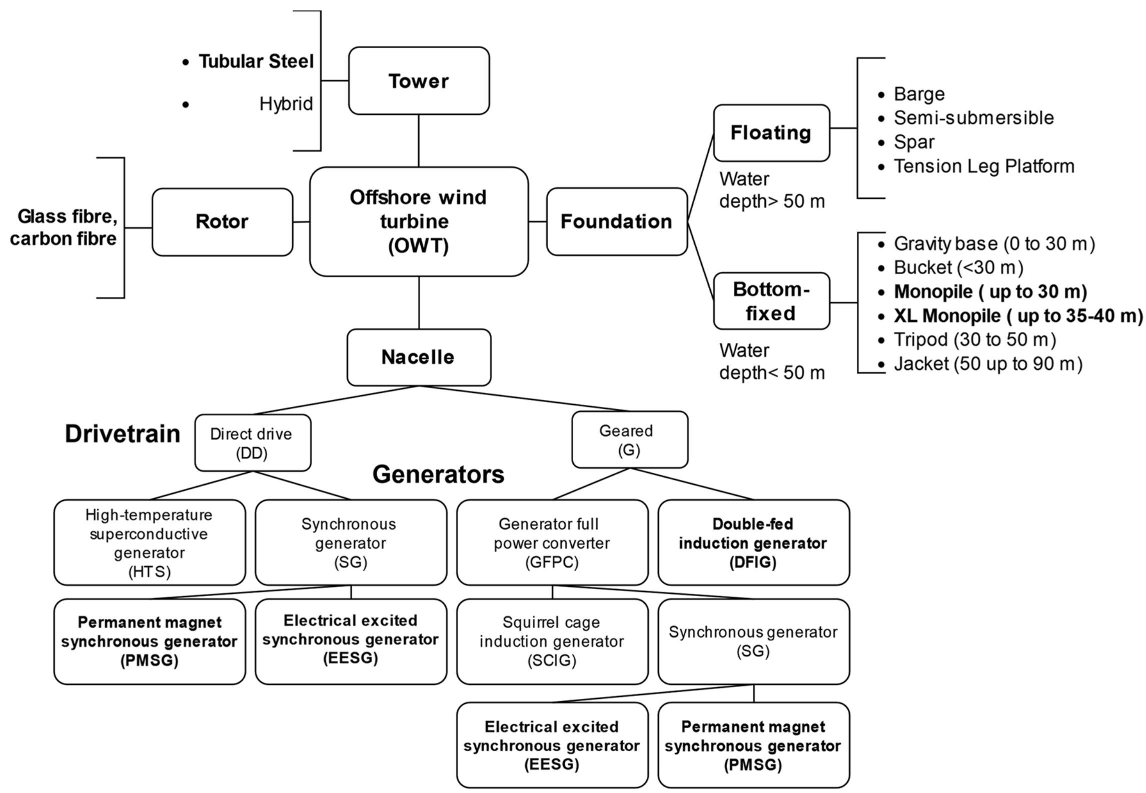

Fig. 2 Offshore wind turbine technical diversity. Based on [30, 66, 81, 104]

the material, GFRP/CFRP rotor blades can be 8 to 12 m longer than GFRP blades for an equivalent OWT nominal capacity [99]. Moreover, GFRP blades can achieve a 3–4% mass reduction through design optimization and manufacturing techniques [83].

Methods

Prospective LCAs have been developed for evaluating potential future environmental impacts, especially related to emerging technologies. This section outlines the steps for calculating future environmental impacts per kWh and per unit of a 9.5-MW OWT. It describes the data and methodology used for modelling OWTs within the pLCA framework. The discussion also introduces scenarios and their respective narratives. Furthermore, it explores technical considerations for modelling prospective inventories of OWTs based on available inventory data (highlighted in Fig. 2). The study's methodology is replicable for other OWT sizes or regions. However, verifying the validity of the technical representativeness of inventories will be necessary, as the selection of some components (e.g., foundation, rotor blades) depends on unique geographical features (e.g., water depth, wind speed, etc.).

Scenario generation through the SIMPL method

Given the unpredictability of complex system development, we use the SIMPL[6] [50] method for our prospective LCA. It facilitates the generation of potential scenarios and consists of a simple four-step method that focuses on the goal and inventory phase of the LCA, based on [50]. Figure 3 shows the implementation of the SIMPL method for our case study. First, key factors for OWE in Germany, such as environmental policy implementation (e.g., achieving climate neutrality), OWE deployment, and development rates, are identified. The arrows in Fig. 3 indicate the relationships between the key factors and inventory parameters specific to the technology under consideration and its supply chain. For example, cumulative OWE deployment (in GW) could vary significantly depending on environmental policy, as shown in the Prognos and Kopernikus scenarios [2, 73]. In turn, OWT technology could experience learning effects as the cumulative OWE capacity increases. These learning effects are related to production costs,

[6] SIMPL: scenario-based inventory modelling for prospective LCA.

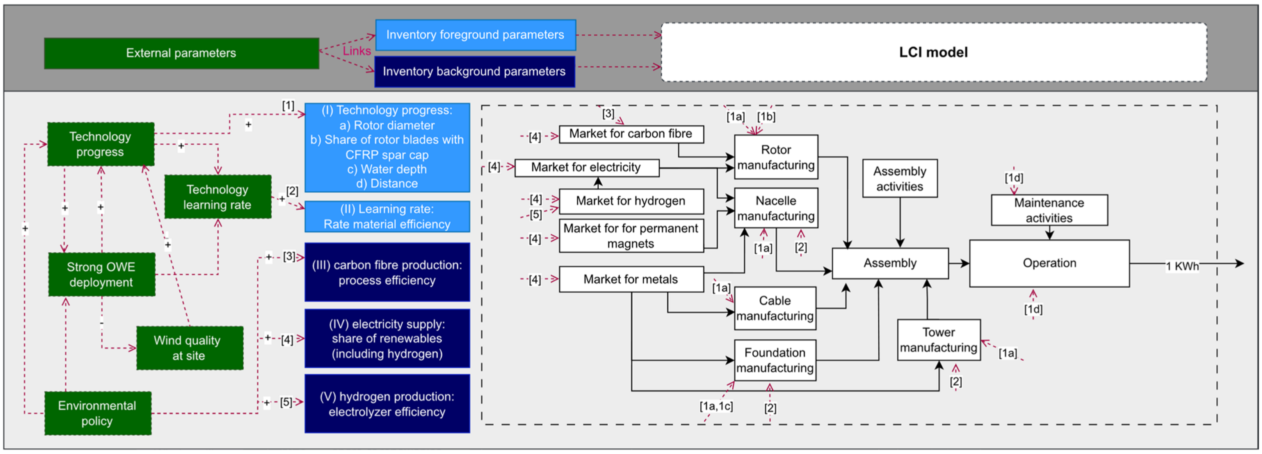

Fig. 3 Implementation of the SIMPL method [50] for the evaluation of an offshore wind turbine. CFRP: Carbon fibre-reinforced polymer

which could vary as the production of OWT components becomes more efficient, benefiting from both economies of scale and material efficiency [78] (see Supplementary Material 1: Figure S2). In addition, rapid expansion of OWE may require taking advantage of sites with lower winds, incentivizing the construction of more efficient OWTs. On the other hand, an environmental policy also influences the OWE supply chain, as the composition of renewable sources in the electricity mix of a country or region will vary significantly over time. For this reason, the study uses prospective versions of ecoinvent 3.7.1 (cut-off) derived via Premise [80].[7] Then, foreground inventory parameters (e.g., rotor diameter, hub height, etc.) and background inventory parameters (e.g., share of renewable energy, carbon fibre production, etc.) are coherently combined according to narratives (see Supplementary Material 1: Table S11) and transferred into the LCA software.

