



Life cycle assessment of external impacts and external costs of a potential offshore wind farm off the Southern African coast

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ABSTRACT

Southern Africa's abundant untapped offshore wind resources present a promising opportunity for advancing the region's transition to cleaner and affordable energy while mitigating climate change. Evaluating potential greenhouse gas (GHG) and non-GHG impacts, together with the life cycle costs associated with offshore wind farms, is critical in determining the overall sustainability of the energy system. By carrying out a life cycle assessment (LCA) of a potential 799.20 MW offshore wind farm, this study aims to fill existing gaps in literature. Findings from the study indicate that climate change impacts contribute 34.61 gCO₂eq/kWh, while human health impacts are the most significant non-GHG impact at 0.49 g/kWh. The offshore wind farm's total life cycle cost ranges from 4.29 to 5.97 ZAc/kWh (2.21–3.08 €/MWh), with a central cost of 5.30 ZAc/kWh (2.73 €/MWh). Lifecycle costs attributed to GHG costs (1.68 ZAc/kWh; 0.86 €/MWh) and human health costs (3.42 ZAc/kWh; 1.76 €/MWh) contribute to 96.5 % of the total central cost. External costs per unit of electricity generated are lower compared to other electricity generation technologies including onshore wind, due to the large generation capacity of the offshore wind farm.

Abbreviations and notations list

AI	Artificial intelligence
C	Construction phase
CO ₂	Carbon dioxide
CSP	Concentrated solar and power
D	Dismantling and disposal phase
GHG	Greenhouse gas
GW	Gigawatt
IoT	Internet of things
kWh	Kilowatt-hour
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCoE	Levelised cost of energy
M	Manufacturing phase
MW	Megawatt
MSW	Municipal solid waste
MWh	Megawatt-hour
NH ₃	Ammonia
NMVOCs	Non-Methane Volatile Organic Compounds
Non-GHG	Non-greenhouse gas
NO _x	Nitrogen oxides
O&M	Operations and Maintenance phase
OWF	Offshore wind farm

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PPM _{co}	Primary particulate matter coarse
PV	Photovoltaic
SO ₂	Sulphur dioxide
T	Transport phase
TWh	Terawatt hour
4IR	Fourth industrial revolution
ZAR	South African Rand
ZAc	South African Cents

1. Introduction

The world's primary energy consumption comes from 81.79 % fossil fuels, 14.21 % renewables, and 3.99 % nuclear [1]. With about 40 % of global carbon emissions occurring from the utilisation of coal, natural gas, and oil for electricity generation, this has led to environmental damages, climate change, impacts on crops, biodiversity, and materials [2]. The increase in electricity demand globally is due to population growth and the fourth industrial revolution (4IR) which is attributed to cloud computing, industrial internet of things (IoT), artificial intelligence (AI), automating manufacturing processes, etc., majorly from

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fossil fuels [3]. With the instability of fossil fuel prices, increasing energy demand, and the need to mitigate greenhouse gas (GHG) emissions globally, renewable energy sources have increased support from developed and developing economies regarding their development and deployment over the past decade [4]. Even though renewable technologies are now being deployed to mitigate GHG emissions, there remains a gap in the literature about the non-GHG emissions (impact on human health, biodiversity, crops, and materials) over the life cycle of renewable energy systems (wind, tidal, solar PV, biomass, etc.) [5,6].

Prior studies that focused on LCAs of wind power generation have not addressed these gaps in the literature, not only within Sub-Saharan Africa but in Africa at large. Studies conducted by Refs. [7–13] to mention a few have been assessing the GHG and non-GHG impacts without quantifying the cost of impacts. The LCA of a potential offshore wind farm was ventured into in this study due to the rapid advancement in wind power design and development as well as being the most profitable and industrially mature offshore renewable energy source [14].

Offshore wind energy has been used to generate electricity based on the abundance of wind energy resources, which can mitigate carbon emissions and advance renewable energy integration with significant expansion in recent decades [15,16]. The overall sustainability of offshore wind turbines is still being studied in terms of their environmental LCA, premised majorly on assessing the GHG impacts associated with the technology. Deployment of offshore wind farms has increased rapidly worldwide in the past several years, with it becoming the most attractive renewable energy source, based on its technology readiness level, manufacturing readiness level, and systems readiness level [17]. Generally, the technology has matured requiring less installation time compared to other renewable energy technologies, and a significant reduction in wind energy's levelised cost of energy (LCoE) by about 56 % between 2010 and 2020 [18].

South Africa is leading the renewable energy transition on the African continent and Southern Africa, with at least 6.2 GW of onshore wind power installed capacity, and now being among the first on the continent to exploit the potential of integrating offshore wind into its energy mix, harnessing from its estimated 504 GW of offshore wind energy potential [19]. It will be beneficial to stakeholders to have a detailed scientific analysis of both the GHG and non-GHG impacts and external life cycle costs (GHG and non-GHG) of a potential offshore wind farm off the southern coast of Africa.

Developments in wind energy over the past decade have been particularly rapid. There has been an unprecedented increase in electricity supply from wind energy attaining 2000 TWh in 2022, accounting for over 7 % of the global electricity supply [20]. Over the 10-year period of 2010–2020, onshore wind increased from 178 GW to 699 GW, while offshore wind has proportionately increased at a higher rate from 3.1 GW to 34.4 GW [18]. This underscores the rapid adoption and deployment of wind energy, making it the renewable energy source with the largest installed capacity globally [21,22].

However, wind farms both onshore and offshore accompany environmental impacts such as greenhouse gases (GHGs) that lead to global warming, and non-GHG impacts on human health, biodiversity, materials, and crops, throughout the life cycle of the wind technology from materials extraction, manufacturing, transportation, construction, operation and maintenance (O&M), dismantling, recycling, and disposal [23]. This is based on the utilisation of fossil fuels in each of the life cycle phases of the wind power facility [24,25].

GHG and non-GHG impacts, in addition to external costs during the life cycle of a product, system, or service from the extraction and manufacturing, transportation, utilisation, maintenance, recycling, dismantling, and disposal, are assessed using a quantitative method termed as life cycle assessment (LCA) [26,27]. LCA comprehensively addresses a product's environmental impact, and when only a few processes are evaluated, it is useful to avoid partial optimisation [28]. For about two decades now, there has been a wide adoption of LCA to assess the life cycle impacts of various systems and products such as

wind power plants (onshore and offshore), concentrated solar and power (CSP), biomass, etc. [28] developed a life cycle model to evaluate the environmental impacts of electricity generation, including wind power, concerning conditions in Europe. Likewise, LCAs to assess the environmental impacts of wind power recently focused on GHG emissions on the country level (e.g., China, USA, UK, Spain, Germany, Italy, etc.) have been evaluated [12,25,29–33].

A comparison of environmental LCAs for offshore and onshore wind power has been conducted by various studies. From these studies, there has been a collective consensus that offshore wind power plants demonstrate higher Global Warming Potential (GWP) per electricity output (kWh) and have a longer energy payback period than onshore wind plants [7,26,34]. [26] highlighted that moving from onshore to offshore proffers great benefits which should be considered, as offshore areas have higher wind resources which allow for the deployment of larger wind turbines. Studies by Refs. [35,36] have shown that based on the economics of scale, there is the possibility of lower GHG emissions from offshore wind farms compared to onshore wind farms. LCA studies on offshore wind farms (OWFs) in Africa are scarce and unavailable for the southern coast of Africa [37]. performed an LCA for four (4) offshore wind turbines rated between 1 and 1.67 MW in Ethiopia, the climate change environmental impact was determined to be 33.6 gCO₂eq, whereas they did not consider the life cycle non-GHG impacts [38]. evaluated the environmental impact of a proposed 20 MW offshore wind turbine along the coast of Libya, but the study only focused on the GHG impacts without considering the non-GHG impacts over the life cycle of the project [39]. determined the environmental impact and LCoE for a proposed 100 MW offshore wind farm in Kenya, with the investigation being limited to GHG impacts. Moreover, the LCA studies conducted solely focused on GHG impacts without considering the non-GHG impacts such as human health, biodiversity, and effects on materials and crops.

There are costs associated with power plants throughout their life cycle, such as capital costs, operation and maintenance (O&M) costs, transportation costs, decommissioning and disposal costs, recycling costs, overhead costs, etc. However, there are other unaccounted costs arising from environmental and societal impacts, which are termed as external costs [40]. These costs are multifaceted, occurring from diverse factors such as climate change, impacts on human health, and effects on materials and crops [41–44]. External costs are either local or global, as characterised by Ref. [45]. Local effects are determined by a particular location and include costs associated with environmental and health effects. In contrast, climate change brought on by GHGs is considered a global impact, regardless of location [22,46–48]. When comparing nuclear and renewable to fossil fuel power plants, various studies have assessed the life cycle cost and environmental impacts [20,45,49–54]. While studies extending to the South African power system, with a specific focus on concentrated solar and power (CSP) [40], coal [55,56,58], onshore wind [57], and nuclear power [55,56] has been carried out, no study has delved into the life cycle GHG and non-GHG impacts, and the external costs of offshore wind farms.

This study, utilising a potential 799.2 MW jacket platform offshore wind farm off the coast in Southern Africa as a case study, fills in the scientific gap in the literature by.

- (1) assessing the life cycle GHG and non-GHG impacts for the offshore wind farm;
- (2) estimating the life cycle costs of GHG and non-GHG impacts associated with the offshore wind farm;
- (3) its uniqueness from an African and a developing country context, in converting external impacts into external costs for an offshore wind power plant.

The innovation of the study lies in integrating methodologies of life cycle impact analysis, life cycle impact costing, and energy technology environmental analysis within the context of an offshore wind farm in

Southern Africa. The study develops a robust framework for analysing external costs across life cycle phases of wind power generation, based on the known effectiveness of LCA methodology. The study also highlights the significance of offshore wind off the Southern African coast, as well as the need to take externalities into account in research, energy policy formulation, and decision-making by potential investors. Our study also contributes towards investor and policy decision-making via insights from GHG and non-GHG impacts, as well as life cycle costs of offshore wind energy off the southern coast of Africa.

