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Life cycle external cost assessment of an onshore wind farm in South Africa

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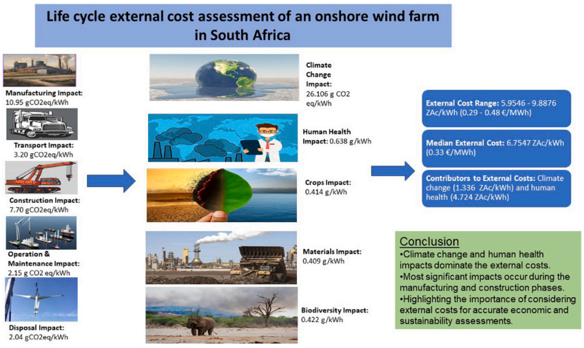
HIGHLIGHTS

- External impact and external cost evaluation of a 138 MW onshore wind farm in South Africa.
- Greenhouse gas and human health impacts contribute to 89.4 % of median costs.
- Manufacturing phase accounts for 39.3 % of total external costs.
- 32.45 % of external cost is accounted by construction phase.
- First of its kind wind energy external cost investigation in Africa.

GRAPHICAL ABSTRACT


Life cycle external cost assessment of an onshore wind farm in South Africa

Manufacturing Impact: 10.95 gCO2eq/kWh

Transport Impact: 3.20 gCO2eq/kWh

Construction Impact: 7.70 gCO2eq/kWh

Operation & Maintenance Impact: 2.15 g CO2 eq/kWh

Disposal Impact: 2.04 gCO2eq/kWh

Climate Change Impact: 26.106 g CO2 eq/kWh

Human Health Impact: 0.638 g/kWh

Crops Impact: 0.414 g/kWh

Materials Impact: 0.409 g/kWh

Biodiversity Impact: 0.422 g/kWh

External Cost Range: 5.9546 - 9.8876 ZAc/kWh (0.29 - 0.48 €/MWh)

Median External Cost: 6.7547 ZAc/kWh (0.33 €/MWh)

Contributors to External Costs: Climate change (1.336 ZAc/kWh) and human health (4.724 ZAc/kWh)

Conclusion
•Climate change and human health impacts dominate the external costs.
•Most significant impacts occur during the manufacturing and construction phases.
•Highlighting the importance of considering external costs for accurate economic and sustainability assessments.

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Keywords:
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ABSTRACT

Wind power has been crucial in global energy transitions over the past decade. Such transitions are evident in sub-Saharan Africa, where South Africa is a leading player. Onshore wind power is pivotal in South Africa's energy transition, but the comprehensive external costs of the technology remain unexplored. Conducting a life cycle assessment (LCA) of a 138 MW wind farm, this study aims to fill the existing gap in the literature, by assessing greenhouse gas (GHG) and non-GHG impacts, and then converting them into costs. This study provides critical insights into the environmental, health, biodiversity, crops, and materials impact of onshore wind power, contributing towards improving the overall sustainability of offshore wind power. Findings from the study indicate that climate change impacts contribute 26.1 gCO_2eq/kWh, while human health impacts emerge as the most significant non-GHG impact. The onshore wind farm's external cost ranges from 5.95 to 9.88 ZAc/kWh (2.9–4.82 €/MWh), with a median of 6.75 ZAc/kWh (3.29 €/MWh), falling within ranges observed in the literature. Climate change and human health jointly account for 89.4 % of the median external costs, primarily associated with the manufacturing and construction phases. This study underscores the importance of including external costs in the comprehensive assessment of wind power, driven by the decreasing technology costs. The findings highlight the need to incorporate climate change and human health costs to better understand the sustainability of onshore wind power across its life cycle.

Abbreviations: C, Construction phase; D, Disposal phase; DMRE, Department of Mineral Resources and Energy; IPP, Independent Power Producers; IRENA, International Renewable Energy Agency; kWh, Kilowatt-hour; LCA, Life cycle Assessment; LCI, Life cycle Inventory; M, Manufacturing phase; MWh, Megawatt hour; O&M, Operations and Maintenance phase; OCGT, Open Cycle Gas Turbine; T, Transport phase.

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1. Introduction

There has been an unprecedented increase in demand for electricity due to the world's population growth, industrialisation, urbanisation, technological advancements, and the fourth industrial revolution [1]. Power generation is still dominated by fossil fuels in developing economies even though they have shown to be unsustainable and have negative long-term environmental impacts [2]. Burning fossil fuels releases greenhouse gasses [GHGs], negatively impacting materials, crops, biodiversity, and human health, worsening the challenge of climate change. Developing nations in Africa are making strides towards integrating renewable energy sources into their energy mix, Egypt, Kenya, Ghana, and Nigeria have a cumulative installed capacity of 3.3 GW solar power, 8.24 GW hydropower, 2.4 GW wind power, etc., but this is insignificant considering the increasing demand for electricity amongst developing nations and the huge potential of renewables that such nations possess [2,3]. China, which is still considered a developing nation, has an installed capacity of 474 GW [3]. South Africa already a leading player in Africa in terms of renewables, has huge potential for generating electricity sustainably using wind, solar, hydro, and biomass [4]. Utilising renewable energy sources would reduce the country's dependency on fossil fuels, improving the country's electricity supply and helping it reach international and national sustainability transition targets [5]. For South Africa to achieve a sustainable power generation transition, concentrating on carbon reduction measures would not be sufficient, but it would need to focus on the effects on the environment and society [6]. Wind power is increasingly being harnessed in South Africa and other developing countries to address the increasing electricity demand and mitigate GHG emissions. Despite being a clean energy source, wind power technology is not without GHG and non-GHG impacts, and external costs [7].

This study aims to add to the body of knowledge of LCA, external cost analysis of wind power generation by assessing GHG impacts, and non-GHG impacts such as human health effects, biodiversity loss, and crop and material impacts, then translating these impacts into costs for an onshore wind farm in South Africa, offering valuable insights into the actual costs of onshore wind power generation. 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 also in developing countries at large.