Scenarios and narratives

This prospective LCA estimates the variation in the environmental impacts of a 9.5-MW OWT technology development for 2030 and 2050. This study proposes three exploratory scenarios, namely, an *optimistic*, a *moderate*, and a *pessimistic* scenario, which describe how OWTs' future environmental impacts could evolve in the future. Before describing our scenarios, it is necessary to clarify certain aspects concerning prospective databases. First, Premise [80] aligns processes from the ecoinvent database [93] associated with energy use, conversion, and supply based on scenarios generated by Integrated Assessment Models (IAMs) such as IMAGE [87], including activities such as steel and cement production, transport, and electricity. Furthermore, Premise updates downstream processes contingent upon these activities, generating prospective life cycle inventories (pLCIs). The generated pLCIs are in accordance with the narratives and geographical representations outlined by the IAMs. For example, IMAGE explorative scenarios, including SSP2-RCP6.5 and SSP2-RCP2.6 [79], illustrate the potential energy supply for countries or regions as a function of different macroeconomic indicator pathways (e.g., population, economic growth, rate of technological development) described by the shared socioeconomic pathways (SSPs) and concentration levels of greenhouse gases (GHGs) described by the representative concentration pathways (RCPs). For instance, SSP2 indicates minimal deviation of macroeconomic indicators from historical patterns [39] and illustrates intermediate development [50]. RCP2.6 refers to the concentration of GHGs required to achieve a radiative forcing of 2.6 W/m^2 and a global mean temperature below 2 °C by 2100, compared with RCP6.5, which represents the GHG concentration required to achieve a global mean temperature of 3.5 °C by 2100. This study employs prospective databases derived from Premise aligned with the SSP2-RCP2.6 and SSP2-RCP6.5 narratives [79]. The study adjusts inventory background parameters such as the share of renewables in the German electricity mix according to Prognos CN65 and CN60 scenarios (Supplementary Material 1: Figure S3). For instance, the Prognos scenarios describe a normative-transformative perspective of the future, outlining how to achieve an envisioned future state. Within this framework, Prognos scenarios propose the expansion of renewable energy sources and a minimal investment in storage infrastructure. Additionally, the study

[7] The study is done in an attributional framework, as it is not aiming for decision support at the meso- or macro-level and for that reason an attributional prospective LCI database is chosen.

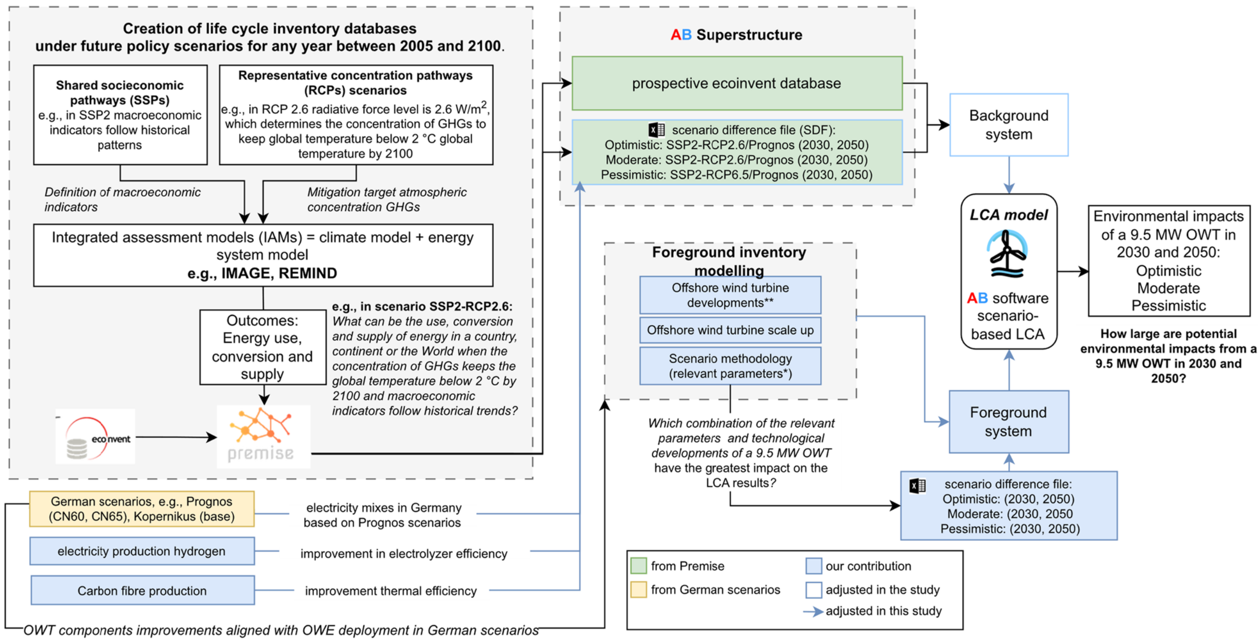

Fig. 4 Implementation of the prospective database and adjustment to the study case. Based on Sacchi [79], Steubing and de Koning [88]

estimates other background parameters, such as the improvement in efficiency that affects carbon fibre production [4] and hydrogen production [100] (see Figs. 3 and 4).

Premise applies several transformations to the ecoinvent datasets to align existing inventories with the IAMs scenario narratives. For example, to match the IAMs' set of technologies and geographical representations, energy conversion technologies in the ecoinvent datasets are adjusted. The efficiency of energy conversion technologies is adjusted over time, resulting in a proportional scaling of biogenic and fossil CO_2 emissions to fuel consumption. However, emissions of certain species (e.g., SO_2, NOx, CH_4 and PM) other than CO_2 are adjusted based on updated power plant conversion efficiencies. With characterization factors held constant, emissions from power conversion technology datasets are scaled proportionally to fuel consumption. Therefore, the representation of impact categories beyond climate change might be inaccurate. For instance, NOx also contributes to marine eutrophication; thus, impact categories that are not directly related to the modified data in Premise should refrain from overinterpretation, as no future adjustments have been made [79].