The rest of the paper is organised in the following manner: Section 2 is about the technology type and LCA framework, where the offshore wind farm site, wind turbine, and platform will be presented, followed by the LCA framework, data and assumptions utilised for the study, and external costs. Section 3 presents the results of the LCA analysis via the GHG impacts, non-GHG impacts, and life cycle external cost per kWh of electricity produced by the offshore wind power plant. The section also discusses the results of the GHG impacts, non-GHG impacts, and external costs. The paper concludes with Section 4 summarising the outcomes of the study and making recommendations for further study.

2. Technology type and LCA framework

Depending on the depth of water, offshore wind farms (OWF) are classified as shallow (0–30m), transitional (30–60m), and deep (50–200m) [59]. The depth of water is a major determinant in selecting a particular offshore wind turbine platform. Fixed base platforms are utilised for shallow water because of their technical and economic feasibility. Because of the technical and economic limitations of fixed base platforms, floating substructures have been developed for deep water to overcome these challenges.

2.1. Offshore wind farm site and technology

Table 1 highlights the various offshore wind turbine platforms, sea depth requirements, and the corresponding turbine capacity. From Table 1, the monopile platform is used in shallow water depths of 0–30m and supports wind turbines that have a power rating of 1–2 MW [60]. The jacket wind turbine is used in transitional waters of 25–50m deep and supports turbines of 2–5 MW capacity [61]. Furthermore, the tension leg platform (TLP) and semi-submersible are floating-based platforms used in deep water that is beyond 50m [59]. These platforms can support offshore wind turbines that have a power rating of up to 10 MW [62]. Finally, the spar platform is a floating base and is used for water depths above 120m, while being able to support turbines with a 5–10 MW power rating [63]. In addition to the offshore wind turbine structures already mentioned, there are emerging platforms being developed to withstand harsh weather conditions. Moreover, there are platforms designed to integrate both offshore wind and solar photovoltaic (PV) systems on the same structure. Fig. 1 illustrates the various types of offshore wind platforms, with the monopile support structure being a large diameter pile driven into the seabed, the jacket support has many legs connected by bearings, while the TLP structure is a vertical moored floating structure tied to the seabed. The semi-submersible platform has large floating hulls that spread out from the tower and are anchored by a mooring system and the spar support structure is a long hollow cylinder

Table 1
Types of offshore wind turbine platforms with corresponding sea depth [60–62].

Platform type	Sea depth (m)
Monopile	0–30
Jacket	25–50
Tension Leg Platform (TLP)	>50
Semi-submersible	>50
Spar	>120

extending from the turbine tower, which is anchored with a mooring line, that floats vertically and with a ballast to reduce the center of gravity of the wind turbine.

South Africa has huge offshore wind energy potential, both in shallow and deep waters [19,64,65]. A study by Sibusiso and Thopil [64] which compared 3 international sites with 4 sites in South Africa, highlighted that South Africa can bolster its power supply by harnessing its rich offshore wind sites [19]. estimated the wind potential of four offshore wind sites in Saldanha Bay, Port Elizabeth, Durban, and Cape Town. The sites showed immense offshore wind potential. A study by Ref. [65] estimated that 44.52 TWh (9.23 GW) of energy can be produced in the shallow water of South Africa at depths below 50m and 2387.08 TWh (495 GW) in the deep sea at depths less than 1,000m, with the Richards Bay area (40–60m) being the optimal offshore wind site as shown in Fig. 2. The Richards Bay area being the optimal site based on its proximity to the nearby port and an existing 820 MW substation infrastructure. Another study by Ref. [66] estimated that South Africa has the potential to produce 189.2 TWh and 2.821 TWh for shallow and deep waters, respectively. The World Bank estimated South Africa's potential to generate electricity from fixed-base offshore wind turbines at 57 GW and 589 GW from floating turbines [67].

This study has adopted the Richards Bay (40–60m) area being the optimal offshore wind site location, as stated by Ref. [65]. With an existing 820 MW substation and the potential to generate 9.23 GW from shallow water, a jacket base platform was selected to support a 3.6 MW Siemens turbine (SWT-3.6-107) based on the sea depth and turbine capacity criteria in Table 1. The GHG and non-GHG LCA, together with the life cycle cost assessment, was based on a 799.2 MW (accounted by 222 S offshore turbines with 3.6 MW power rating) jacket platform offshore wind farm based on the above-mentioned shallow water wind potential and existing substation.

2.2. Framework for LCA

The environmental sustainability of a product or system over its life cycle is determined by the utilisation of the LCA framework. The life cycle phases of the product or system involve extraction/manufacturing, transportation, operation and maintenance (O&M), and disposal. For the results of the LCA to be consistent, reliable, and credible, the ISO 14040 standard was adopted for this study. The ISO 14040 standard ensures that results are reliable and comparable with different studies. In Fig. 3, the adopted ISO 14040 standard is represented. The LCA 14040 standard is based on 4 phases, which include: Goal and Scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. Whereas Fig. 4 highlights the offshore wind farm system's boundary that incorporates all the phases of the LCA. The modeling and simulation of the LCA in determining impacts was conducted using the licensed Sphera software [70].

• Goal and Scope

In this phase of the 14040 standards, the study's aim is defined, including the specification of the functional unit, identification of system boundaries, allocation procedures, impact categories, LCI models utilised, and data quality requirements. Precisely defining the functional unit is essential for LCA as it acts as a benchmark for comparing system performance, facilitating the comparison of fundamentally dissimilar systems. This is a standard practice in the LCA of wind power, where quantifiable flows are associated with a reference unit, typically a single unit of electricity output (kWh or MJ). This study's goal is to conduct an LCA for a potential offshore wind farm off the southern coast of Africa, employing these established parameters to ensure accurate and reliable comparisons.

The end-of-life phase for this study accounts only for the decommissioning of the wind farm, based on data limitation of recycling methods used for offshore wind infrastructure due to the novelty and

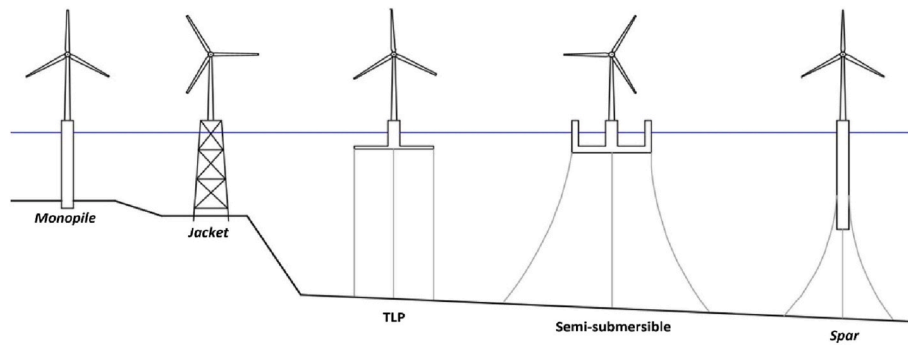


Fig. 1. Types of offshore wind turbine platforms [68].

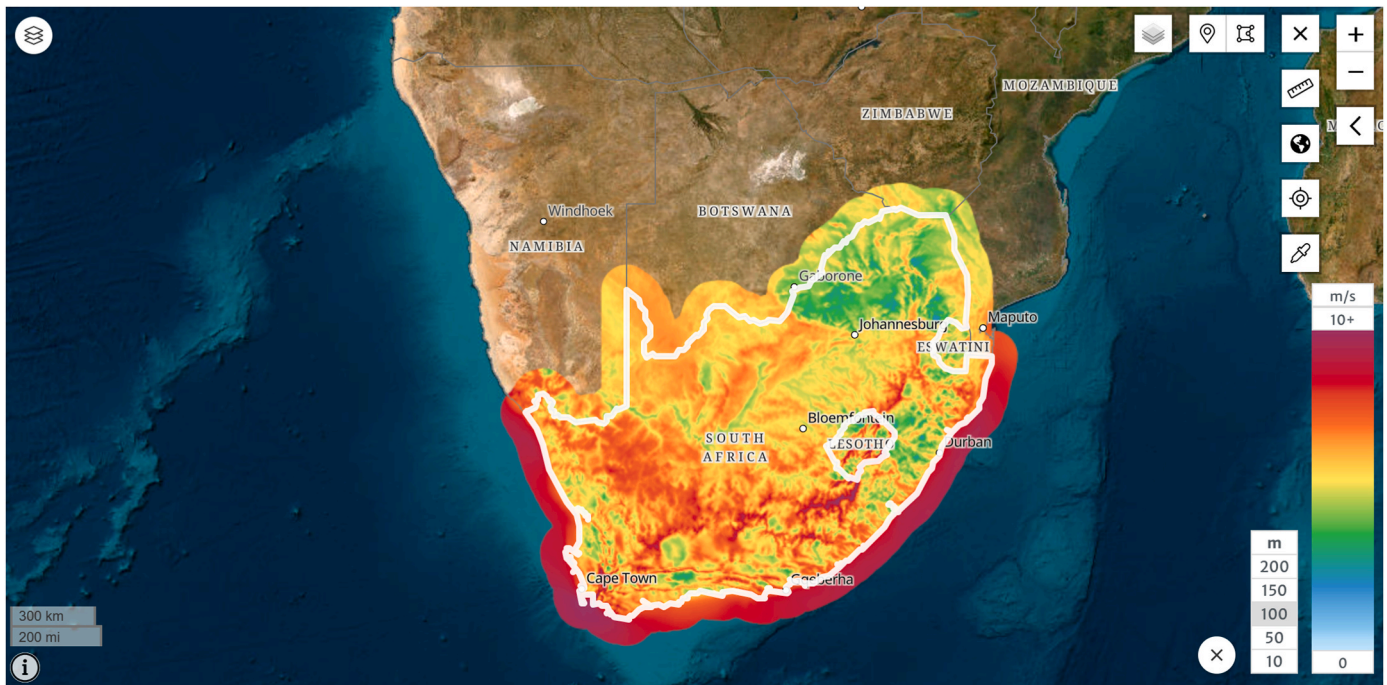


Fig. 2. Offshore wind potential off South Africa's coastline [69,84]

longevity of these systems. The scope of the study is a cradle-to-grave LCA for the 799.2 MW offshore wind farm off the coast of Richards Bay area in South Africa.