External costs, signified by unaccounted monetary value, involve the economic burdens arising from environmental and societal impacts. These financial implications are multifaceted, arising from diverse factors such as climate change, impacts on human health, and effects on crops, etc. [8–10]. Externalities as categorised by Owen [11] have both local and global effects. Local effects are determined by a given place and include costs associated with environmental, health, biodiversity, crops, and materials effects. In contrast, climate change brought on by GHGs is considered a global impact, regardless of location [12–15]. When comparing nuclear energy and renewable energy sources to fossil fuels, researchers have looked at the financial and environmental effects of each power generation system [16–18]. Various researchers have delved into assessing fossil fuel and renewable energy externalities on a global scale, encompassing various technologies and fuel sources on an international scale. Owen [11] found that internalising fossil fuel damage costs could make renewable energy more competitive. Corona et al. [19] used Full Environmental Life Cycle Costing (FeLCC) to assess the economic performance of a 50 MW CSP plant with varying natural gas inputs. Weisser [20] reviewed GHG emissions across energy technologies, noting high upstream emissions for fossil fuels and significant lifecycle emissions for RETs and nuclear, with hydro, nuclear, and wind having the lowest global warming impacts. Markandya [21] estimated externalities from electricity generation, highlighting their importance for policy design. Sovacool et al. [22] reported global externalities for energy and mobility totaling $24.662 trillion, emphasising the need to internalise these costs. South African studies by Mahlangu and Thopil [23], Thopil and Pouris [24], Van Horen [25] and Spalding-Fecher et al. [26] evaluated external costs for CSP, non-renewable electricity, and coal. Mahlangu and Thopil [23] found climate change and health impacts for a 100 MW CSP plant, suggesting localisation could reduce costs. Thopil and Pouris [24] quantify non-renewable electricity's environmental impacts in South Africa, with externality costs ranging from 5.86 to 35.36 SA c/kWh (1.31–7.95 US c/kWh) and a central estimate of 13.43 SA c/kWh (3.02 US c/kWh), representing 68.5 % of 2008 electricity prices, mainly due to GHG emissions and health effects from coal, and Spalding-Fecher et al. [26] analysed the external costs of coal-fired electricity generation in South Africa, estimating a central cost of R7.3 billion (4.4 cents per kWh), or 40 % and 20 % of industrial and residential tariffs. It assesses air pollution impacts, GHG damages, and avoided health costs from electrification, and discusses policy options such as taxation, tradable permits, integrated resource planning, regional energy trade, and climate funding for cleaner energy.

Delucchi & Jacobson [95] investigated a scenario where they assumed a future scenario where all wind turbines are manufactured and transported using renewable energy, thus leading to zero external impacts and costs. This scenario has not yet been achieved, warranting investigation of impacts and costs associated to wind energy. To our knowledge, no study has combined the assessment of GHG and non-GHG impacts, and external costs of onshore wind farms in South Africa and the rest of Africa. The study assesses the life cycle GHG and non-GHG impacts, then converts them into costs, for a 138 MW (the turbines have a 2.3 MW power rating each, making the total number of wind turbines 60) Jeffreys Bay onshore wind farm, which has an operational lifespan of 20 years.

2. Literature review

There are primarily two ways of utilising wind energy for power generation, which are either onshore or offshore. Wind farms located onshore are on land, often in high-wind potential regions with an average wind speed ranging from 6 to 9 m/s [27]. Whereas offshore wind farms are positioned in water bodies such as oceans and typically near coastlines. Recent studies indicate advancements in onshore and offshore wind technologies, leading to increased efficiency and reliability. Projections suggest a potential attainment of 55 % for onshore wind and 58 % for offshore wind by the year 2030 [28]. Wind turbines operate on the fundamental principle of converting wind energy into electricity. The turbine, which is placed in areas with consistently constant winds, has aerodynamically shaped blades that harness the wind's kinetic energy. The generator is the focal point of the rotating blades' axis, which is essential for electromagnetically inducing energy transformation from mechanical to electrical. Wind power utilisation for electricity generation acts as a driver for continuous improvements in the efficiency, design enhancement, and environmental sustainability of wind turbines [29]. These critical aspects of wind power generation have been extensively researched in multiple scholarly works by Wiser et al. [30] and Veers et al. [31]. Onshore wind farm installations are more cost-effective and efficient to operate and maintain. In contrast, offshore wind farms capitalise on stronger and steadier winds of up to 25 m/s to mitigate the intermittency challenges faced by onshore wind farms [32]. Also, they can address some of the challenges premised on aesthetics and noise that onshore wind farms possess [33]. Nonetheless, offshore wind farms require significantly higher capital investment ranging from $2 million to $6 million per megawatt (MW) compared to onshore wind turbines which cost between $1 million and $2.5 million per megawatt [34]. There are logistical challenges associated with the installation of offshore wind turbines in deep waters. Integrating wind technology with other renewable sources or energy storage systems provides a more reliable and steady power supply [35].

When analysing the power supply mix of South Africa, it is evident that the nation relies significantly on coal for approximately 70 % of its production. [36]. The substantial reliance on non-renewable energy sources has adverse negative effects as already stated. To mitigate these negative impacts and develop a sustainable power system, it is crucial to transition towards a diverse and environmentally friendly power mix by integrating wind and other renewable energy sources [37]. Renewable energy is crucial in replacing fossil fuels and mitigating the pressing need to reduce emissions from power generation to tackle climate change. The main obstacle lies not in the scarcity of fossil fuels, but rather in the harmful impact of GHGs on the environment resulting from their use for generating electricity. Multiple studies have consistently emphasised the diverse environmental and societal impacts, as well as associated external effects, of different methods of electricity generation [38–48]. These studies collectively emphasise the complexity of the challenges presented by power generation.

The Integrated Resource Plan (IRP) 2010–2030, in conjunction with the Renewable Independent Power Producer Programme (REIPPPP), has considerably improved renewable energy penetration in South Africa, with 59 power plants providing 3692 MW of electricity in 2017. These achievements resulted from competitive bidding within the REIPPPP. Subsequently, South Africa increased its renewable energy capacity to 10,486 MW in 2023 [49]. Market incentives, such as the successful REIPPPP, were developed to support renewable energy integration into South Africa's power mix. This program aligns with South Africa's 2030 targets and encourages private sector investments, earning recognition in the Fieldstone Africa Renewables Index. South Africa proposed a carbon tax to motivate emission reductions and diversify electricity production in line with national and global initiatives.

With an estimated 978,066 TWh/y of wind energy, Africa has a renewable energy potential 1000 times greater than its projected energy consumption in 2040, indicating significant untapped potential [50,51]. Despite possessing substantial untapped wind energy potential, South Africa has demonstrated remarkable progress in integrating wind energy into its power supply mix. Table 1 provides a comparative overview, highlighting South Africa's significant onshore wind power additions. Table 2 provides details on the locations and capacities of operational onshore wind farms across South Africa, showcasing the diverse sites contributing to the country's wind energy capacity.