The optimistic scenario illustrates rapid OWE expansion and the inventory foreground internal parameters are consistent with greater technological progress, indicating a greater likelihood of introducing new technologies and improving the design and manufacturing process of OWTs; moreover, a stricter environmental policy means more rigorous climate mitigation targets consistent with the SSP2-RCP2.6 scenario (see Supplementary Material 1: Figure S4). Additionally, the optimistic scenario considers high-quality wind sites, where higher and sustained wind speeds enable shorter rotor diameters without compromising power out (see Supplementary Material 1: Figure S7). Thus, in the *optimistic scenario,* foreground parameters align with lighter components, less scheduled maintenance, and increase the replacement rate for the rotor blades (see Table 1). The *pessimistic scenario* pertains to a low-wind site that is more likely to be found in shallow waters closer to the coast. Consequently, to ensure optimal electricity yield (in GWh), this scenario considers larger rotor diameters, which in turn lead to higher torque and an increased risk of nacelle failures, e.g., generator and drive train components [3, 66]. Therefore, in the *pessimistic scenario*, inventory foreground parameters are compatible with more robust generators, taller towers, higher requirements for the foundation (heavier monopiles), and higher replacement rates for the nacelle (see Supplementary Material 1: Table S10), as well as slower technical expansion rates. Additionally, the pessimistic scenario considers climate goals consistent with the prospective inventories aligned with the SSP2-RCP6.5 narrative (see Supplementary Material 1: Figure S4). The *moderate scenario* describes an intermediate trend between these two extremes (see Table 2).

Table 1 Overview of scenario narratives and main assumptions

Scenarios	Pessimistic	Moderate	Optimistic
Narratives	How large are the potential environmental impacts of a 9.5-MW OWT in 2030 and 2050 if the OWT is constructed and operated under less favourable conditions?	How large are the potential environmental impacts of a 9.5-MW OWT in 2030 and 2050 if the OWT is constructed and operated under average conditions?	How large are the potential environmental impacts of a 9.5-MW OWT in 2030 and 2050 if the OWT is constructed and operated under the most favourable conditions?
Wind quality* (average wind speed North Sea)	6 m/s (poor)	10 m/s (average)	14 m/s (good)
Deployment rate of offshore wind energy	low	medium	high
Technology progress	low	medium	high
Share of renewables in the electricity mix	low	medium	high
Maintenance	high for nacelle, low for blades	medium	low for nacelle, high for blades
Background database	in line with greenhouse gases concentrations to keep global mean temperatures below 3.5 °C by 2100	in line with greenhouse gases concentrations to keep global mean temperatures below 2 °C by 2100	in line with greenhouse gases concentrations to keep global mean temperatures below 2 °C by 2100

*The wind quality is assessed by the average wind speed (10.17 ± 4.48 m/s) evaluated in 5 sites of the North Sea at different hub heights (see Supplementary Material 1: Table S7 and Supplementary Material 1: Figure S7)

Table 2 Wind offshore technology trends and scenarios considered in the study

Component	Technology considered	Parameters	Scenario OWT 9.5-MW (year)		
			Pessimistic (Φ174 m)	Moderate (Φ169 m)	Optimistic (Φ164 m)
Nacelle	G-DFIG, G-SG (EESG and PMSG), DD-PMSG	Market share (year)	Unknown	Unknown	Unknown
		Mass, t	286 (current) 292 (2030) 238 (2050)	274 (current) 241 (2030) 218 (2050)	256 (current) 222 (2030) 200 (2050)
		% mass reduction	9% (2030) 17% (2050)	12% (2030) 20% (2050)	13% (2030) 22% (2050)
		Magnets	2% nacelle mass	2% nacelle mass	2% nacelle mass
Rotor	GFRP/GFRP spar cap—GFRP/CFRP spar cap (year)	Market share (year)	Base: 50–50% SE1: 40–60% SE2: 0–100% (2030 and 2050)	Base: 50–50% SE1: 40–60% SE2: 0–100% (2030 and 2050)	Base: 50–50% SE1: 40–60% SE2: 0–100% (2030 and 2050)
		Mass, t	254 t—188 t (2030 and 2050)	229 t—182 t (2030 and 2050)	221 t—165 t (2030 and 2050)
		Carbon fibre	8% rotor mass	8% rotor mass	8% rotor mass
Foundation	Monopile (XL monopile) D/t = 160 feasible for XL monopile, weight reduction up to 30%	Market share (year)	100% (2030 and 2050)	100% (2030 and 2050)	100% (2030 and 2050)
		Mass, t	1028 t (2030) 904 t (2050)	943 t (2030) 833 t (2050)	858 t (2030) 762 t (2050)
		% mass reduction	4% (2030) 15% (2050)	7% (2030) 18% (2050)	11% (2030) 21% (2050)
Tower	Tubular steel towers (height at least half rotor diameter)	Market share (year)	100% (2030 and 2050)	100% (2030 and 2050)	100% (2030 and 2050)
		Mass, t	520 t (2030) 462 t (2050)	463 t (2030) 403 t (2050)	406 t (2030) 343 t (2050)
		% mass reduction	16% (2030) 29% (2050)	9% (2030) 21% (2050)	3% (2030) 14% (2050)

G-DFIG: Geared double fed induction generation, *G-PMSG:* Geared permanent magnet synchronous generator, *DD-PMSG:* Direct drive permanent magnet synchronous generator, *EE*: Electrically excited, *Φ:* Monopile diameter, *GFRP:* Glass fibre-reinforced polymer, *CFRP:* Carbon fibre-reinforced polymer. Source: (Li et al. [51], Hengstler et al. [40], Ennis et al. [32] , Sommer et al. [86], Durakovic [29], Marques [58], Kurian et al. [49]). For the transmission cables and substations, see Supplementary Material 1: Table S2

Table 3 Relevant parameters considered in the foreground systems for the scenario analysis

Relevant parameters in the foreground systems		Scenarios					
		2030			2050		
Description	Units	Pessimistic	Moderate	Optimistic	Pessimistic	Moderate	Optimistic
Distance shore	km	40	40	40	40	40	40
Water depth	m	20	30	35	20	30	35
Visits maintenance	units	3	2	1	3	2	1
Cut in; rated; cut off	m/s	3; 9; 25	4; 10; 25	5; 13; 25	3; 9; 25	4; 10; 25	5; 13; 25
Hub heights	m	140	120	100	140	120	100
Rotor diameter (9.5-MW)	m	174	169	164	174	169	164
Annual electricity (9.5- MW)	GWh	37	39	41	37	39	41
Unit mass (8 MW reference; Φ 167 m)*	t	1785 ± 135			1582 ± 129		
Unit mass (9.5-MW)*	t	2075	1955	1839	1826	1660	1498
Lifetime	years	20	20	20	20	20	20
Background data (database)	–	SSP2-RCP6.5/CN60	SSP2-RCP2.6/CN65	SSP2-RCP2.6/CN65	SSP2-RCP6.5/CN60	SSP2-RCP2.6/CN65	SSP2-RCP2.6/CN65

*Estimated values include foundation, tower, rotor, and nacelle, without transmission cables. Φ: Rotor diameter

Estimation of OWT electricity generation

The annual electricity generation is calculated based on the hourly wind speed and power density corresponding to the sites mentioned in Supplementary Material 1: Table S6, with hub heights ranging between 90 and 150 m, rotor diameters and OWT operating speeds (i.e. cut-in, rated, and cut-off wind speeds) outlined in Table 3. The wind speed and power density data are obtained from the new European Wind Atlas.[8]