- Life cycle inventory (LCI) analysis

In the life cycle inventory analysis phase, data from Ecoinvent and literature on energy, materials, emissions, distance, etc., are collected to quantify the inputs and outputs of the offshore wind farm as presented in Appendix (Table A.1). This consists of data on energy consumption, materials used, waste generated, emissions released, and other relevant factors. These data points are validated and normalised relative to the functional unit, ensuring consistency and accuracy throughout the assessment process. This phase provides a comprehensive understanding of the environmental impacts associated with the offshore wind farm, laying the groundwork for the subsequent phase where these impacts will be evaluated and interpreted.

- Life cycle impact assessment (LCIA)

The LCA analyses the environmental impacts across all stages of the offshore wind farm's life cycle, encompassing raw material extraction,

manufacturing, usage, maintenance, recycling, and disposal. It tracks emissions, resource use, and energy consumption from the initial acquisition of raw materials through to the eventual disposal or recycling of materials, providing a comprehensive assessment of environmental burdens associated with the entire life cycle of the product or system. This holistic approach ensures that the GHG and non-GHG impacts associated with developing an offshore wind farm in South Africa are considered, facilitating informed decision-making towards sustainable practices and resource management.

- Interpretation

In this study, the interpretation phase will analyse the outcomes of the LCA, aligning them with the predefined goals and scope of assessing the offshore wind farm. This phase includes verifying the consistency, completeness, and accuracy of the results specific to the environmental impacts associated with the wind farm's life cycle phases, providing insights crucial for sustainable development and resource management strategies.

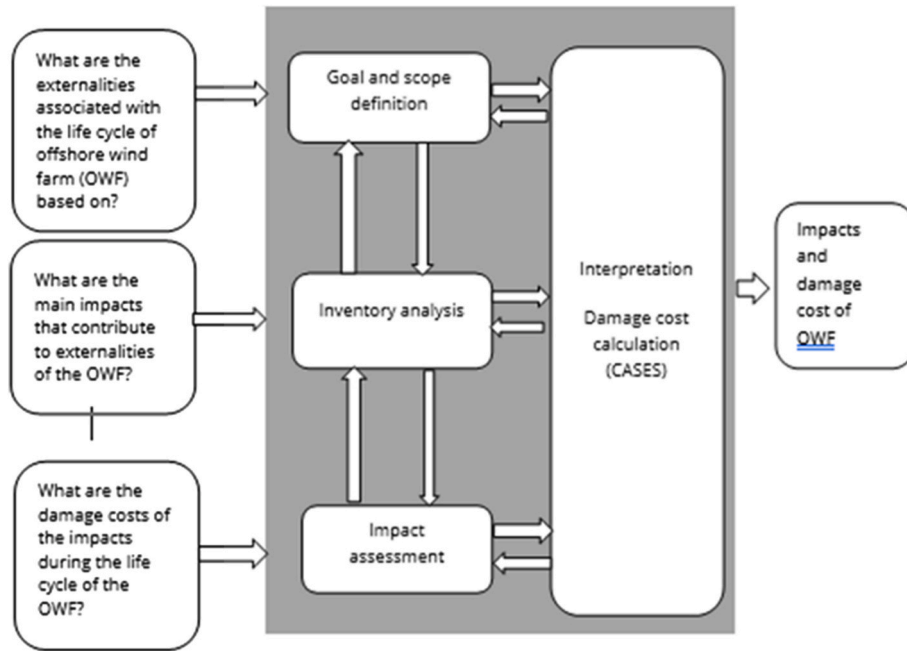


Fig. 3. Framework adopted for the study, ISO 14040 [27].

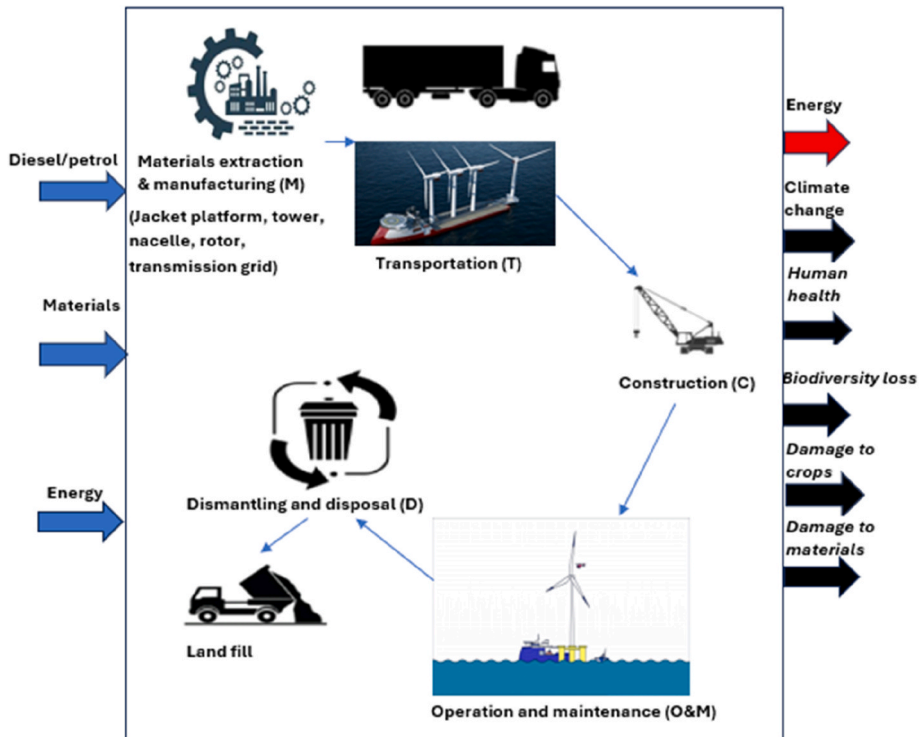


Fig. 4. Offshore wind farm ISO 14040-43 life cycle system boundary.

2.3. LCA stage data assumptions

This section details the life cycle process, data and assumptions utilised to assess the GHG and non-GHG impacts, and life cycle costs to assess the potential 799.2 MW offshore wind farm in the Richards Bay area.

2.3.1. Manufacturing (M) phase

This phase entails both the extraction of materials and the

manufacturing of parts. The parts of the offshore wind turbine include the jacket platform, tower, transmission grid, nacelle, cables, rotor, stator, and gearbox. In Table A. 1 (appendix), materials data for this study were sourced from the manufacturer and literature. The Siemens turbine used for this study has a power rating of 3.6 MW (SWT-3.6-107) (222 in number). The manufacturing phase of the LCA involves extracting and manufacturing the wind turbine’s components (jacket platform, tower, transmission grid, nacelle, cables, rotor, stator, and gearbox). The LCA tool (Sphera software) was utilised to assess

emissions, representing each major system as an individual plan [70]. The component materials are used to illustrate the processes and required flows for manufacturing in each phase, with emissions calculated and documented accordingly.

2.3.2. Transportation (T) phase

The transportation of materials and equipment for the wind farm requires substantial involvement from maritime shipping and road transportation. Several plans were contained in the LCA model for the offshore wind farm, each plan included a transport component along with estimated distances. The wind turbine components are delivered by sea from Cuxhaven, Germany, to the port of Richards Bay in South Africa (15,777 km). The assessment of transport energy considers the hourly energy consumption of vessels or trucks while also accounting for relevant environmental emissions from the diesel burned using emission factors from the Ecoinvent database.

2.3.3. Construction (C) phase

At this phase, the parts of the offshore wind turbine, which will be shipped pre-assembled to the Richards Bay offshore site, and the jacket platform for the wind turbine will be installed on-site. These parts are imported from Germany and not produced locally in South Africa. Fuel consumption during the construction phase, including the use of equipment such as cranes, is also considered. The LCA model encompasses various scenarios for the wind turbine's key components, with detailed data for this phase provided in Table A.1 (Appendix).

2.3.4. Operation and maintenance (O&M) phase

The greasing, repairing, and replacing parts such as turbine blades, bearings, gearboxes, generators, lubricants, and more are the main duties associated with maintaining the offshore wind farm. As per the wind turbine maintenance recommendations, it is expected that each offshore wind turbine will undergo a few scheduled maintenance sessions and experience up to four unplanned maintenance events annually. This pattern persists throughout the anticipated 20-year lifespan of a wind turbine. In Table A.1 (Appendix), the materials required during the operation and maintenance (O&M) phase are represented.

2.3.5. Dismantling and disposal (D) phase

The disposal phase considers that after decommissioning, blades and concrete are disposed of in landfills as part of municipal solid waste (MSW), since South Africa mostly uses landfills for waste disposal, steel, iron, and copper will be recycled. However, the lubricant was deemed hazardous and was returned to the manufacturer, and the transportation component was also considered in the modeling. These materials inputs are shown in Table A. 1 (Appendix).

2.4. Life cycle costing of GHG and non-GHG impacts

In determining the life cycle external cost of the offshore wind farm, we adopted the methodology of [40], by multiplying each GHG and non-GHG impact with the corresponding unit cost attributed to GHG marginal cost, human health, biodiversity, and effect on crops and materials. The unit cost was adopted from the CASES (2008) [71] dataset.

The emissions associated with each impact over the LCA of the offshore wind farm are subcategorised and described in Table 2. The climate change emissions-related external cost was computed using the marginal damage cost provided by CASES (2008) [71] in Table 3, whereas human health, biodiversity, effects on crops, and materials-related pollutants are shown in Table 4. The June 2024 exchange rate of €1 to R19.4 was used for the conversion between the Euros (€) and South African Rand (R) in this study to adjust to the regional requirements.