Evaluating the externalities linked to the production of electricity is essential for deriving the true cost of power generation, thereby facilitating informed discussions on the cost competitiveness of various energy sources and the mitigation of externalities. Extensive research, as exemplified by Mahlangu and Thopil [23], Thopil and Pouris [24,54,55], Rentzelas and Georgakellos [56], Meyerhoff et al. [57], Rennert et al. [58], and Al-Qahtani et al. [59] has demonstrated that incorporating the monetary value of externalities into the conventional cost metrics reveals a considerably higher overall cost of electricity. The computation of total external costs not only contributes to a comprehensive understanding of process efficiency but also allows for meaningful comparisons with alternative technologies when including unaccounted impacts and costs. Such insights are decisive for both technical decision-making at an engineering level and policy formulation, guiding decisions related to energy planning and electricity policies. This perspective on external cost assessment holds significant implications for advancing technological advancements and sustainable energy policy considerations.

Table 1
Onshore wind farms across Africa and their capacities in 2023 [52].

S. No.	Country	Capacity (MW)	Wind farms number
1	South Africa	3560	38
2	Morocco	1958	19
3	Egypt	1890	12
4	Tanzania	903	3
5	Ethiopia	665	6
6	Kenya	475	5
7	Tunisia	243	3
8	Senegal	159	1
9	Ghana	150	1
10	Sudan	125	1
11	Mozambique	121	2
12	Mauritania	111	3
13	Djibouti	59	1
14	Algeria	31	1
15	Cape Verde	28	6
16	Mauritius	11	2
17	Nigeria	11	1
18	Namibia	6	2
19	Seychelles	6	1
20	Chad	2	1
21	Gambia	2	1
22	Eritrea	1	1

Table 2
Onshore wind farms in south Africa and their capacities in 2023 [53].

S. No.	Wind farm name	Capacity (MW)
1	Roggeveld	140
2	Oyster Bay	140
3	The Karusa	139.8
4	Soetwater	139.4
5	Nxuba	138.9
6	Longyuan Mulilo Green Energy De Aar 2 North	138.9
7	Loeriesfontein 2	138.23
8	Jeffreys Bay	138
9	Khobab	137.74
10	Kangnas	136.7
11	Garob	135.93
12	Cookhouse	135.8
13	Gouda	135.5
14	Amakhala Emoyeni	131.05
15	Golden Valley	117.72
16	Red Cap - Gibson Bay	108.25
17	Perdekraal East	107.76
18	Copperton	102
19	Dorper	97.53
20	Longyuan Mulilo De Aar Maanhaarberg	96.48
21	Tsitsikamma Community	93.68
22	Aurora	90.82
23	Nojoli	86.6
24	Noupoort	79.05
25	Kouga	77.7
26	Nobelsfontein Phase 1	73.8
27	Umoya Energy	65.4
28	Grassridge	59.8
29	Wesley-Ciskei	32.7
30	Excelsior	31.9
31	Dassieklip	27
32	Metrowind Van Stadens	27
33	Waainek	23.28
34	Chaba	21

An LCA of the "Jeffreys Bay Wind Farm" was carried out in this study, a South African onshore wind farm in the Eastern Cape, halfway between Jeffreys Bay and Humansdorp. The site displayed in Fig. 1., spans 3700 ha and is advantageous for harnessing wind energy due to its flat topography, limited environmental restrictions, favourable wind conditions, and proximity to the national grid. The wind farm has a power output of 460,000 MWh at a rated capacity factor of 38 %, meeting the electricity needs of around 100,000 average South African households [60].

The environmental impact of various systems arises due to the utilisation of fossil fuels across their life cycle, this could be minimised if the fossil fuels are replaced with renewables, which are deemed beneficial to the environment, health, crops, etc. [61]. Converting life cycle impacts (LCI) into external costs provides a clearer picture of the true cost and sustainability of an energy system. However, existing literature has primarily focused on assessing LCI without explicitly quantifying the external costs associated with these impacts. Only a few studies have quantified external costs, as shown in Table 3, where the specific types of externalities assessed in each study are now listed to facilitate accurate comparison.

Fig. 1. Jeffreys bay wind farm location [80].

It has become evident that the utilisation of the LCA methodology holds a prominent position in evaluating the impacts associated with power generation from renewables, particularly in the instance of onshore wind turbines as determined from the literature. Table 4 summarises and presents the outcome of a review of onshore wind LCA studies. Despite the diverse geographical locations of the case studies, the results exhibit minimal variation, falling between 5 and 33.6 gCO_2eq/kWh in the climate change subcategory. This consistency in findings underscores the reliability and consistency of LCA in assessing the environmental impact of onshore wind turbine technologies across different contexts.

3. Material and methods

The overall objective of the study is to assess the GHG and non-GHG impacts and translate them into external costs for an onshore wind farm in South Africa. This section outlines the cradle-to-grave Life Cycle Assessment (LCA) methodology used to evaluate the environmental impacts of an onshore wind farm. The LCA framework encompasses all stages of the product life cycle, from raw material extraction and manufacturing to transportation, construction, operation, maintenance, and disposal. The analysis follows the ISO 14040 methodology, which includes Goal and Scope definition, Life Cycle Inventory (LCI) Analysis, Life Cycle Impact Assessment (LCIA), and Interpretation. The Sphera software was employed for modeling and simulation to determine impacts across these phases.

Key elements of the study involve defining the functional unit, system boundaries, and impact categories, alongside data collection for inputs and outputs in each life cycle phase. The assessment includes evaluating external costs related to GHG and non-GHG impacts.

3.1. Life cycle assessment framework

Throughout a system's life cycle, its environmental impacts are evaluated using the LCA framework. This covers several phases, including extraction/manufacturing, transportation, operation and maintenance (O&M), and disposal. Fig. 2 shows the phases of LCA where the ISO 14040 methodology was applied. The LCA 14040 methodology is based on 4 phases which include: Goal and Scope, Life cycle Inventory (LCI), Life cycle Assessment (LCA), and Interpretation. Whereas Fig. 3 highlights the onshore 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 Sphera software.

- Goal and Scope

The aim of the study is defined in this phase of the framework. This includes defining the functional unit, system boundaries identification, identifying allocation procedures, impact categories being studied, LCI models utilised, and data quality requirements identification. The functional unit is essential for LCA and needs to be defined precisely. It functions as a meter for the system's performance and offers a standard against which inputs and outputs may be compared. This makes it easier to compare two fundamentally dissimilar systems and is standard practice in the LCA of wind power to associate quantifiable flows with an established reference unit. A commonly recognised reference unit (functional unit) for wind energy systems is a single unit of electricity output, expressed in kWh or MJ. The goal of the current study is to perform an LCA for an onshore wind farm.

The scope of the study is a cradle-to-grave LCA for the 138 MW Jeffreys Bay Wind Farm in South Africa.

- Life Cycle Inventory Analysis

In this phase, data will be obtained to quantify the inputs and outputs of the system. Data pertaining, to energy, materials, waste, emissions, etc., are validated and put in relationship to the functional unit. Primary plant data is estimated in Table A1 (Appendix).