Inventory analysis

OWT component manufacturing and assembly

For modelling the foreground system, a 9.5-MW OWT is considered to consist of five components, namely the foundation, tower, nacelle, rotor, and transmission cable, including the substation. The functional unit is 1 kWh of electricity generated in the German Bight of the North Sea, including conversion and transmission from the OWT to offshore station and the onshore station. The lifetime is 20 years, and transmission distance is 40 km. The three scenarios are outlined in Tables 2 and 3. This study assessed two types of rotor blades made of GFRP, one with carbon fibre spar caps and another with glass fibre spar caps (Supplementary Material 1: Table S2). The masses of the rotor blades and hub are estimated based on Fingersh et al. [34] and Ennis et al. [32]. The study considered that the construction of rotors demands 0.5 kWh/kg of component [26, 40, 82] for GFRP rotors and 0.97 kWh/kg for GFRP/CFRP rotors, corresponding to the fabrication of carbon fibre spar caps by pultrusion [25]. The inventory of the carbon fibre is taken from [4]. The study estimates a 50% market share of rotor blades with a carbon fibre spar cap. For the nacelle, direct drive and geared drive trains are considered. The inventory accounts for synchronous generators (e.g., permanent magnets and electrical excited) and double-fed induction generators (see Fig. 2). Accordingly, the reference inventory accounts for 2% of the total weight of magnets. The inventory for permanent magnets is taken from Marx et al. [59]. Although a prototype HTS generator has been tested in Germany [98], access to the data is limited; therefore, high-temperature superconductive generators are excluded. After 2030, Germany plans to construct wind farms with units ranging from 9.5 to 15 MW. Therefore, an 8-MW OWT taken as a reference inventory (see Supplementary Material 1: Figure S2) is scaled to determine the material and energy requirements for constructing and operating a 9.5-MW OWT according to Caduff et al. [17] (see Supplementary Material 1: Table S3 and Supplementary Material 1: Table S4). The reference inventory is taken from the literature according to Hengstler et al. [40] and [10, 19, 24, 40, 44, 65, 76, 82, 92, 95, 96] (see Supplementary Material 1: Table S1 and Supplementary Material 1: Figure S2).

The material requirements for the monopile are estimated based on the ratio of the monopile diameter to its thickness (e.g., a ratio of 160 is feasible for the XL monopile) [20]. The monopile diameter is related to the water depth, and the scour protection area is assumed to be circular with a radius of 2.5 times the monopile diameter. As an estimation rule, the monopile diameter is considered to be between 0.8 and 1.5 times the nominal capacity of a wind turbine [64]. The installation accounts for the transport and dumping of rocks for scour protection [52]. The tower weighs approximately 500 t, 98% is steel, and the rest constitutes a protective coating (e.g., epoxy resin).

In this study, a 33-kV XLPE[9] submarine cable connects the OWT to an offshore substation (23 t/km), and a 245-kV cable connects the offshore substation to the grid. The submarine 245-kV XLPE cable systems weigh 68 t/km. About 52% of the total distances are underwater, with the remaining 48% being land cables weighing 18 t/km. The manufacturer's datasheet provides the cable mass per distance, and the ratio of materials is taken from [40]. The amount of 33-kV cable per OWT is assumed to be seven times the rotor diameter, and the 245-kV cable depends on the distance to shore. Furthermore, this study considers an offshore substation of 800 MW, and its inventory is taken from [40].

The study considers the assembly and transportation of the components. According to Li et al. [51], assembly activities account for the fuel burnt (e.g., heavy fuel oil and diesel), which depends on the working hours and the distance of the installed transmission cable [51, 52]. Additionally, the transportation of the remaining components is a function of the mass of the OWT and the distance to shore; see Supplementary Material 1: Table S9. Regarding the lifetime of the wind turbine components, the most critical one is the gearbox, which can barely reach 20 years [90]. The second most important component is the rotor blade. Therefore, the lifetime of the nacelle, rotor, foundation, and tower are 20 years Dones et al. [15, 26]. In addition, the study considers replacement rates for the nacelle, rotor blades and other small components (see Supplementary Material 1: Table S8).

[8] Wind speed/North Sea/map obtained from the "New European Wind Atlas", a free, web-based application developed, owned, and operated by the NEWA Consortium. For additional information see www.neweuropeanwindatlas.eu. The year 2012 is used as proxy.

[9] XLPE is the insulated material for the cable and stands for cross-linked polyethylene.

OWT operation and maintenance The operation phase accounts for the replacement of the nacelle, rotor blades and small components after some time (see Supplementary Material 1: Table S8). Additionally, the study included transport by helicopter and fuel burnt during operation and maintenance (O&M) (see Supplementary Material 1: Table S9).

Decommission and end of life For the end of life (EoL), 10% of the input materials are treated (e.g., landfill and incineration), for instance, metal scrap, glass and plastic waste from the nacelle, tower, rotor, and hub. The decommissioning process omits the removal of the foundation and transmission cable. According to the EU Waste Regulation and the Circular Economy Action Plan, landfilling should be considered as a last option when the reuse or recycling of components is not feasible [33]. However, rotor blades contribute to 40% of landfilled materials [22]. The study assumes that the OWT will operate for 20 years. Although decommissioning and construction of OWTs take place at different times (e.g., if construction takes place in 2030, decommissioning would be in 2050), the limited accessibility to OWT decommissioning inventory data challenges the disaggregation of these two phases; therefore, the end-of-life is considered a part of the construction phase of the OWTs. For the same reason, the assessment of the EoL is limited.

Sensitivity analysis Assessing technology development in the long-term future means dealing with unknowns, which this study addresses by presenting results in the form of optimistic and pessimistic exploratory scenarios. However, parameters such as lifetime, distance to shore, and market share are held constant and should therefore be investigated through sensitivity analyses by modifying the lifetime to 25 years and the distance to shore to 40, 60, and 80 km. Given that the market share for rotor blades with carbon fibre spar caps is only an approximation, the study conducts a sensitivity analysis, considering both 0% and 100% market shares for rotor blades with glass fibre spar caps. Finally, the study investigated the variation in the results from the selection of prospective databases.

Life cycle impact assessment The inventory analysis indicates that the construction of OWT components is resource and energy-intensive. In addition, prospective databases (at the time of the analysis) can update a few emissions other than CO_2, such as CO and NOx, concerning improvements in the conversion efficiency of specific technologies [79]. For example, NOx is also relevant for marine eutrophication. Therefore, the study evaluates the impact categories of climate change, marine eutrophication, and material resources through the indicators of global warming potential (GWP in kg CO_2-eq), fraction of nutrients reaching marine end compartment (in kg N-eq) and abiotic resource depletion (ADP in kg Sb-eq). For the life cycle impact assessment (LCIA), the impact assessment method package Environmental Footprint v3.0 (EF v3.0) was used. The LCA is modelled in the Activity Browser [89].

Results and discussion

Based on the data described in the previous section, specific LCA results for the lifetime of an OWT are presented, followed by the contribution analysis and the sensitivity analysis.