Therefore, this current exchange rate (€ to R) was used in converting marginal damage costs related to GHG emissions in Table 3, and

Table 2
Emissions for non-GHG impact subcategory.

Subcategories of external costs	Description
Climate change	Global externalities include the costs associated with climate change, which are caused by GHG emissions (CO ₂).
Human health	Emissions of Non-Methane Volatile Organic Compounds (NMVOCs), ammonia (NH ₃), NO _x , sulphur dioxide (SO ₂), and primary particulate matter (PPM) in the 2.5 (PM _{2.5}) to 10 (PM ₁₀) micron range are responsible for the expenses linked to human mortality and morbidity. These emissions have both local and global health effects.
Loss of biodiversity	Emissions, such as ammonia (NH ₃), NMVOCs, NO _x , PPM, and sulphur dioxide (SO ₂), are the cause of the expense associated with adverse environmental effects.
Effect on crops	Crop damage and positive externalities resulting from emissions of NH ₃ , NMVOCs, NO _x , and SO ₂ are evaluated in terms of cost. The emissions are linked to the effects on crops, both local and non-local (global).
Effects on materials	The cost incurred from the deterioration of buildings, infrastructure, and materials results from the emission of sulphur dioxide (SO ₂), which, in turn, gives rise to acid rain, causing corrosion. Additionally, nitrogen oxides (NO _x) contribute to the damaging effects.

Table 3
GHG emissions marginal costs CASES (2008) [71].

	Low cost	Central cost	High cost
€/t CO ₂ eq.	10	25	35
R/t CO ₂ eq. ^a	194	485	679

^a Exchange rate of €1 to R19.4 (June 2024 rate), was used for the conversion between the Euros (€) and South African Rand (ZAR) in this study. The ZAR is a volatile currency, affected by commodity prices and geopolitics. Thus, exchange rates should be treated within context and with caution.

Table 4
Emission costs (2024) [40,71].

Country: European Union (EU-27) €/kg	ZAR/kg	
Human health		
Ammonia (NH ₃)	4.7	91.180
Non-methane volatile organic compounds (NMVOC)	0.191	3.705
Nitrogen oxides (NO _x)	5.334	103.480
Primary particulate matter coarse (PPM _{co} ^a)	1.112	21.573
Primary particulate matter (PPM _{2.5} ^b)	19.422	376.787
Sulphur dioxide (SO ₂)	5.376	104.294
Loss of biodiversity		
Ammonia (NH ₃)	2.771	53.757
Nitrogen oxides (NO _x)	0.729	14.143
Sulphur dioxide (SO ₂)	0.162	3.143
Effect on crops		
Non-methane volatile organic compounds (NMVOC)	0.062	1.203
Nitrogen oxides (NO _x)	0.263	5.102
Effect on materials		
Nitrogen oxides (NO _x)	0.042	0.815
Sulphur dioxide (SO ₂)	0.153	2.968

^a Primary Particulate Matter "coarse" with an aerodynamic diameter smaller than 10 mm but larger than 2.5 mm (PPM_{co}).

^b In the CASES (2008) (European Commission, 2008) study, in certain instances PM_{2.5} is also referred to as PM₂₅.

pollutants of the non-GHG impact categories in Table 4. The categorisation of non-GHG unit pollutant cost in Table 4 is subcategorised into four different impact groups (human health, loss of biodiversity, effect on crops and materials) based on the relative contributions of different pollutants (ammonia (NH₃), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), primary particulate matter 2.5 µm diameter or less (PPM_{2.5}), primary particulate matter coarse (PPM_{co}), aerodynamic diameter smaller than 10 mm but larger than 2.5 mm, and

sulphur dioxide (SO₂) CASES (2008) [71].

3. Results and discussion

The results from the simulation of the 799.2 MW jacket platform OWF are presented and discussed in this section. The first part presents the findings of the GHG and non-GHG life cycle impacts. The second part presents the life cycle costs. The results were normalised to a functional unit of 1 kWh, which makes it easier for analysis and comparison, based on the ISO (2006) [71] standards.

Capacity factors are an important performance metric for offshore wind energy projects, as they indicate how efficiently a given project generates electricity [72]. The OWF will produce 2,660,376.96 MWh of energy based on the OWF's assumed design specifications. It was considered that the OWF would have the capacity to generate 799.2 MW of electricity, with a capacity factor of 38 %. Over the moderate 20-year life span of the wind farm, the total electricity production will attain 53,207,539.2 kWh. The life cycle impacts (GHG and non-GHG) presented in Table 5 were calculated by dividing both the GHG and non-GHG impacts obtained from the Sphera LCA tool by the total amount of energy produced over the life span of the OWF (53,207,539.2 kWh). As already stated, this will allow for easy analysis and comparisons between various results.

A breakdown of the GHG and non-GHG impacts in each life cycle phase (manufacturing-M; transportation-T; construction-C; operation and maintenance-O&M; disposal-D) is shown in Table 5. This breakdown identifies areas where costs and emissions can be reduced, allowing one to fully understand how each phase of the life cycle contributes to the overall environmental impact.

The total GHG impact of the OWF is 34.611 g/kWh which is distributed over the various life cycle phases: M: 12.613 g/kWh; T: 5.282 g/kWh; C: 2.842 g/kWh; O&M: 10.788 g/kWh; D: 3.086 g/kWh. The manufacturing life cycle phase is the most emissions-intensive for the GHG impact category, contributing 36.4 % of total emissions (12.613 g/kWh), closely followed by the O&M phase with 31.2 % (10.788 g/kWh). This is a result of the energy-intensive production of steel, neodymium, cast iron, epoxy resin, fiberglass, and cast iron for the manufacture of vital parts such as the rotor and stator for the wind turbine, and the jacket base for mounting the offshore wind turbine. The manufacturing process of these components involves significant fossil fuel consumption and emissions of CO₂ during material extraction, processing, and component fabrication. The O&M phase is emissions-intensive because O&M activities are carried out over the life span of the wind farm (20 years), including vessel operations to convey people, equipment (cranes), replacement of parts, and repairs, all diesel-powered, and lead to CO₂ emissions.

The life cycle costs (GHG and non-GHG) are presented in Table 6, which have been calculated by multiplying each GHG and non-GHG impact with the corresponding unit cost attributed to GHG marginal cost, human health, biodiversity, and effect on crops and materials. The

Table 5
Offshore wind farm impacts over the life cycle.

Impacts over the life cycle of the jacket platform offshore wind farm						
GHG and non-GHG subcategory	Impact (g/kWh)	Impact per life cycle phase (g/kWh)				
		M	T	C	O&M	D
Climate change (GHG eq.)	34.611	12.613	5.282	2.842	10.788	3.086
Human health	0.490	0.201	0.065	0.022	0.120	0.082
Loss of biodiversity	0.228	0.063	0.028	0.014	0.065	0.058
Effects on crops	0.228	0.057	0.031	0.013	0.072	0.056
Effects on materials	0.213	0.058	0.027	0.013	0.059	0.056
Total non-GHG	1.159	0.279	0.150	0.061	0.316	0.252

unit cost was adopted from the CASES (2008) [71] dataset.

Fig. 5 illustrates the combined GHG impacts together with the central GHG life cycle cost. It can be seen that the GHG impacts are proportional to the life cycle cost, with the manufacturing phase (0.612 ZAc/kWh) having the highest cost, followed by the O&M (0.523 ZAc/kWh). These phases contribute significantly to both the environmental impact and life cycle cost of the GHG subcategory. These impacts can be reduced through efficient maintenance schedules, using renewable energy sources instead of fossil fuels for operational needs, and enhancing the reliability and durability of components to reduce the frequency of repairs and replacements. This will optimise the overall sustainability of the OWF. Additionally, incorporating cutting-edge technologies like digital monitoring systems and predictive maintenance can further optimise resource usage, reduce waste, and boost operational efficiency, ultimately resulting in an offshore wind farm (OWF) that is more economical and sustainable [73].

The transportation phase accounts for 15.3 % of total GHG emissions (5.282 g/kWh), while the construction and decommissioning phases account for 8.2 % (2.842 g/kWh) and 8.9 % (3.086 g/kWh), respectively. The transportation phase entails the sea shipment and road transportation of the assembled offshore wind turbines with the base platform to the offshore installation site, which is from Germany to the port of Richards Bay in South Africa. The emissions of the transportation phase primarily arise from the utilisation of fossil fuels for sea and land shipment. Optimising logistical routes and using more efficient shipping methods will lead to improved environmental sustainability of the offshore wind farm. The emissions from the construction phase arise from the assembly and installation of the wind farm components at the offshore site, which involves the use of cranes, machinery, and vessels. Innovating how the offshore wind turbines are installed in construction methodologies and the possible utilisation of low-emission equipment can aid in mitigating emissions. Decommissioning, being the final phase of the life cycle, involves dismantling the wind farm, transporting materials for recycling or disposal. Maximising material recovery and improving the efficiency of the recycling process can reduce the carbon footprint associated with this phase.

The non-GHG impact over the life cycle of the OWF is shown in Fig. 6. The total non-GHG impact is 1.159 g/kWh, distributed across several subcategories: Human Health, Loss of Biodiversity, Effects on Crops, and Effects on Materials. Each subcategory is analysed across the life cycle phases.

The total human health impact over the life cycle of the OWF is 0.490 g/kWh. The manufacturing phase has the highest human health impact (0.201 g/kWh) due to emissions of particulate matter (PM), nitrogen oxides (NO_x), sulphur oxides (SO_x), and volatile organic compounds (VOCs) from industrial activities. These pollutants contribute to respiratory and cardiovascular diseases. The O&M phase also has a significant impact (0.120 g/kWh), stemming from ongoing emissions during maintenance activities. Reducing these impacts could involve stricter emission controls, cleaner production technologies, and improved occupational health and safety standards. The human health impacts over transportation, construction, and decommissioning are 0.065 g/kWh, 0.022 g/kWh, and 0.082 g/kWh respectively.