- Life Cycle Impact Assessment

The LCA analyses the environmental impacts of raw material extraction, manufacturing, usage, maintenance, recycling, and disposal throughout the life cycle of a product or system. It meticulously tracks pollution, resource use, and energy consumption from the acquisition of raw materials to the disposal of materials. Our assessment considers a combination of abatement approach and top down approach where estimated national damages are divided by total pollutant depositions to produce a measure of physical damage per unit of pollutant [92,93]. These physical damages are then attributed to power plants and converted to damage costs using available monetary estimates on the damages arising from the pollutants under study rather than an impact

Table 3

Externality costs comparison of different power generation technologies.

Technology	Authors	Externality cost (€/MWh)[1]	Life cycle phase(s) considered for the study	Type of externality
Wind	Owen (2006) [11]	0–3.50	• Operation	• Climate change
	Markandya (2012) [21]	0.99–12.43	• Extraction • Construction • Operation • Disposal	• Human health • Impact to building materials and crops • Impacts and damage to biodiversity
	Schleisner (2000) [62]	12.63–18.92	• Extraction • Manufacturing • Transportation • Construction • Operation • Decommissioning • Disposal	• Impact to material production • Noise, visibility, bird accidents, accidents
Solar PV	Owen (2006) [11]	0–8.40	• Operation	• Climate change
	Rennert et al. (2021) [58]	0.94–1.25	• Operation	• Climate change
	Markandya (2012) [21]	7.96–11.07	• Extraction • Construction • Operation • Disposal	• Human health • Impact to building materials and crops • Impacts and damage to biodiversity
Solar CSP	Mahlangu and Thopil (2018) [23]	19.64–30.86	• Manufacturing • Construction • Operation • Dismantling • Disposal	• Climate change • Human health • Loss of biodiversity • Effects on crops • Damage to materials
	Corona et al. (2016) [19]	21.46–21.60	• Manufacturing • Construction • Operation and maintenance • Dismantling and disposal	• Human Health • Loss of Biodiversity • Local and Global Damage to Crops • Damage to Materials and Climate Change
	Markandya (2012) [21]	**1.12–1.49**	• Extraction • Construction • Operation • Disposal	• Human health • Impact to building materials and crops • Impacts and damage to biodiversity
Biomass	Owen (2006) [11]	0–70.01	• Operation	• Climate change
Hydro	Owen (2006) [11]	0–14	• Operation	• Climate change
	Markandya (2012) [21]	**0.50–0.99**	• Extraction • Construction • Operation • Disposal	• Human health • Impact to building materials and crops • Impacts and damage to biodiversity
Coal	Owen (2006) [11]	28–210.04	• Operation	• Climate change
	Thopil and Pouris (2015) [24]	**6.87–40.09**	• Operation	• Climate change • Human health • Water usage
	Markandya (2012) [21]	32.70–39.06	• Extraction • Construction • Operation • Disposal	• Human health • Impact to building materials and crops • Impacts and damage to biodiversity
Oil	Owen (2006) [11]	42.01–154.03	• Operation	• Climate change
	Markandya (2012) [21]	21.90–29.84	• Extraction • Construction • Operation • Disposal	• Human health • Impact to building materials and crops • Impacts and damage to biodiversity
Gas	Owen (2006) [11]	14–56.01	• Operation	• Climate change
	Markandya (2012) [21]	14.68–17.26	• Extraction • Construction • Operation • Disposal	• Human health • Impact to building materials and crops • Impacts and damage to biodiversity
Nuclear	Owen (2006) [11]	2.80–9.80	• Operation	• Climate change
	Thopil and Pouris (2015) [24]	0.12–0.23	• Operation	• Human health
	Markandya (2012) [21]	1.99–2.61	• Extraction • Construction • Operation • Disposal	• Human health • Impact to building materials and crops • Impacts and damage to biodiversity

[1] A 2 % discount rate was applied for studies located in Europe and 7 % discount rate for studies located in Africa.

pathway approach (bottom up approach). The abatement approach is used due to the unavailability of primary plant data and emission data from the plant. The abatement approach is used for GHG impacts and costing, and we have expanded the same approach towards non-GHG impacts and costs.

- Interpretation

The outcome of the LCIA and LCA will be interpreted in this phase by the goal and scope stated. This phase entails consistency checks, sensitivity, completeness, and accuracy of the results.

3.2. Data and assumptions for LCA stages

This section describes the data and assumptions used for the Life LCA of onshore wind turbines, focusing on five key phases: manufacturing, transportation, construction, operation and maintenance, and disposal.

Table 4
Onshore wind turbine GHG emissions impact comparison.

Study overview	Emissions (gCO_2eq/kWh)	Location of study	Year	Reference
The research evaluated environmental, economic, and energy aspects for possible wind farms in many feasible areas in Libya using LCA.	32–70	Libya	2024	[63]
To determine whether the type of wind turbine is more carbon-efficient, the study measures carbon emissions over the course of two wind turbines using LCA.	8.48–10.43	China	2023	[64]
A 10-turbine, 20 MW Gamesa wind farm's life cycle was examined, and the results showed that 2082 GWh of electrical energy was produced and 56 GWh of primary energy was used.	8.83	Ethiopia	2023	[65]
The purpose of this research is to carry out an LCA on a 10-turbine Vestas 1.65 MW onshore wind farm located in Karnataka, India.	11.3	India	2022	[66]
Analysing 26,821 wind farms, the study considered turbine specifics, LCI data, and location-specific meteorological information for a comprehensive evaluation of global greenhouse gas impact.	10	Global	2022	[67]
The research precisely assesses the ecological consequences linked to wind energy systems delivering high-voltage electrical power to the national grid.	33.6	Libya	2021	[68]
A carbon footprint assessment of a 1.3 MW Nordex turbine in the Texas Panhandle was carried out in this study.	14.45	USA	2021	[69]
The LCA of hybrid towers with a height of 185 m was the focus of the study. The stages of erection and transportation are given special attention in the extensive documentation of the LCA procedure. The erecting step has an even greater environmental effect than the production stage.	10	USA	2020	[70]
Over a wind turbine's lifetime, LCA evaluated emissions from 2 MW onshore and offshore units.	25.4–31.8	China	2019	[71]
Through LCA, the study evaluated China's large wind turbines' environmental impact, contrasting it with the nation's fossil power facilities.	8.65	China	2018	[72]
Wind turbine installations in shallow, underwater, and onshore areas all had their LCAs evaluated.	5–9	Denmark	2018	[73]
China's maiden wind project created a process-oriented LCI model to assess life-cycle energy and emissions for wind power.	25.5	China	2018	[74]
An LCA contrasted two wind farms—one offshore and the other onshore.	7–11	USA	2016	[75]
In the assessment, energy, environmental effects, and economic issues were conducted.	17.8	Canada	2012	[76]
The study analysed GHG emissions throughout the entire life cycle of an onshore wind turbine.	7.2	China	2011	[77]
The study examined the LCA of two wind turbines to analyse the link between energy production and turbine size.	10.8	Australia	2009	[78]
The study determined the LCA of an onshore and offshore wind farm	7	Spain	2016	[79]