Specific environmental impacts

The environmental impacts *of* the generation of 1 kWh of electricity are estimated based on three scenarios for a 9.5-MW OWT, with projections for 2030 and 2050. The optimistic and pessimistic scenarios show an 11% difference in OWT mass and a 6% difference in rotor diameter. For a 20-year lifetime with rotors featuring carbon fibre and glass fibre spar caps, the mean GWP could reach 13 ± 3 g CO_2-eq/kWh by 2030, decreasing to 10 ± 3 g CO_2-eq/kWh (23% drop) by 2050. The optimistic scenario projects the lowest GWP per kWh, up to 50% lower than the pessimistic scenario in 2030 and up to a 33% difference between the optimistic and pessimistic scenarios in 2050, resulting in a GWP as low as 8 ± 2 g CO_2-eq/kWh (see Fig. 5). Concerning marine eutrophication (MEP), the findings vary between 0.012 and 0.024 g N-eq/kWh in 2030, with a mean value of 0.017 ± 0.004 g N-eq/kWh. MEP could reach 0.034 ± 0.007 g N-eq/kWh by 2050. The reason for higher MEP values is nitrogen oxides (NOx), resulting from the combustion of green hydrogen in gas power plants (see Supplementary Material 1: Figure S3) in the electricity mix. As both background datasets use hydrogen in gas turbines in similar shares by 2050, the choice of background scenario is of negligible importance under these considerations. The abiotic depletion potential (ADP) in 2050 slightly decrease to less than 10% compared to the value in 2030. For instance, in both years, the values ranged from 0.0008 to 0.0016 g Sb/kWh, resulting in a mean of 0.0012 g Sb/kWh. The variation is related to the copper and steel content in the nacelle and transmission cables (see Supplementary Material 1: Table S2). Regarding climate change, Li et al. [52] reported 15.8 g CO_2-eq/kWh for their base scenario, with a 14–25% improvement in the scenarios with new developments. The results found in this paper, see Fig. 5 indicate a significant increase in MEP which is in line with the opinion of the authors, whereas Li et al. [52] found a specific MEP (g N-eq/kWh) that tends to decrease. An explanation for this difference lies in the level of NOx emissions during

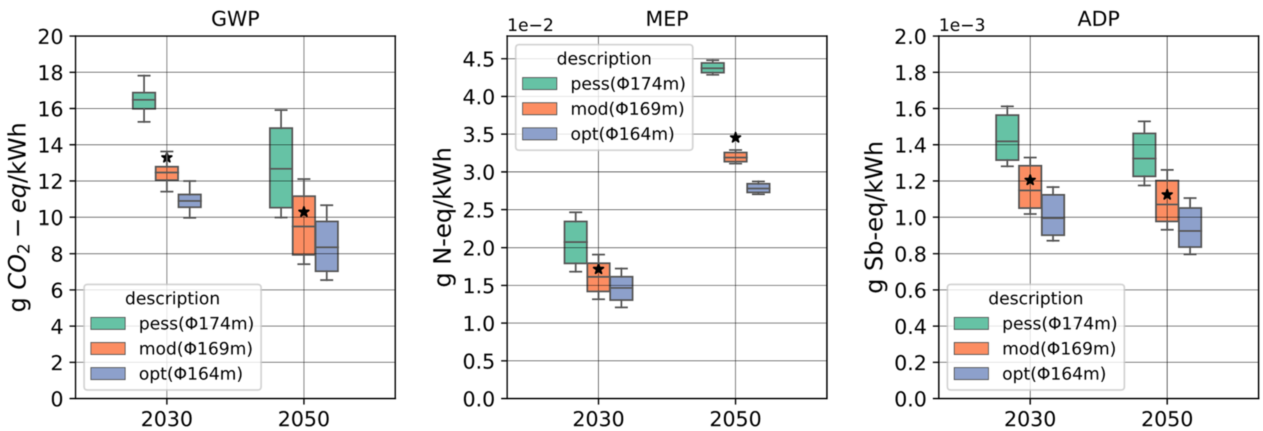

Fig. 5 Specific LCA indicators of a 9.5-MW offshore wind turbine for the optimistic (opt), moderate (mod), and pessimistic (pess) scenarios, which consider a 20-year lifetime and a distance to the shore of 40, 60 and 80 km, respectively. The black stars indicate average annual values for global warming potential (GWP), marine eutrophication (MEP), and abiotic depletion potential (ADP)

hydrogen combustion. For example, this study assumed a stoichiometric reaction between hydrogen and air without employing NOx removal treatment. Hengstler et al. [40] estimated that the GWP of an 8 MW OWT ranged from 5 to 12 g CO_2-eq/kWh, which is lower than the average GWP determined in this study due to the use of different rotor blade materials and component replacement rates. Overall, differences are attributable to system boundaries, impact assessment methods (LCIA), and the adaptation of prospective databases to the location under consideration (e.g., German electricity mix). Figure 5 and Supplementary Material 1: Table S12 show the environmental impacts per kWh for 2030 and 2050.

Additionally, these specific environmental impacts are influenced by the annual electricity yield, which depends on the rotor diameter, the wind distribution at the site, and the wind speed operation range of the wind turbine. The evaluation of wind speed data for multiple sites at different hub heights and wind speed operational ranges (e.g., cut-in, rated, and cut-off wind speeds) shows that the latter can have a greater impact on electricity yield (see Supplementary Material 1: Figure S7). This study estimates that an average of 39.60 ± 2.65 GWh per year could be generated by a 9.5 MW wind turbine.

Contribution analysis

The contribution analysis revealed that, on average, 81% of the GWP emissions come from component construction and the end of life (EoL), with 90% of emissions originating from material extraction and the remaining 10% from manufacturing (see Fig. 6). The nacelle, foundation and rotors significantly contribute to the GWP (see Fig. 7). In the nacelle, chromium steel, aluminium and copper significantly contribute to the climate change. The magnets constituted 2% of the nacelle mass but contributed nearly 50% to marine eutrophication (MEP). The remaining 40% of MEP came from the electricity consumed during nacelle manufacturing. The manufacturing of the components takes place in Europe. For ADP, significant contributions came from the copper and chromium steel in the nacelle. While concrete constituted 3% of the foundation mass, it contributed more than 45% to the MEP. Glass fibre in rotor blades is relevant for climate change. Carbon fibre comprised approximately 8% of the rotor mass but contributed 44% of greenhouse gas emissions. Notably, 56% of the MEP came from the electricity used during rotor blade manufacturing. The rotor diameter significantly impacts the environmental indicators of rotor blades featuring carbon fibre spar caps, reaching an 80% difference between the optimistic and pessimistic scenarios. Considering a 20% improvement in efficiency during the thermal treatment of carbon fibre production and the omission of carbon fibre recycling, the environmental impacts of carbon fibre may decrease by 2050, despite emissions falling on the upper end of the spectrum at approximately 60 kg CO_2-eq/kg by 2030 (see Supplementary Material 1: Figure S5). This approach suggests potential GWP reductions by 2050, indicating that the environmental impacts of rotor blades with carbon fibre spar caps are comparable to those of blades made with glass fibre spar caps. Concerning lifetime emissions, the assembly process accounts for approximately 5% of the GWP emissions on average (see Fig. 6). Assembly activities consider the fuel burnt per hour during the installation of the components and, for the case of transmission cables, the hours per km of installed transmission cable. However, fuel consumption might be affected by the characteristics of the sites, vessel