The loss of biodiversity non-GHG impact is the most significant in the manufacturing (0.063 g/kWh) and O&M phases (0.065 g/kWh). The primary contributors to the loss of biodiversity are habitat disruption as a result of raw material extraction and operational noise, with pollution. The decommissioning and disposal phase also has a moderate impact of 0.058 g/kWh, due to habitat disruptions during dismantling activities. The strategies to mitigate these challenges include adopting biodiversity-friendly practices, conducting environmental impact assessments, and implementing conservation measures.

The effect on crops' non-GHG impact is highest in the manufacturing (0.057 g/kWh) and O&M phases (0.072 g/kWh). The NO_x and SO_x pollutants affect crop yields and soil quality. Overall, the results underscore the manufacturing phase's crucial role in determining

Table 6
Offshore wind farm life cycle costs.

	Impact (g/kWh)	External costs ZA c/kWh	M	T	C	O&M	D
Climate change (GHG eq.)	34.611	0.671 (Low) 1.679 (Central) 2.350 (High)	0.245 0.612 0.856	0.102 0.256 0.359	0.055 0.138 0.193	0.209 0.523 0.732	0.060 0.150 0.210
Human health	0.490	3.432	1.406	0.453	0.154	0.841	0.578
Loss of biodiversity	0.228	0.162	0.045	0.020	0.010	0.046	0.041
Effect on crops	0.228	0.014	0.004	0.002	0.001	0.005	0.004
Effect on materials	0.213	0.008	0.002	0.001	0.000	0.002	0.002
Total non-GHG	1.159	3.616	1.457	0.476	0.165	0.894	0.624
Total External Cost	-	4.288 (Low) 5.295 (Central) 5.967 (High)	1.702 2.069 2.313	0.578 0.732 0.834	0.220 0.303 0.358	1.104 1.418 1.627	0.684 0.774 0.834

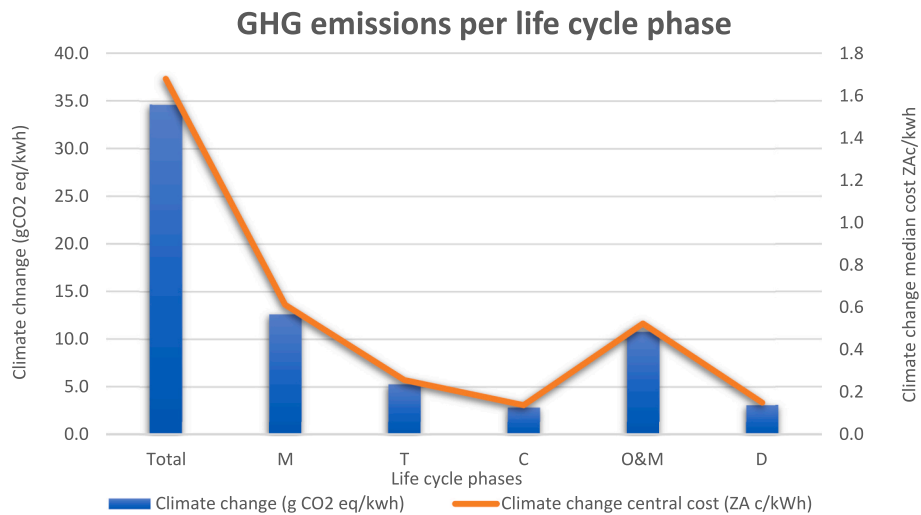


Fig. 5. GHG emissions (gCO₂eq/kWh) per life cycle impact (ZAc/kWh).

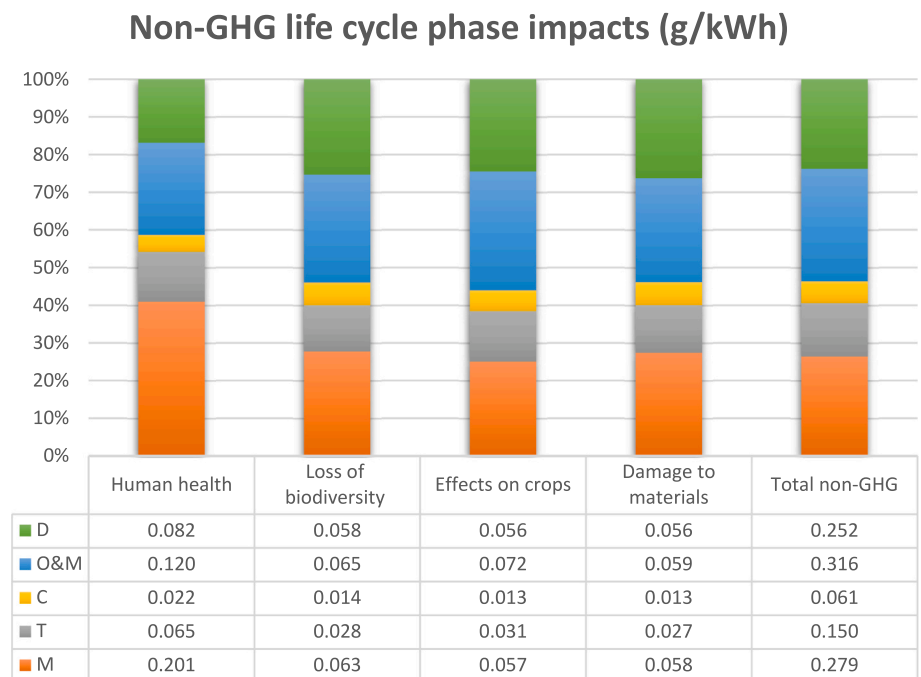


Fig. 6. Non-GHG life cycle impacts (g/kWh).

environmental impacts and show its significance across a range of sub-categories across the wind farm's life cycle. The decommissioning and disposal phase also contributes to this impact (0.056 g/kWh), through soil disturbance and potential contamination during dismantling. Mitigating these impacts can be achieved by reducing emissions of harmful pollutants through neutralisation of the gases and employing sustainable agricultural practices.

The effect on materials impact is maximum in the manufacturing (0.058 g/kWh) and O&M phases (0.059 g/kWh). This is connected to the wearing out of components and the degradation of protective coatings over time, which release harmful substances. The decommissioning and disposal phase also has a significant impact of 0.056 g/kWh, due to the potential contamination of the environment from the dismantled materials. It was assumed that materials, specifically fiberglass and epoxy resins, would be disposed of by landfilling as an integral part of MSW [74]. South Africa predominantly attributes the disposal of waste towards landfill sites [75]. Excluding hazardous materials, specifically lubricants, was imperative due to their classification as hazardous materials. These substances are systematically returned to the manufacturer, adhering to stringent safety protocols associated with their potentially harmful nature [76]. Developing advanced materials with higher resistance to environmental stressors and improving protective coatings can help mitigate these impacts.

In Fig. 7, it is evident that the O&M and manufacturing phases play a critical role in the overall impact of non-GHG emissions, contributing 27.2 % and 24.1 % respectively. Notably, these phases significantly influence the human health category, with substantial contributions to impacts related to loss of biodiversity. In both the O&M and manufacturing phases, effects on crops are significant, while the O&M phase further exhibits significant effects on crops, marginally surpassing the impact on materials. Conversely, in the manufacturing phase, damage to materials is marginally more than the effects on crops.

The life cycle costs of both GHG and non-GHG have been presented in Table 6. Notably, while climate change has substantially larger impacts (34.611 gCO₂eq/kWh) than pollutants impacting human health (0.490 g/kWh), the external life cycle cost associated with human health (3.432 ZAc/kWh) is greater than that of climate change (median of 1.679 ZAc/kWh). This difference is a result of the unit cost adopted from the CASES (2008) [71] dataset, whereby pollutants contributing to human health impacts incur a higher external cost comparison to those of climate change, as seen in Tables 3 and 4. Despite the greater environmental impact of climate change, this disparity emphasises the disproportionate economic burden of the effects on human health, highlighting the necessity of a focused approach to cost mitigation

strategies across all impact categories.

To further elaborate on the non-GHG life cycle costs of the jacket-based offshore wind farm, Fig. 8 illustrates that human health impacts dominate, especially in the manufacturing (1.406 ZAc/kWh) and O&M (0.841 ZAc/kWh) life cycle phases, followed by loss of biodiversity in O&M (0.046 ZAc/kWh) and decommissioning (0.041 ZAc/kWh). The effects on crops and materials are comparatively minimal.

According to the study, overall external costs range between 4.288 (Low), 5.295 (Central), and 5.967 (High). Notably, NH₃, SO₂, and NO_x are the most common emissions across all non-GHG categories. When assessing the effects on crops and materials for offshore wind farms, they have comparatively moderate external costs when compared to human health and biodiversity loss.

Focusing exclusively on the climate change (GHG) subcategory, identified as the primary contributor to environmental impact, a comparative analysis between various studies was carried out. This entails cross-referencing the findings of this study with those presented in Table 7. The results of various LCA's as obtained after a comprehensive literature review, range from 9 to 48 gCO₂eq/kWh. In this study, the GHG environmental impact is 34.61 gCO₂eq/kWh, which falls within the range obtained from the literature. The GHG impact results from this study closely match the range reported in the literature, signifying little variance even with modifications in the research model. This coherence suggests that the results from the current study's climate change category are consistent with those from prior studies. The results' robustness and dependability are further supported by their alignment with earlier research, giving assurance regarding the accuracy of the GHG impact assessment for offshore wind farms.

With the study focusing on the shallow water of South Africa, differences in results are based on assumptions made in transportation requirements, modeling, O&M schedules, data sources, and availability. The influence of these factors on the overall impact results obtained by the harmonisation method further emphasises the need for a comprehensive understanding of the intricacies involved in offshore wind farm studies.