- *Manufacturing phase (M)*

The 2.3 MW Siemens turbines used in this study were manufactured in Germany, where the national energy grid includes over 50 % renewable energy sources. This energy mix is incorporated in the emissions assessment using the Sphera LCA tool, which accounts for the energy sources involved in each stage of the manufacturing process. The foundation, cables, rotor, stator, and gearbox are the main parts of a wind turbine. Design specifications and technical data for the components of the 2.3 MW Siemens turbine were used to determine material quantities for manufacturing, as represented in Table A1 (Appendix). The LCA model represents each major system as an individual plan, with material and energy inputs reflecting the German energy mix, thus allowing Sphera to accurately compute and document emissions for each manufacturing stage.

- *Transportation phase (T)*

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 onshore turbine, and each plan included a transport component along with estimated distances. The wind turbine components are delivered from Germany to the assembly base in the Eastern Cape, South Africa, which is located between Jeffreys Bay and Humansdorp. The assessment of transport energy considers the hourly energy consumption of vessels or trucks while also accounting for relevant environmental emissions from the diesel burnt using emission factors from the Ecoinvent database with the data represented in Table A1 (Appendix).

- *Construction phase (C)*

At this point, the assembly of the wind turbine's essential parts is the main priority. These parts are imported rather than produced in South Africa. The fuel used during the building phase is also taken into consideration in this phase using equipment such as cranes. The LCA model includes many scenarios for the wind turbine's key components. The data used for this phase of the modeling is represented in Table A1 (Appendix).

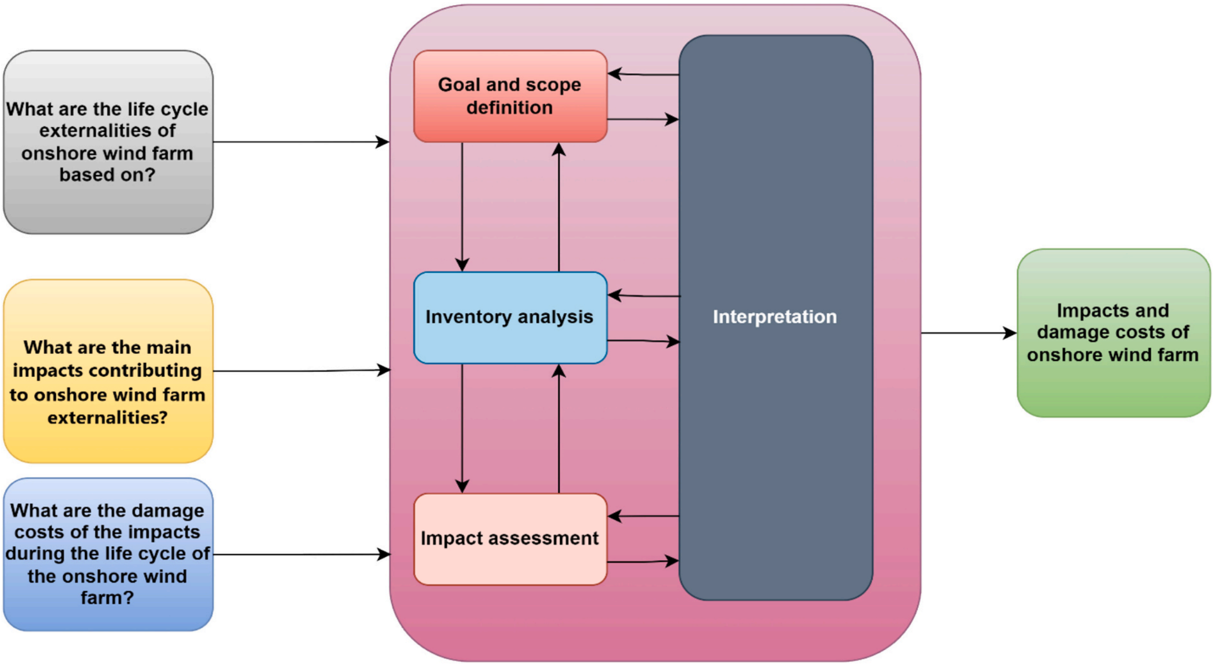


Fig. 2. Framework adopted for the methodology ISO 14040 [81].