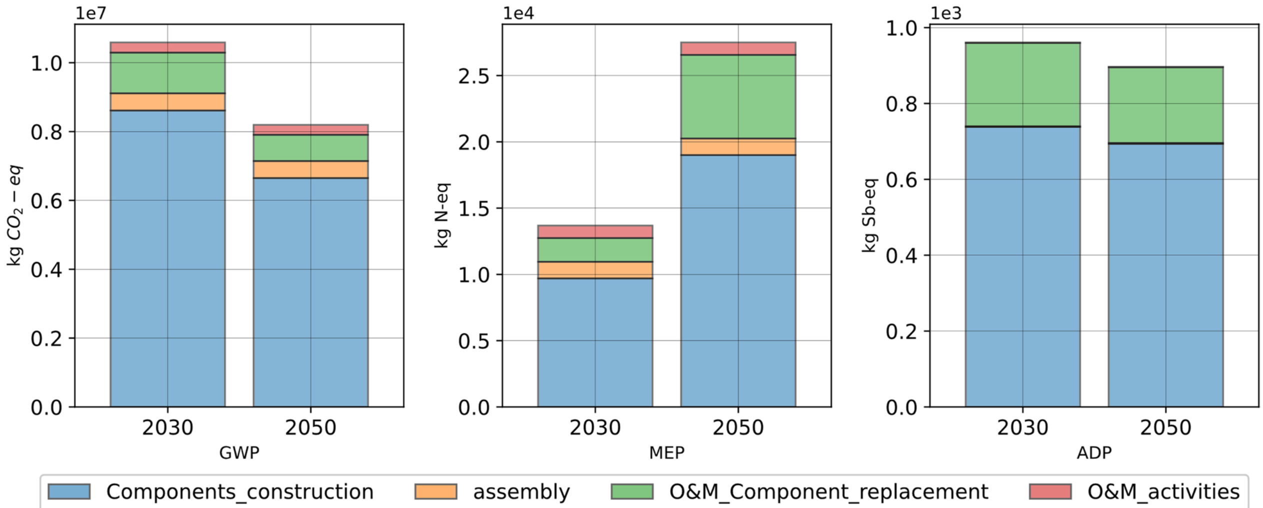

Fig. 6 Contribution analysis of LCA phases based on average values for 2030 and 2050. Global warming potential (GWP), marine eutrophication (MEP), and abiotic depletion potential (ADP). Operation and maintenance (O&M). The results correspond to the entire life cycle, and the functional unit is 1 kWh generated by a 9.5-MW OWT

types, and weather conditions. Additionally, in the future, synthetic fuels could replace heavy marine fuels. For instance, liquefied natural gas (LNG), hydrogen, marine biodiesel, or different blends are potential low-carbon fuel alternatives. However, it is unclear how migration to those fuel alternatives would affect vessel performance [27]. The potential replacement of rotor blades, nacelles, and small components is considered part of the operation phase, which also accounts for fuel consumed during transport and replacement activities. Therefore, the operation phase in total could contribute up to 17% of GWP emissions, 30% to the MEP and 32% to the ADP. The difference between the optimistic and pessimistic scenarios reflects the effect of the various component replacement rates; therefore, the GWP indicator varies significantly. For instance, a 66% difference arose between the optimistic and pessimistic scenarios due to maintenance considerations during the operation phase. The study assumed that 90% of the materials from the nacelle, tower, and rotors could be recycled, while the remaining 10% would be treated as waste, accounting for processes such as incineration and landfill, which are already part of the construction phase. On average, the construction of a 9.5-MW OWT in 2050 could represent a 22% GWP reduction, 101% more MEP and 6% lower ADP in comparison with the 2030 average values (see Fig. 7).

Sensitivity analysis

The life cycle inventory of offshore wind turbine components depends on the reference model, scenario, improvement rate and rotor diameter, which are crucial for scaling the components and leading to significant variation in the environmental impacts across the scenarios. For the sensitivity analysis, the rotor diameter, lifetime, distance, market share and prospective database are compared with the 2030 and 2050 annual averages for each impact category. In 2030, the GWP experiences a 60% variation between the optimistic (7.6 g CO_2-eq/kWh) and pessimistic (18.8 g CO_2-eq/kWh) scenarios (Fig. 8). In the optimistic scenario, the GWP is 39% lower than its average value (12.1 g CO_2/kWh), while the pessimistic scenario is 35% above the average. Extending the lifetime to 25 years might increase the impacts of the operational phase due to additional maintenance. However, when assessing the overall environmental impact per kWh, a 25-year lifetime could lead to a 17% reduction in both GWP and MEP and approximately 15% for ADP, compared to a 20-year lifetime. A longer lifetime results in more electricity generation (Supplementary Material 1: Figure S8). The lifetime could represent approximately 10% of the variation in comparison to the average values.

The distance to the shore had a modest impact on climate change, as fuel consumption depends mainly on working hours rather than the distance, except for the transmission cable (Supplementary Material 1: Figure S8c). Consequently, the GWP indicator could increase by 4–13% at distances of 40 km, 60 km, and 80 km, respectively, compared to 2030 average values. GWP could reach values as high as 18 g CO_2-eq/kWh. In contrast, the MEP could increase by 53–63% compared with the average value. The reason was longer transmission cables that demanded more fuel during installation. Additionally, the ADP increased by 30% when the distance doubled. Higher ADP values resulted from copper within the