4. Conclusion

This paper presents an LCA of GHG and non-GHG impacts, and external costs of a potential jacket base offshore wind farm in South Africa, which provides critical insights into the environmental and economic implications of offshore wind energy within sub-Saharan Africa and beyond. It was observed from the study that the GHG impact of the OWF was 34.61 gCO₂eq/kWh, which is consistent with the 9 to 48

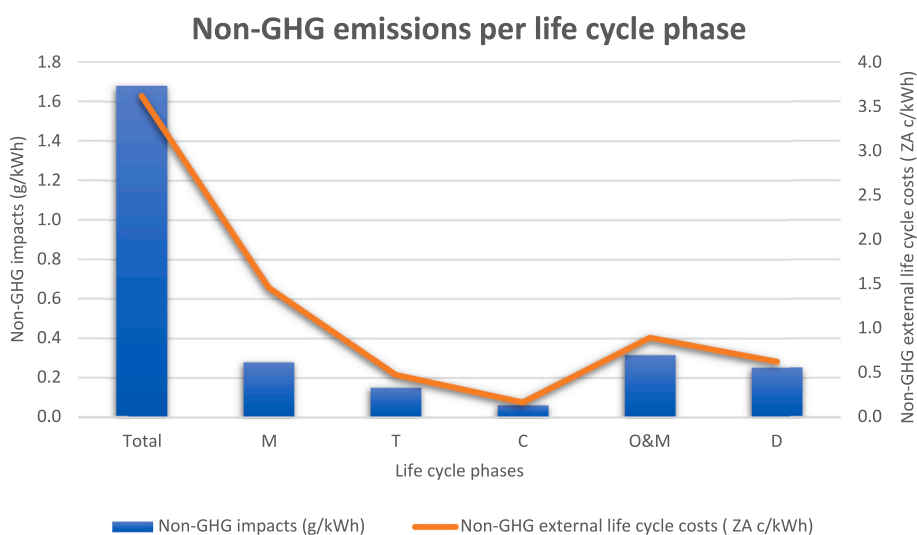


Fig. 7. Non-GHG emissions (gCO₂eq/kWh) per life cycle impact (ZAc/kWh).

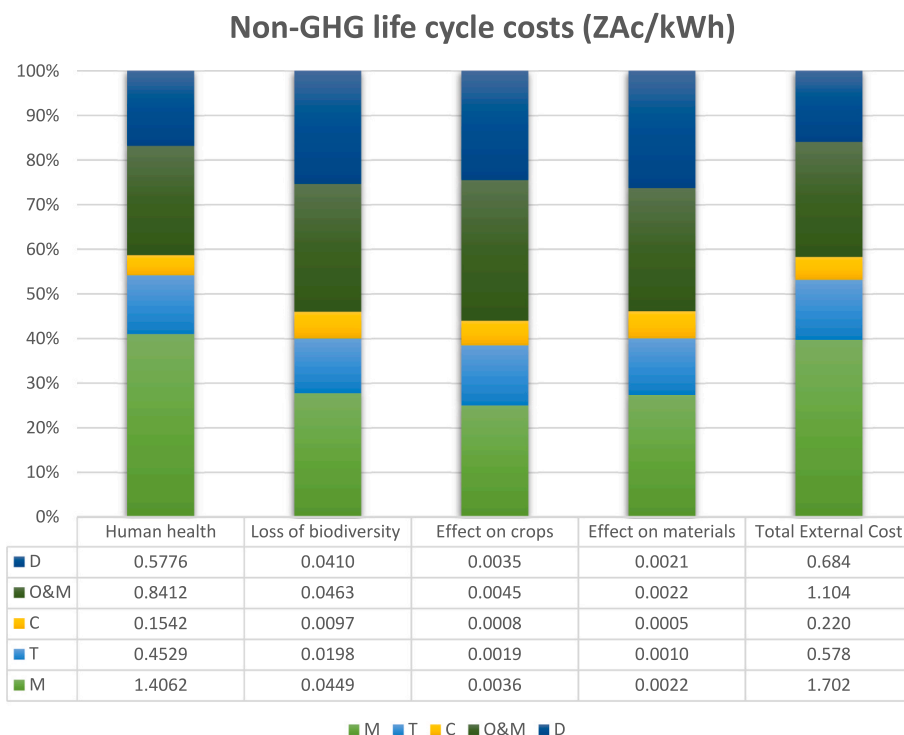


Fig. 8. Non-GHG life cycle costs (ZAc/kWh).

Table 7
LCA of offshore wind farms from literature.

S. No.	GHG impact (gCO ₂ eq/kWh)	Lifespan (years)	Capacity per turbine (MW)	Location	Ref.
1	9	20	6	Denmark	[7]
2	12	20	4	Denmark	[7]
3	17	20	5	Norway	[77]
4	11	20	6	Spain	[78]
5	31.4	20	5	Norway	[77]
6	48	25	6	United Kingdom	[8]
7	25.5	25	3.6	China	[46]
8	30	25	5	Canada	[79]
9	11.8	25	1.5	United Kingdom	[80]
10	13.7	20	2.5	Norway	[81]
11	9.7	20	0.5	Denmark	[11]
12	34.6	20	3.6	South Africa	This study

gCO₂eq/kWh range from the literature (in Table 7). The total non-GHG impacts were obtained as 1.159 g/kWh, with human health impact being the most significant (0.490 g/kWh), mainly from particulate matter, nitrogen oxides, sulphur ISO, 2006 oxides, and volatile organic compounds emitted during the manufacturing (0.201 g/kWh) and operation & maintenance (0.120 g/kWh) phases. There is a need for more emission controls as these pollutants are responsible for respiratory and cardiovascular diseases.

The life cycle external cost attributed to human health is the highest among the other subcategories due to its higher level of significance. The manufacturing phase accounts for 1.406 ZAc/kWh, with the operation & maintenance phase contributing 0.841 ZAc/kWh. Overall, the total life cycle external costs for the OWF range from 4.288 to 5.967 ZAc/kWh, with human health impacts as the most significant. This highlights the need for cleaner production technologies, enhanced emission controls, and improved recycling processes to mitigate offshore wind energy's environmental and economic impacts.

Policymakers and stakeholders aiming to optimise the overall

sustainability of OWF will get critical insights from this study. The specific impacts and costs associated with each phase of the OWF life cycle are being elaborated, and valuable data to the discourse on sustainable energy solutions and their implications for human and environmental health have been contributed by this study. Investors are being provided with essential information for strategic decision-making, reducing environmental and economic risks associated with offshore wind farm investments, which will enhance the project's overall sustainability from this study.

This study's novelty is premised by combining LCA, life cycle costing, and energy technology environmental analysis within an offshore wind context in Southern Africa. However, the investigation in this study is limited to a jacket platform. Future research could look at other support structures such as spar-buoy, semi-submersible, and tension leg platforms, which may produce different results. Additionally, future research should also try to integrate LCA with techno-economic assessments, which will give a more comprehensive understanding of the true costs and sustainability implications of wind power. This will help make informed decisions and encourage sustainable practices in the wind energy sector, highlighting the crucial role of renewables in South Africa's and Africa's energy transition.

CRediT authorship contribution statement

Hanif Auwal Ibrahim: Visualization, Methodology, Writing – original draft, Software, Investigation, Validation, Project administration, Data curation, Writing – review & editing, Formal analysis, Conceptualization. **George Alex Thopil:** Resources, Supervision, Investigation, Writing – review & editing, Validation, Methodology, Funding acquisition, Formal analysis, Visualization, Project administration.

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

Table A. 1
Material inputs for the offshore wind farm LCA [82,83].

Materials	Input	Unit
Steel	4.04×10^{10}	kg
Concrete	1.198×10^9	kg
Cast iron	1.82×10^7	kg
Copper	3.84×10^7	kg
CroMag Steel	1.82×10^7	kg
Stainless steel	9.1×10^8	kg
Ester oil	1.99×10^6	kg
Neodymium	3.99×10^6	kg
Fibreglass (epoxy)	5.01×10^7	kg
Carbon Fibre (epoxy)	5.11×10^7	kg
Polymer	2.22×10^5	kg
Grease	1.8×10^5	l
Coolant	4.88×10^6	l
Nitrogen	2.26×10^7	l
SF6	3.99×10^4	kg
Hydraulic oil	3.51×10^5	l
Gear oil	6.89×10^8	l
Diesel	2.22×10^5	l
Copper wire core	253.8	km
Steel cable	253.8	km
Yarn and tapes	253.8	km
Steel rebar	1.33×10^8	kg
Scrap copper	1.06×10^3	kg
Waste glass	2.56×10^2	kg
Iron scrap, unsorted	2.56×10^6	kg

Data availability

Data will be made available on request.