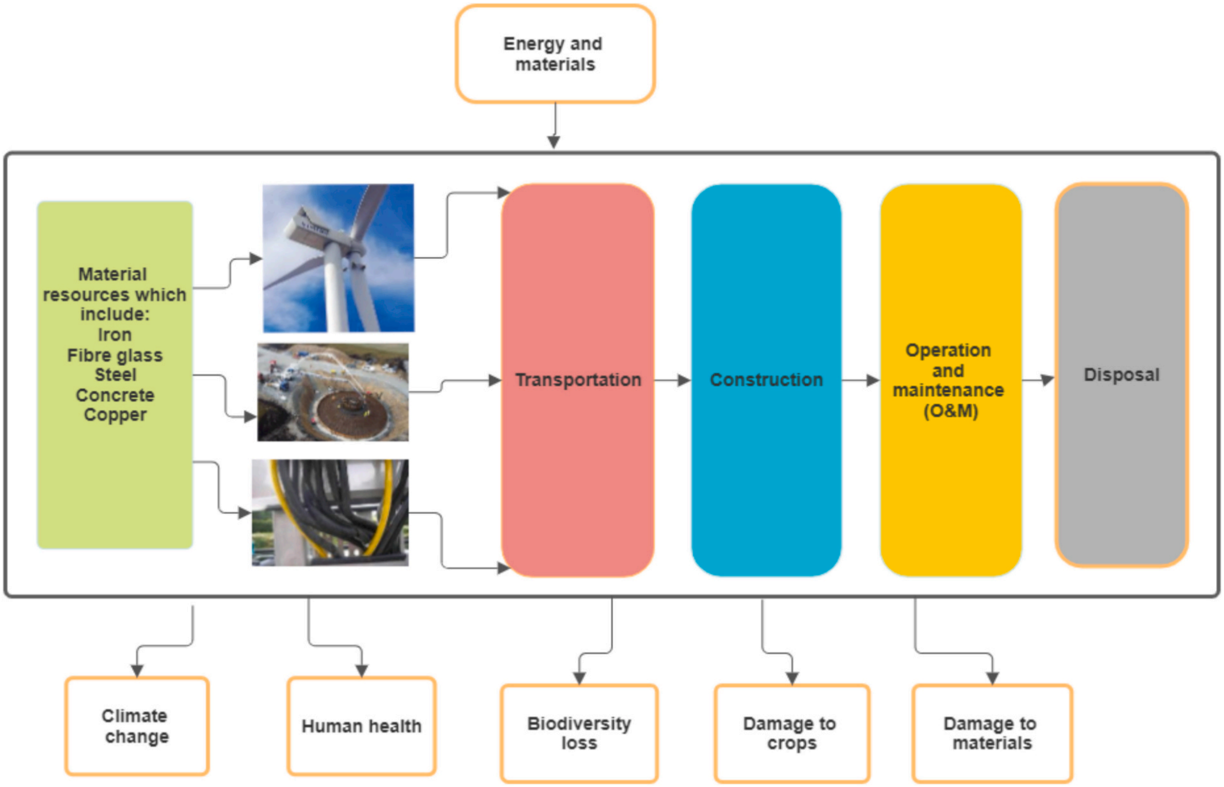


Fig. 3. Onshore wind farm system boundary.

- *Operation and maintenance (O&M) phase*

The cleaning, repairing, and replacing parts such as turbine blades, gearboxes, generators, lubricants, and more are the main duties associated with maintaining and managing the wind farm. As per the wind turbine maintenance recommendations, it is expected that each onshore 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 A1 (Appendix), the energy use and emissions during the operation and maintenance (O&M) phase are represented.

- *Disposal phase (D)*

This study adopts a cradle-to-grave LCA approach with a 20-year operational lifespan for the wind turbines, consistent with the operational timeline of the Jeffreys Bay Wind Farm, which has a 20-year power purchase agreement with the national grid operator. At the end of this period, the turbines are assumed not to be retrofitted or repowered. Recyclable materials, such as steel and copper, are expected to be sold as scrap, while non-recyclable materials like concrete and plastics are classified as inert waste and disposed of in landfills, in accordance with South African waste disposal practices. Hazardous materials, such as lubricants, are returned to the manufacturer, with transportation for disposal accounted for.

3.3. Externality cost

Eq. 1 was then used to determine the external cost for each subcategory concerning the externality, as defined by Mahlangu and Thopil [23]. The impact is multiplied by the externality's unit cost to determine the external cost.

$$\text{External cost} = \text{Impact x Cost} \tag{1}$$

where,

$\text{External cost} = \text{total monetary cost},$

$\text{Impact} = \text{pollutant per externality},$

$\text{Cost} = \text{monetary unit value of pollutant}$

Table 5 shows each emission assessed in the study's subcategories along with the descriptions that correspond with them. Climate change emissions-related external cost was computed using the marginal damage cost provided by CASES [86] in Table 6. As indicated in Table 7, the CASES dataset for emissions from an unknown height is used since emission height data is lacking. The 2023 exchange rate was used for the conversion between the Euros and the South Africa Rand.

The 2023 cost projections used a conversion rate of R20.5/Euro, which aids in converting marginal damage costs related to GHG emissions in Table 6 and pollutants that have an impact on non-GHG categories in Table 7, into Rands (ZA). Table 7 presents the categorisation of non-GHG unit pollutant costs, which were divided into four different impact groups based on the relative contributions of different pollutants.

Table 5
Descriptions of emissions for each external factor subcategory.

Subcategories of external costs	Description
Climate change	Global externalities include the costs associated with climate change, which are caused by GHG emissions. The primary greenhouse gas (GHG) considered in this study is carbon dioxide (CO_2), as it is the major GHG emitted from fossil fuel combustion. Marginal Damage Costs for Greenhouse Gases according to IPCC 2013 [91]
Health	Emissions of Non-Methane Volatile Organic Compounds (NMVOCs), ammonia (NH_3), NOx, sulphur dioxide (SO_2), and primary particulate matter (PPM) in the 2.5 ($PM_{2.5}$) to 10 (PM_{10}). These emissions have both local and global health effects.
Biodiversity degradation	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 effect.
Impacts on crops	Crop damage 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).
Damage to 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. Nitrogen oxides (NO_x) contribute to the damaging effects.

Table 6
GHG emissions marginal costs CASES [86].

	Minimum cost	Median cost	Maximum cost
€/tCO_2 eq.	10	25	35
ZAR/tCO_2 eq.	205	513	718

Table 7
Emission costs at unknown height (2024) CASES [23,86].

Country: European Union (EU-27) €/kg		ZAR/kg
Human health		
Ammonia (NH_3)	4.7	96.4
Non-methane volatile organic compounds (NMVOC)	0.191	3.92
Nitrogen oxides (NO_X)	5.33	109
Primary particulate matter coarse (PPMco[2])	1.11	22.8
Primary particulate ($PPM_{2.5}$[3])	19.4	398
Sulphur dioxide (SO_2)	5.38	110
Loss of biodiversity		
Ammonia (NH_3)	2.77	56.8
Nitrogen oxides (NO_X)	0.729	14.9
Sulphur dioxide (SO_2)	0.162	3.32
Effect on crops		
Non-methane volatile organic compounds (NMVOC)	0.062	1.27
Nitrogen oxides (NO_X)	0.263	5.39
Damage to materials		
Nitrogen oxides (NO_X)	0.042	0.861
Sulphur dioxide (SO_2)	0.153	3.14

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

[3] In the CASES (2008) [90] study, in certain instances $PM_{2.5}$ is also referred to as $PM_{25.}$

These numbers then functioned as inputs for Eq. 1. The approach used here is based on the abatement and top-down approach rather than an impact pathway approach. The use of exposure response functions and combining it with meteorological data, population data and wind dispersion models would be ideal if detailed plant emission data is available across all stages of the life cycle. Alternatively, if any one specific life stage has detailed emission data then the use of the impact pathway approach with exposure response functions would have been preferred. This approach is seen in Thopil & Pouris [24].

However, since detailed emission data is not available for this study, emissions had to be modelled from plant inventory data, after which the abatement cost and top-down approach is used to quantify costs. This approach was initially identified by Hohmeyer [92] to cater for limited plant/emission data. Mahlangu & Thopil [23] used a similar approach. The use of different approaches for impacts and costs have also been identified by Sundqvist [93] and more recently by Amadei, de Laurentiis and Sala [94].

While the abatement method is useful in instances with limited primary data, it should be noted that unlike GHGs (which are well-mixed and long-lived) pollutants such as NO_x, SO_2, and PM_{10} have localised effects on human health, crops, materials, and biodiversity. These impacts vary based on regional factors such as population exposure and exposure response functions, thus implying that the abatement cost approach may lead to overestimations. Given the absence of a comprehensive non-GHG emission data encountered during sea and land transportation, we adopt the abatement cost approach. To assess the implications of utilising such an approach for the non-GHG externalities, a sensitivity analysis was performed by removing transport related non-GHG external costs, providing a range within which the total external cost estimates may vary.