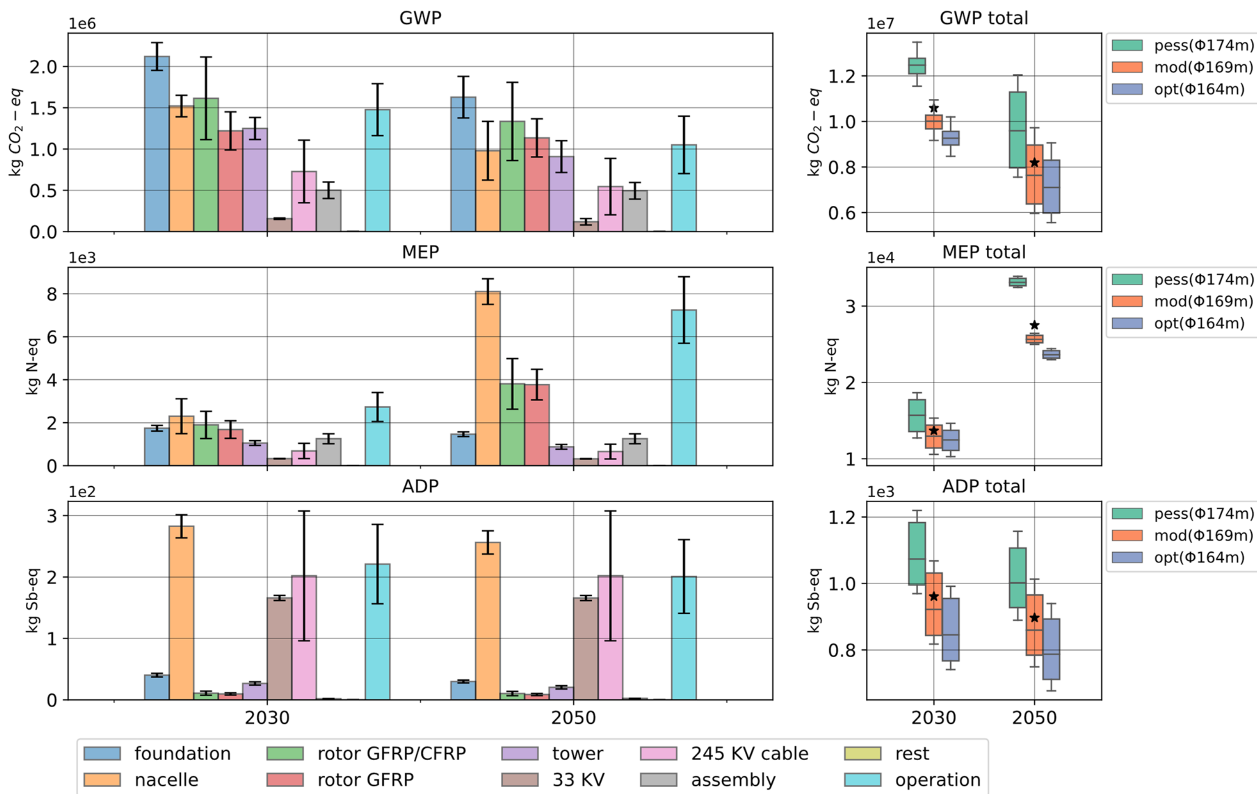

Fig. 7 Contribution analysis average values 9.5- MW OWT in 2030 and 2050 for a 20-year lifetime, showing variabilities in the foreground system, such as optimistic (opt), moderate (mod), and pessimistic (pess) scenarios, distances to the shore (40, 60 and 80 km), as well as prospective databases. The black stars in the right diagrams indicate average annual values for global warming potential (GWP), marine eutrophication (MEP), and abiotic depletion potential (ADP)

transmission cables. Initially, the study assumed an equal share of rotor blades with carbon fibre and glass fibre spar caps. Although rotor size has a more pronounced effect on environmental indicators, future trends indicate an increased adoption of rotor blades featuring carbon fibre spar caps. For the sensitivity analysis, the market share of rotor blades using only glass fibre spar caps and carbon fibre spar caps was analysed (Supplementary Material 1: Figure S8d). Using only GFRP spar caps led to an 11% reduction in GWP emissions compared to the 2030 average. By 2050, there was no significant difference between the use of spar cap materials.

The influence of the prospective inventory on the GWP was relatively modest in 2030. The use of a prospective database caused a 3% difference in GWP emissions, depending on the scenario narrative, for instance, the optimistic (e.g., SSP2-RCP2.6/CN65) or pessimistic (e.g., SSP2-RCP6.5/CN60). However, by 2050, if the economy follows the optimistic trajectory, the impacts of offshore wind turbines could experience an 18% reduction in GWP (kg CO_2-eq/kWh) with respect to the 2050 average. Overall, the MEP increased by 85% (kg N-eq/kWh) for the optimistic background scenario compared to the average for that year, and the choice of databases was negligible in the year 2050 (see Supplementary Material 1: Figure S8).

Overall, the assessment of environmental impacts in the year 2050 reveals a distinct trend toward a reduction in GWP emissions, which could decrease by at least 23% compared to the 2030 average. The 2050 ADP average shows a minor variation of 6% with respect to that of 2030. In contrast, compared with that of 2030, the 2050 MEP average exhibits a substantial increase—as much as 103%. The study suggested that substantial reductions in the environmental impact of nacelles are feasible, primarily because of improvements in the supply chain. Notably, since aluminium production and chromium steel production rely heavily on electricity, adopting low-carbon electricity sources or, even more so, incorporating recycled materials can significantly reduce the carbon footprint. The prospective database plays a role in MEP emissions because it follows two different narratives regarding the penetration of hydrogen in the electricity market and thus on NOx emissions. For instance,

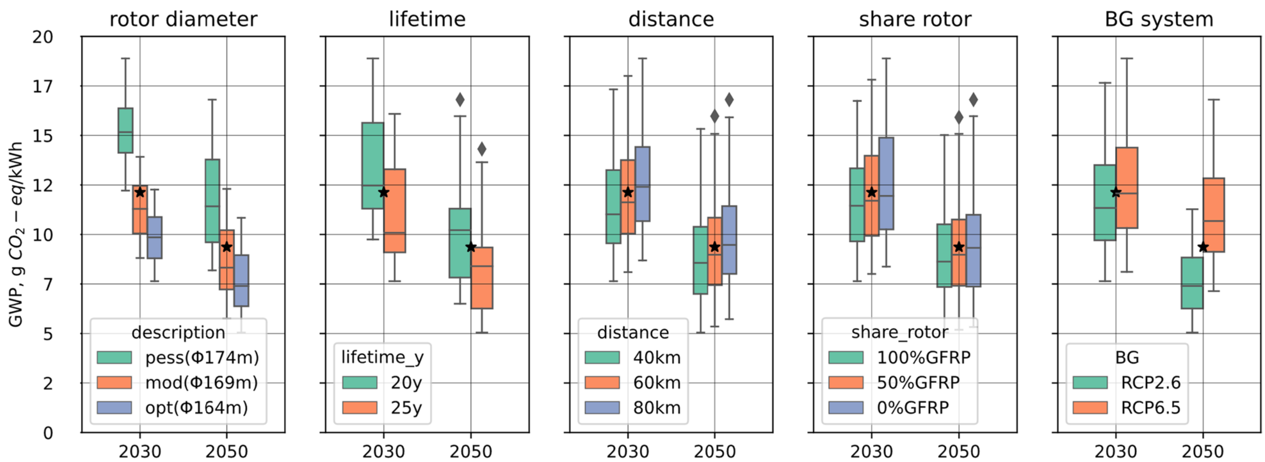

Fig. 8 Sensitivity analysis of a 9.5-MW OWT expressing the variation in rotor diameter (scenarios), lifetime, distance to shore, market share of rotor blades with glass fibre-reinforced polymer (GFRP) and carbon fibre-reinforced polymer (CFRP) spar caps, and optimistic (RCP2.6) and pessimistic (RCP6.5) prospective databases for the years 2030 and 2050. The black stars indicate average annual values for the global warming potential (GWP)

the pessimistic scenario introduces hydrogen after 2030, while the optimistic scenario does so from 2030 onwards.

It is important to emphasize that the contribution of aluminium production could influence the results. For instance, opting for aluminium produced in China could lead to 8% more GWP emissions in comparison to aluminium produced in Europe, as the prospective aluminium production in China relies on Chinese electricity. The background scenarios assume the Chinese electricity sector, as the German electricity sector, achieve carbon neutrality by 2050; therefore, the variation is due to potential improvements in the electricity mix of China. It is important to note that the narratives expressed in the prospective database reflect the world as depicted in the IAMs, which can provide a limited vision of the future (albeit a vision nonetheless). The interpretation of results should consider this context. Therefore, regional variations in the life cycle inventory can be relevant. Further results of the sensitivity analysis can be found in Supplementary Material 1: Figure S8.

Limitations and future research

Despite the focus on Germany, replicating the research for other countries is feasible by adapting inventory data. The trend leans toward larger OWTs, but significant variability exists in terms of size and installed capacity. For instance, OWTs ranging from 4 to 12 MW, potentially reaching 18 MW, with rotor diameters between 130 and 242 m are emerging in Asia (e.g., China and Japan) [94], while in Europe, the average capacity is 10 MW [70]. Technical aspects, such as local conditions (e.g., ocean current and water depth) [66], are decisive for selecting the foundation type, with options such as a jacket, gravity base, monopiles and floating foundations, each having distinct material requirements [51]. Monopile foundations prevail in Germany and the Netherlands, while in France, new wind farms will hold gravity base foundations. Floating foundations are becoming a reality in Spain, Norway and Japan [94].