References

- [1] Energy Institute. Statistical Review of World Energy (2023) – with major processing by our world in Data. “Share of primary energy consumption that comes from fossil fuels – using the substitution method 2023.
- [2] Ibrahim HA, Ayomoh MK, Bansal RC, Gitau MN, Yadavalli VSS, Naidoo R. Sustainability of power generation for developing economies: a systematic review of power sources mix. *Energy Strategy Rev* 2023;47. <https://doi.org/10.1016/j.esr.2023.101085>.
- [3] Çam E, Hungerford Z, Schoch N, Pinto Miranda F, Yáñez de León CD. Electricity 2024 - analysis and forecast to 2026. *Electricity 2024 analysis and forecast to 2026 2024*. <https://doi.org/https://iea.blob.core.windows.net/assets/6b2fd954-2017-408e-bf08-952fdd62118a/Electricity2024-Analysisandforecastto2026.pdf>.
- [4] Ibrahim HA, Ayomoh MK. Identification and prioritization of factors affecting the transition to renewables in developing economies. *Energy Rep* 2022;8:94–104. <https://doi.org/10.1016/j.egy.2022.10.064>.
- [5] Cormos CC, Dragan M, Petrescu L, Cormos AM, Dragan S, Balthori AM, et al. Synthetic natural gas (SNG) production by biomass gasification with CO2 capture: Techno-economic and life cycle analysis (LCA). *Energy* 2024;312. <https://doi.org/10.1016/j.energy.2024.133507>.
- [6] Fang Y, Li X, Ascher S, Li Y, Dai L, Ruan R, et al. Life cycle assessment and cost benefit analysis of concentrated solar thermal gasification of biomass for continuous electricity generation. *Energy* 2023;284. <https://doi.org/10.1016/j.energy.2023.128709>.
- [7] Bonou A, Laurent A, Olsen SI. Life cycle assessment of onshore and offshore wind energy-from theory to application. *Appl Energy* 2016;180:327–37. <https://doi.org/10.1016/j.apenergy.2016.07.058>.
- [8] Garcia-Teruel A, Rinaldi G, Thies PR, Johanning L, Jeffrey H. Life cycle assessment of floating offshore wind farms: an evaluation of operation and maintenance. *Appl Energy* 2022;307. <https://doi.org/10.1016/j.apenergy.2021.118067>.
- [9] Weinzettel J, Reenaas M, Solli C, Hertwich EG. Life cycle assessment of a floating offshore wind turbine. *Renew Energy* 2009;34:742–7. <https://doi.org/10.1016/j.renene.2008.04.004>.
- [10] Tsai L, Kelly JC, Simon BS, Chalal RM, Keoleian GA. Life cycle assessment of offshore wind farm siting: effects of locational factors, Lake depth, and distance from shore. *J Ind Ecol* 2016;20:1370–83. <https://doi.org/10.1111/jiec.12400>.
- [11] Schleisner L. Life cycle assessment of a wind farm and related externalities. *Renew Energy* 2000;20:279–88. [https://doi.org/10.1016/S0960-1481\(99\)00123-8](https://doi.org/10.1016/S0960-1481(99)00123-8).
- [12] Cao Y, Meng Y, Zhang Z, Yang Q, Li Y, Liu C, et al. Life cycle environmental analysis of offshore wind power: a case study of the large-scale offshore wind farm in China. *Renew Sustain Energy Rev* 2024;196. <https://doi.org/10.1016/j.rser.2024.114351>.
- [13] Le ST, Nguyen TN, Bui DK, Ngo TD. Techno-economic and life cycle analysis of renewable energy storage systems in buildings: the effect of uncertainty. *Energy* 2024;307. <https://doi.org/10.1016/j.energy.2024.132644>.
- [14] Saenz-Aguirre A, Saenz J, Ulazia A, Ibarra-Berastegui G. Optimal strategies of deployment of far offshore co-located wind-wave energy farms. *Energy Convers Manag* 2022;251. <https://doi.org/10.1016/j.enconman.2021.114914>.
- [15] Liu S, Li Q, Lu B, He J. Prediction of offshore wind turbine wake and output power using large eddy simulation and convolutional neural network. *Energy Convers Manag* 2025;324. <https://doi.org/10.1016/j.enconman.2024.119326>.
- [16] de Moura Ribeiro A, Hallak PH, de Castro Lemonge AC, dos Santos Loureiro F. Automatic grouping of wind turbine types via multi-objective formulation for nonuniform wind farm layout optimization using an analytical wake model. *Energy Convers Manag* 2024;315. <https://doi.org/10.1016/j.enconman.2024.118759>.
- [17] Musial W, Spitsen P, Duffy P, Beiter P, Shields M, Mulas Hernando D, et al. Offshore wind market report. 2023 Edition 2023.. <https://www.energy.gov/sites/default/files/2023-09/doe-offshore-wind-market-report-2023-edition.pdf>.
- [18] Renewable Energy Agency I. Renewable energy STATISTICS 2024 statistiques D'ÉNERGIE RENOUVELABLE 2024 ESTADÍSTICAS DE ENERGÍA RENOVABLE 2024. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Jul/IRENA_Renewable_Energy_Statistics_2024.pdf; 2024.
- [19] Roro K, Grobler J-H, Carter-Brown C, Calitz J. Draft Final Report Potential of offshore wind energy as a power source for South Africa PREPARED FOR : EU-SA partners for Growth Programme. https://www.euchamber.co.za/wp-content/uploads/2022/03/POTENTIAL-FOR-OFFSHORE-WIND-IN-SA_EUSA-PARTNERS-FOR-GROWTH-CSIR-FINAL-REPORT.pdf; 2022.
- [20] Markandya A. Externalities from electricity generation and renewable energy. Methodology and application in Europe and Spain. *Revistas ICE*; 2012. <https://www.revistasice.com/index.php/CICE/article>.
- [21] Wilmhurst JJ, Nsude CC, Greene JS. Standardizing the factors used in wind farm site suitability models: a review. *Heliyon* 2023;9:e15903. <https://doi.org/10.1016/j.heliyon.2023.e15903>.
- [22] Li H, Peng W, Huang CG, Guedes Soares C. Failure rate assessment for onshore and floating offshore wind turbines. *J Mar Sci Eng* 2022;10. <https://doi.org/10.3390/jmse10121965>.
- [23] Jung C, Sander L, Schindler D. Future global offshore wind energy under climate change and advanced wind turbine technology. *Energy Convers Manag* 2024;321. <https://doi.org/10.1016/j.enconman.2024.119075>.