4. Results and discussion

The outcomes of the study are presented in two categories. The initial part presents the findings of the LCA done with the Sphera LCA tool to determine the LCI. The second part represents the externality costs that emerge from monetising the LCI using costs (in Tables 6 and 7).

According to the ISO (2006) [81] standards, a functional unit is a product system's measurable performance that acts as a reference unit. Offering a baseline to standardise data for system comparisons, makes it easier to analyse and comprehend the results. The study's results were standardised to a functional unit of 1 kWh. The functional unit is defined as an impact per unit of supplied service.

The yearly production of 460,000 MWh of energy was determined based on specifications, considering the 138 MW Jeffreys Bay Wind Farm, which operates at a 38 % capacity factor. This corresponds to a production of 918,748,900 kWh during a 20-year lifespan of the onshore wind farm. External costs per kWh were calculated by dividing the overall externalities cost—which included both GHG and non-GHG external costs—by the total amount of electricity generated over the life cycle of the onshore wind farm. This allowed for valid comparisons between various results.

A breakdown of the impacts associated with each subcategory during the life cycle phases is shown in Table 8. Significantly, emissions related to climate change are the largest contribution, and the manufacturing phase has the most impact (10.957 gCO_2eq/kWh), as shown in Fig. 4. This is a result of an energy-intensive production process, which is especially noticeable when producing vital parts like the stator and rotor magnet, for the wind turbine.

The manufacturing phase is the largest contributor in the human health subcategory, with the construction phase coming in second, as shown in Table 8. Fig. 5 (for non-GHG impacts) illustrates the increased emissions of ammonia, sulphur dioxide, nitrogen oxides, fine particulate matter, and sulphur dioxide during these stages. The manufacturing phase has a higher external cost (2.1 ZAc/kWh) than the other phases, with the construction phase coming in second (1.7 ZAc/kWh).

The O&M phase emissions are calculated cumulatively over the turbine's 20-year lifespan, incorporating regular maintenance, transportation, and component replacement. The disposal phase emissions include those from dismantling, transporting, and processing turbine components, which may involve specialised handling.

The significance of the manufacturing phase is also shown in the subcategory of loss of biodiversity, where it is the largest contributor to emissions. The impacts on crops and material degradation caused by high levels of sulphur dioxide and nitrogen oxides come next. Overall, the results underscore the manufacturing phase's crucial role in determining environmental impacts and show its significance across a range of subcategories across the wind farm's life cycle.

In Fig. 6 (and Table 8), it is evident that the manufacturing and construction phases play critical roles in the overall impact of non-GHG emissions, contributing 36.3 % and 35.83 %. Notably, these phases significantly influence the human health category (0.638 g/kWh), with substantial contributions to impacts related to the loss of biodiversity (0.422 g/kWh). In both the manufacturing and construction phases, effects on crops are noteworthy (0.149 g/kWh and 0.148 g/kWh), while the manufacturing phase exhibits significant effects on crops (0.1489 g/kWh), marginally surpassing the impact on materials (0.1489 g/kWh). Conversely, in the construction phase, damage to materials (0.1482 g/kWh) is marginally more evident than effects on crops (0.1480 g/kWh).

Table 8
Onshore wind farm impacts over the life cycle.

Externalities subcategories	Impact (g/kWh)	Impact at each life cycle phase (g/kWh)				
		M	T	C	O&M	D
Climate change (GHG eq.)	26.1[4]	11.0	3.20	7.70	2.16	2.04
Human health	0.638	0.233	0.052	0.227	0.065	0.060
Loss of biodiversity	0.422	0.153	0.032	0.152	0.044	0.040
Effects on crops	0.414	0.149	0.035	0.148	0.043	0.040
Damage to materials	0.410	0.149	0.031	0.148	0.042	0.039
Total non-GHG	1.88[5]	0.684	0.150	0.675	0.194	0.179

[4] gCO_2eq

[5] Aggregation of impacts from multiple pollutants affecting human health, loss of biodiversity, effects on crops, damage to materials which have been normailsed (per kWh) (e.g., $PPM_{2.5}$, PPM_{CO}, NH3, NMVOC, NO_x, and SO_2)

Comparatively, pollutant emissions in the transportation, O&M, and disposal phases, although relatively small, collectively account for 7.99 %, 10.313 %, and 9.53 %. This emphasises the prominence of the manufacturing and construction phases in influencing non-GHG emissions across all externality subcategories.

Table 9 summarises the study's overall results, including the external costs. Notably, while climate change has substantially larger impacts (26.1 gCO_2eq/kWh) than pollutants impacting human health (0.638 g/kWh), the external cost associated with human health (4.724 ZAc/kWh) outnumber those related to climate change (median of 1.336 ZAc/kWh). This disparity stems from the higher cost estimate of pollutants contributing to human health impacts in comparison to climate change, as seen in Tables 6 and 7.

The outcomes of the transportation phase are intricately linked to the subsequent O&M and disposal phases, primarily driven by the estimated transportation requirements within the scope of this study. In the disposal phase, this study assumes that materials such as fibreglass and epoxy resins would be landfilled as part of municipal solid waste (MSW), consistent with global practices due to their high cost and difficulty of breakdown. This approach is adopted in the study, and while research on alternative disposal methods is still ongoing, it aligns with South Africa's current waste management practices, which are expected to adopt similar methods for disposing of these materials [82.83]. 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 [84].

According to the study, overall external costs range between 5.946 ZAc/kWh (minimum), 6.747 (median), and 9.876 ZAc/kWh (maximum). With a significant drop in NO_x concentration according to Kamyab et al. [85], it has been noticed that NH_3, SO_2, and NO_X are the most common emissions across all categories of the life cycle phases. When assessing local effects on crops and material damage for onshore wind farms, these suffer comparatively moderate external costs when compared to other sub-categories such as human health and biodiversity loss.

A sensitivity analysis was performed by excluding all non-GHG external costs related to sea and land transportation, which includes effects on human health, loss of biodiversity, crop impacts, and damage to materials. This was carried out to assess how transport related non-GHG costs affect the total external cost estimates. The sensitivity analysis results in Table 10 highlight reductions of 8.75 % (low estimate), 7.71 % (central estimate), and 5.27 % (high estimate) in total external costs. This analysis provides a bounding estimate of the uncertainty introduced as part of the abatement approach to non-GHG externalities. Given that air pollutants are localised and not well-mixed, utilising an impact pathway approach in further studies will be crucial for improved estimations.