The limited access to primary data, describing wind turbine component manufacturing and assembly, has been addressed through literature-based inventory. The confidentiality constraints in Hengstler et al. [40] resulted in aggregated nacelle inventory data, masking the market share of this technology. Thus, the study kept the nacelle market share constant. However, opportunities for improvements in OWT drivetrains and generators exist due to their non-site-specific nature [66], leading to a spectrum of technological choices for nacelles (see Fig. 2). While 3–6 MW OWTs often use geared doubly fed induction generators, 5–7 MW OWTs are suitable for direct drive with permanent magnet synchronous generators (DD-PMSG) and geared PMSG (G-PMSG) for those above 10 MW. As the OWT size increases, the advantages of direct drive technology over geared technologies become less evident. A comparison between two OWTs with identical generators—one using direct drive and the other using geared technology—revealed that the former might require a generator four times heavier and more voluminous, potentially compromising reliability, particularly when scaling up components [66]. The operation phase focused on fuel consumption during maintenance activities, omitting monitoring systems due to data restrictions. Sensors and monitoring systems might enhance overall OWT performance and substantially reduce future maintenance costs [45, 54, 58, 91]. This innovation requires additional research, as it may influence abiotic depletion potential, given that electronics demand precious metals such as gold, silver, and copper. Additionally, this impact indicator lacks characterization factors connecting rare earth physical flows to environmental impacts, possibly underestimating nacelle impacts and other elements (e.g., radium) that could be relevant for hydrogen production. Rapid decarbonization of the power sector, supported by carbon capture technologies, manifests in rising ADP values. This trend is evident in power generation inventories derived from Premise, particularly for low-alloyed steel (manganese), which is crucial for pipeline construction. However, Germany has committed to phasing out coal-fired power plants, making carbon capture in the power sector inapplicable [72] and resulting in minimal variation in ADP values. In addition, the overall modest ADP results are related with the consideration of photovoltaic (PV) systems only in the low-voltage electricity market, as in conventional ecoinvent databases [93]. This results from the assumption that the majority of installed PV systems are for self-consumption (e.g., residential and small commercial PV applications) and are generally connected to the low-voltage grid [8]. Yet, PV systems between 1 and 10 MW are typically connected to the distribution grid (e.g., 6 to 60 kV) [13, 85]. In addition, large utility-scale (> 10 MW) PV systems are connected to the high-voltage grid (e.g., 110 kV). Although only 2% of the PV units installed in 2023 are large-scale PV systems [8], this figure is expected to increase in the future [16]. PV technology is expected to play a significant role in achieving climate neutrality. In Germany, around 11 gigawatts (GW) of ground-mounted PV systems are expected to be added each year from 2026, according to the country's Renewable Energy Act (EEG) 2023 [77]. In addition, Germany's solar strategy aims for half of future PV installations to be ground-mounted systems, including utility-scale photovoltaic power plants [12].

The consideration of PV systems at medium and high voltage levels is of crucial importance, as they could have a significant impact on other environmental categories such as land use. For example, 1 MW of ground-mounted PV systems could require up to twice the size of a soccer field (approximately 1 ha) [35], in addition to critical resources, and in consequence affect ADP results. At the time this study was being developed, commercial PVs (at the high-voltage level) were not yet included in the version of the prospective database utilized. It is important to consider this aspect, given that Premise is in a constant state of development, and new inventories have been added in the most recent versions. However, given the expansion of utility-scale PV power plants is constrained by the availability of land, which should be in proximity to a substation or high-voltage transmission lines, these conditions may differ from country to country. Therefore, it is necessary to take these factors into account when deriving prospective databases. Hydrogen blends in gas turbines increase combustion temperatures, increase NO_x levels, and subsequently increase marine eutrophication potential (MEP) as the share of hydrogen in the German electricity mix grows. This underscores the importance of NO_x removal treatments [28, 64]. Regional inventories from Premise might not align with the latest energy policies of the country of interest. The implementation of energy policies takes place at the national level; therefore, energy strategies and goals may differ among countries [18]. Therefore, this study emphasizes the importance of customizing prospective databases according to the context of the country.

For the EoL phase, this study adopts the recycled content approach [5]. Under this approach, any credits or benefits derived from additional recycling are directly attributed to the product utilizing the recycled material. This study omits the benefits of recycling materials due to a lack of information regarding the proportion of recycled materials used in constructing the wind turbine. Specifically, recycled materials obtained from rotor blades may find application in other processes. Additionally, the study omits the decommissioning of components due to uncertainty about the transportation methods and vessels used during both installation and dismantling, emphasizing the need for a more comprehensive understanding of these aspects.

Conclusions

In this paper, a scenario-based prospective life cycle assessment (LCA) is presented for the examination of the future environmental effects of a sample 9.5-MW offshore wind turbine in Germany. There are notable disparities between the optimistic and pessimistic scenarios, as does the risk of doubling 2050 marine eutrophication (MEP) values in comparison to values for 2030. Given the increasing complexity of offshore wind technologies, their rapid expansion, and potential structural changes, this prospective LCA helps to inform the offshore wind industry by revealing relevant foreground and background parameters related to the development of offshore wind turbines and offshore wind supply chains using prospective databases. The study provides a framework to identify components or lifecycle phases with high environmental impacts and to spot opportunities for improvement. These improvements may relate to the technology itself or to the quality of datasets. The results could indicate which components are more likely to improve their environmental performance. At the same time, the study contributes to deliberating on methodological aspects that future-oriented LCA studies might require improvements. Although the study exclusively focused on Germany, wind turbines in other regions can be assessed after tailoring to technological choices, wind capacity factors, and prospective inventories according to necessity. This study highlights the need to improve the technical representativeness and accessibility of data to enhance the transparency and communication of LCA results and underscores the significance of examining environmental indicators beyond just the GWP. Finally, these findings can have substantial repercussions at the energy system level, given the increasing installed capacity deployment of wind energy. For this reason, the study recommends incorporating all relevant environmental indicators into energy system models to enhance the representation of offshore wind technologies and their environmental impacts.

Abbreviations

BG	Background system
BMWi	Bundesministerium für Wirtschaft und Energie; engl. German Federal Ministry for Economic Affairs and Energy (translation from 2015)
DD	Direct drive (or gearless)
DD-EESG	Direct drive electrically excited synchronous generator
DD-PMSG	Direct drive permanent magnet synchronous generator
DFIG	Double-fed induction generator
EEG	Renewable Energy Sources Act
ESM	Energy system models
FG	Foreground system
G	Geared
GFPC	Generator full power converter
GFRP	Glass fibre-reinforced polymer
HTS	High-temperature superconductive generator
IAMs	Integrated Assessment Models
LCA	Life cycle assessment
LCI	Life cycle inventory
OWE	Offshore wind energy
OWT	Offshore wind turbine
pLCI	Prospective life cycle inventory
PS	Product system
RCP	Representative concentration pathways
SDF	Scenario difference file
SG	Synchronous generator
SSPs	Shared socioeconomic pathways
WT	Wind turbine

Supplementary Information

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Supplementary Material 1.

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Availability of data and materials
All data generated or analysed during this study are included in this published article [and its supplementary information files].

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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