- [24] Das U, Nandi C. Life cycle assessment on onshore wind farm: an evaluation of wind generators in India. *Sustain Energy Technol Assessments* 2022;53. <https://doi.org/10.1016/j.seta.2022.102647>.
- [25] Mello G, Ferreira Dias M, Robaina M. Wind farms life cycle assessment review: CO2 emissions and climate change. *Energy Rep* 2020;6:214–9. <https://doi.org/10.1016/j.egy.2020.11.104>.
- [26] Kaldellis JK, Apostolou D. Life cycle energy and carbon footprint of offshore wind energy. Comparison with onshore counterpart. *Renew Energy* 2017;108:72–84. <https://doi.org/10.1016/j.renene.2017.02.039>.
- [27] ISO 14040:2006. Environmental management — life cycle assessment — principles and framework. <https://www.iso.org/standard/37456.html>; 2006.
- [28] Carvalho ML, Marmiroli B, Girardi P. Life cycle assessment of Italian electricity production and comparison with the European context. *Energy Rep* 2022;8:561–8. <https://doi.org/10.1016/j.egy.2022.02.252>.
- [29] Brussa G, Grosso M, Rigamonti L. Life cycle assessment of a floating offshore wind farm in Italy. *Sustain Prod Consum* 2023;39:134–44. <https://doi.org/10.1016/j.spc.2023.05.006>.
- [30] Chen J, Mao B, Wu Y, Zhang D, Wei Y, Yu A, et al. Green development strategy of offshore wind farm in China guided by life cycle assessment. *Resour Conserv Recycl* 2023;188. <https://doi.org/10.1016/j.resconrec.2022.106652>.
- [31] Kouloumpis V, Azapagic A. A model for estimating life cycle environmental impacts of offshore wind electricity considering specific characteristics of wind farms. *Sustain Prod Consum* 2022;29:495–506. <https://doi.org/10.1016/j.spc.2021.10.024>.
- [32] Moussavi S, Barutha P, Dvorak B. Environmental life cycle assessment of a novel offshore wind energy design project: a United States based case study. *Renew Sustain Energy Rev* 2023;185. <https://doi.org/10.1016/j.rser.2023.113643>.
- [33] Scolaro M, Kittner N. Optimizing hybrid offshore wind farms for cost-competitive hydrogen production in Germany. *Int J Hydrogen Energy* 2022;47:6478–93. <https://doi.org/10.1016/j.ijhydene.2021.12.062>.
- [34] Chipindula J, Botlaguduru VSV, Du H, Kommalapati RR, Huque Z. Life cycle environmental impact of onshore and offshore wind farms in Texas. *Sustainability* 2018;10. <https://doi.org/10.3390/su10062022>.
- [35] Kadiyala A, Kommalapati R, Huque Z. Characterization of the life cycle greenhouse gas emissions from wind electricity generation systems. *International Journal of Energy and Environmental Engineering* 2017;8:55–64. <https://doi.org/10.1007/s40095-016-0221-5>.
- [36] Besseau R, Sacchi R, Blanc I, Pérez-López P. Past, present and future environmental footprint of the Danish wind turbine fleet with LCA_WIND_DK, an online interactive platform. *Renew Sustain Energy Rev* 2019;108:274–88. <https://doi.org/10.1016/j.rser.2019.03.030>.
- [37] Teffera B, Assefa B, Björklund A, Assefa G. Life cycle assessment of wind farms in Ethiopia. *Int J Life Cycle Assess* 2021;26:76–96. <https://doi.org/10.1007/s11367-020-01834-5>.
- [38] Elmariami A, Elost W, Elfleet M, Khalifa Y. Assessment of energy and environment footprint of a proposed wind farm in Western Coast of Libya using LCA. <http://doi.org/10.21203/rs.3.rs-1095513/v1>; 2021.
- [39] Nyambegera KK. A feasibility study of sustainable offshore wind energy A feasibility study of sustainable offshore wind energy development in Kenya development in Kenya. https://commons.wmu.se/all_dissertations/; 2021.
- [40] Mahlangu N, Thopil GA. Life cycle analysis of external costs of a parabolic trough Concentrated Solar power plant. *J Clean Prod* 2018;195:32–43. <https://doi.org/10.1016/j.jclepro.2018.05.187>.
- [41] Costa CR de S, Ferreira P. A review on the internalization of externalities in electricity generation expansion planning. *Energies* 2023;16. <https://doi.org/10.3390/en16041840>.
- [42] Winikoff JB, Parker DP. Farm size, spatial externalities, and wind energy development. *Am J Agric Econ* 2024;106:1518–43. <https://doi.org/10.1111/ajae.12438>.
- [43] Rokhmawati A, Sugiyono A, Efni Y, Wasnury R. Quantifying social costs of coal-fired power plant generation. *Geogr Sustain* 2023;4:39–48. <https://doi.org/10.1016/j.geosus.2022.12.004>.
- [44] Yang H-J, Zhao Z-Y. Wind power integration control technology for sustainable, stable and smart trend: a review. *J Technol Innovat Renew Energy* 2015;4:25–40. <https://www.lifescienceglobal.com/pms/index.php/jtire/article/view/2835/1674>.
- [45] Owen AD. Renewable energy: externality costs as market barriers. *Energy Policy* 2006;34:632–42. <https://doi.org/10.1016/j.enpol.2005.11.017>.
- [46] Yang J, Chang Y, Zhang L, Hao Y, Yan Q, Wang C. The life-cycle energy and environmental emissions of a typical offshore wind farm in China. *J Clean Prod* 2018;180:316–24. <https://doi.org/10.1016/j.jclepro.2018.01.082>.
- [47] Kiciükül E, Cerin P, Liu Y. Enhancing the value of corporate sustainability: an approach for aligning multiple SDGs guides on reporting. *J Clean Prod* 2022;333. <https://doi.org/10.1016/j.jclepro.2021.130005>.
- [48] Varun Bhat IK, Prakash R. LCA of renewable energy for electricity generation systems-A review. *Renew Sustain Energy Rev* 2009;13:1067–73. <https://doi.org/10.1016/j.rser.2008.08.004>.
- [49] Marszal AJ, Heiselberg P, Lund Jensen R, Nørgaard J. On-site or off-site renewable energy supply options? Life cycle cost analysis of a Net Zero Energy Building in Denmark. *Renew Energy* 2012;44:154–65. <https://doi.org/10.1016/j.renene.2012.01.079>.
- [50] Sims REH, Rogner H-H, Gregory K. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. *Energy Policy* 2003;31:1315–26.
- [51] Sovacool BK. Valuing the greenhouse gas emissions from nuclear power: a critical survey. *Energy Policy* 2008;36:2950–63. <https://doi.org/10.1016/j.enpol.2008.04.017>.
- [52] Corona B, Cerrajero E, López D, San Miguel G. Full environmental life cycle cost analysis of concentrating solar power technology: contribution of externalities to overall energy costs. *Sol Energy* 2016;135:758–68. <https://doi.org/10.1016/j.solener.2016.06.059>.
- [53] Weisser D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy* 2007;32:1543–59. <https://doi.org/10.1016/j.energy.2007.01.008>.
- [54] Galetovic A, Muñoz CM. Wind, coal, and the cost of environmental externalities. *Energy Policy* 2013;62:1385–91. <https://doi.org/10.1016/j.enpol.2013.07.140>.
- [55] Thopil GA, Pouris A. Aggregation and internalisation of electricity externalities in South Africa. *Energy* 2015;82:501–11. <https://doi.org/10.1016/j.energy.2015.01.059>.
- [56] Richard Van Horen C. The cost OF power: externalities in South Africa's energy sector. <https://open.uct.ac.za/server/api/core/bitstreams/2a3aed7b-b8b7-4b03-8c64-df35676f98fe/content>; 1996.
- [57] Auwal Ibrahim H, Thopil GA. Life cycle external cost assessment of an onshore wind farm in South Africa. *Appl Energy* 2025;388. <https://doi.org/10.1016/j.apenergy.2025.125708>.
- [58] Spalding-Fecher R, Matibe DK. Electricity and externalities in South Africa. *Energy Policy* 2003;31:721–34. [https://doi.org/10.1016/S0301-4215\(02\)00123-4](https://doi.org/10.1016/S0301-4215(02)00123-4).
- [59] Vázquez A, Izquierdo U, Enevoldsen P, Andersen FH, Blanco JM. A macroscale optimal substructure selection for Europe's offshore wind farms. *Sustain Energy Technol Assessments* 2022;53:102768. <https://doi.org/10.1016/J.SETA.2022.102768>.
- [60] Nasab NM, Kilby J, Bakhtiarifard L. Analysis and design of monopile foundations for offshore wind and tidal turbine structures. *Water* 2022;14:3555. <https://doi.org/10.3390/w14213555>. 2022;14:3555.
- [61] Tran TT, Lee D. Development of jacket substructure systems supporting 3MW offshore wind turbine for deep water sites in South Korea. *Int J Nav Archit Ocean Eng* 2022;14:100451. <https://doi.org/10.1016/J.IJNAOE.2022.100451>.
- [62] Gallardo Y, Tampier G, Palma V, Cifuentes C, Ahumada JM, Troncoso C, et al. An early-stage structural design of a semi-submersible platform for floating offshore wind turbines in Chilean waters. *J Mar Sci Eng* 2024;12:1951. <https://doi.org/10.3390/JMSE12111951>. Page 1951 2024;12.
- [63] Pham TD, Shin H. A new conceptual design and dynamic analysis of a spar-type offshore wind turbine combined with a moonpool. *Energies* 2019;12:3737. <https://doi.org/10.3390/EN12193737>. 2019;12:3737.
- [64] Engineering News. Offshore wind farms: a potential energy source. <https://www.engineeringnews.co.za/Article/Offshore-Wind-Farms-a-Potential-Energy-Source-2022-10-072022>.
- [65] Rae G, Erfort G. Offshore wind energy - south Africa's untapped resource. *J Energy South Afr* 2020;31:26–42. <https://doi.org/10.17159/2413-3051/2020/v31i4a7940>.
- [66] Elsner P. Continental-scale assessment of the African offshore wind energy potential: spatial analysis of an under-appreciated renewable energy resource. *Renew Sustain Energy Rev* 2019;104:394–407. <https://doi.org/10.1016/j.rser.2019.01.034>.
- [67] World Bank. GOING GLOBAL GOING GLOBAL expanding offshore wind to emerging markets. <https://documents1.worldbank.org/curated/pt/716891572457609829/pdf/Going-Global-Expanding-Offshore-Wind-To-Emerging-Market.s.pdf;2019>.
- [68] Harger A, Carmo LHS, Gay Neto A, Simos AN, Franzini GR, Vieira GHR. Modal analysis of 15 MW semi-submersible floating wind turbine: investigation on the main influences in natural vibration. *Wind* 2023;3:548–66. <https://doi.org/10.3390/wind3040031>.
- [69] Umoh K, Hasan A, Kenjegaliev A, Al-Qattan A. Assessment of the locational potential of floating offshore wind energy in South Africa. *Sustainable Energy Research* 2024;11. <https://doi.org/10.1186/s40807-024-00104-4>.
- [70] Life cycle assessment software and data | sphera (GaBi) n.d. <https://sphera.com/product-stewardship/life-cycle-assessment-software-and-data/?tab=1>.
- [71] CASES. Final report Summary - CASES (cost assessment for sustainable energy systems). <https://cordis.europa.eu/project/id/518294/reporting>; 2008.
- [72] Wilkie D, Galasso C. A Bayesian model for wind farm capacity factors. *Energy Convers Manag* 2022;252. <https://doi.org/10.1016/j.enconman.2021.114950>.
- [73] Mahmood M, Chowdhury P, Yeassin R, Hasan M, Ahmad T, Chowdhury NUR. Impacts of digitalization on smart grids, renewable energy, and demand response: an updated review of current applications. *Energy Convers Manag X* 2024;24:100790. <https://doi.org/10.1016/J.ECMX.2024.100790>.
- [74] Tao Y, Hadigh SA, Wei Y. Recycling of glass fibre reinforced polymer (GFRP) composite wastes in concrete: a critical review and cost benefit analysis. *Structures* 2023;53:1540–56. <https://doi.org/10.1016/j.istruc.2023.05.018>.
- [75] Adeleke OA, Akinlabi SA. Comparative Analysis of the waste-to-energy (WtE) technologies using municipal Solid Waste (MSW). <https://ujcontent.uj.ac.za/esploro/outputs/doctoral/Comparative-analysis-of-the-Waste-to-Energy-WtE/9912083707691#file-0>; 2021.
- [76] Lee RP, Meyer B, Huang Q, Voss R. Sustainable waste management for zero waste cities in China: potential, challenges and opportunities. *Clean Energy* 2020;4:169–201. <https://doi.org/10.1093/ce/zkaa013>.
- [77] Raadal HL, Vold BI, Myhr A, Nygaard TA. GHG emissions and energy performance of offshore wind power. *Renew Energy* 2014;66:314–24. <https://doi.org/10.1016/j.renene.2013.11.075>.
- [78] Sustainable solutions for your offshore wind power project. n.d. <https://doi.org/https://assets.new.siemens.com/siemens/assets/api/uiid:cd30e8065854a8a88>

- [ccb8ea6b5a4693bd88ba108/version:1541967033/siemens-wind-power-offshore-solutions-brochure-web-doublepages.pdf](https://doi.org/10.1016/j.renene.2011.06.003).
- [79] Kabir MR, Rooke B, Dassanayake GDM, Fleck BA. Comparative life cycle energy, emission, and economic analysis of 100 kW nameplate wind power generation. *Renew Energy* 2012;37:133–41. <https://doi.org/10.1016/j.renene.2011.06.003>.
- [80] Ozoemena M, Cheung WM, Hasan R. Comparative LCA of technology improvement opportunities for a 1.5-MW wind turbine in the context of an onshore wind farm. *Clean Technol Environ Policy* 2018;20:173–90. <https://doi.org/10.1007/s10098-017-1466-2>.
- [81] Arvesen A, Hertwich EG. Erratum: environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment (environmental Research Letters (2011) 6 (045102)). *Environ Res Lett* 2012;7. <https://doi.org/10.1088/1748-9326/7/3/039501>.
- [82] Awel y môr offshore wind farm life cycle assessment for the awel y môr offshore windfarm deadline 5. https://consultation.dublincity.ie/planning/awel-y-mor-offshore-windfarm/supporting_documents/EN0101120001505.1_AyM_ConsultationReport_vFinal.pdf; 2023.
- [83] P WB, O VC. Overview and methodology. Data quality guideline for the ecoinvent database. https://lca-net.com/files/Overview_and_methodology.pdf; 2007.
- [84] Global Wind Atlas. <https://globalwindatlas.info/en/area/South%20Africa>. Retrieved 07 September 2025.