Exclusively focusing on the climate change subcategory, identified as the primary contributor to environmental impact, this section undertakes a comparative analysis. The comparisons entail cross-referencing the findings of this study with those presented in Table 4 (Section 2). This cross-referencing has resulted in Fig. 7, which compares the GHG impacts from the literature with the results obtained in this study. The results of various LCA as obtained after a comprehensive literature review, range from 5 to 33.6 gCO_2eq/kWh and correspond to an external cost range of 0.05–11.76 €/MWh (calculated by multiplying

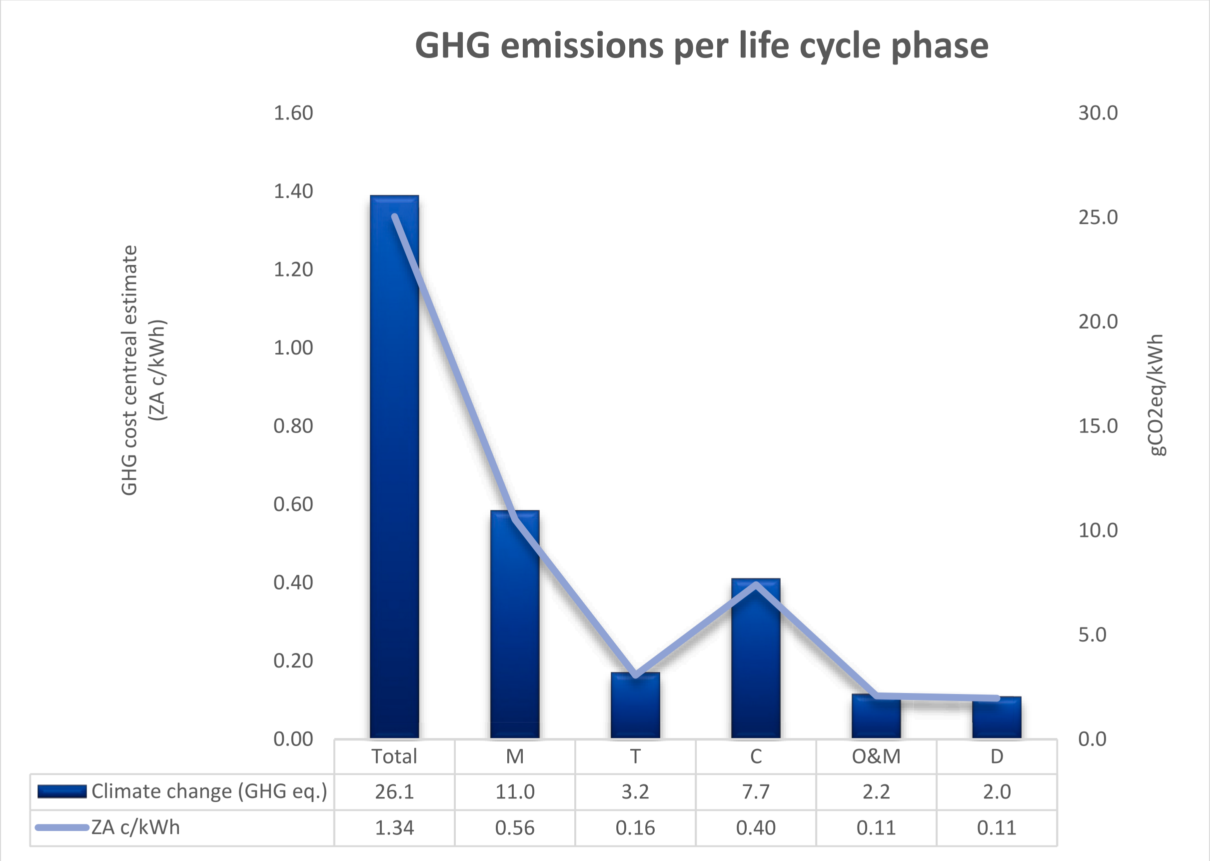


Fig. 4. GHG emissions (g CO_2 eq/kWh) per life cycle impact (ZAc/kWh).

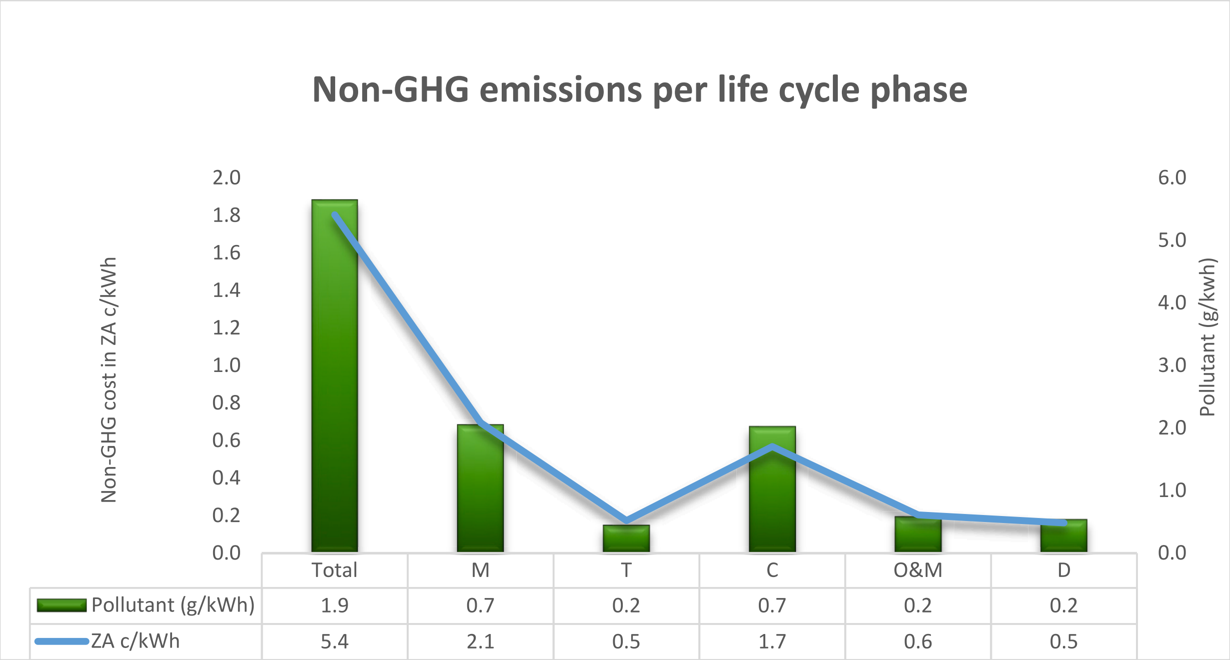
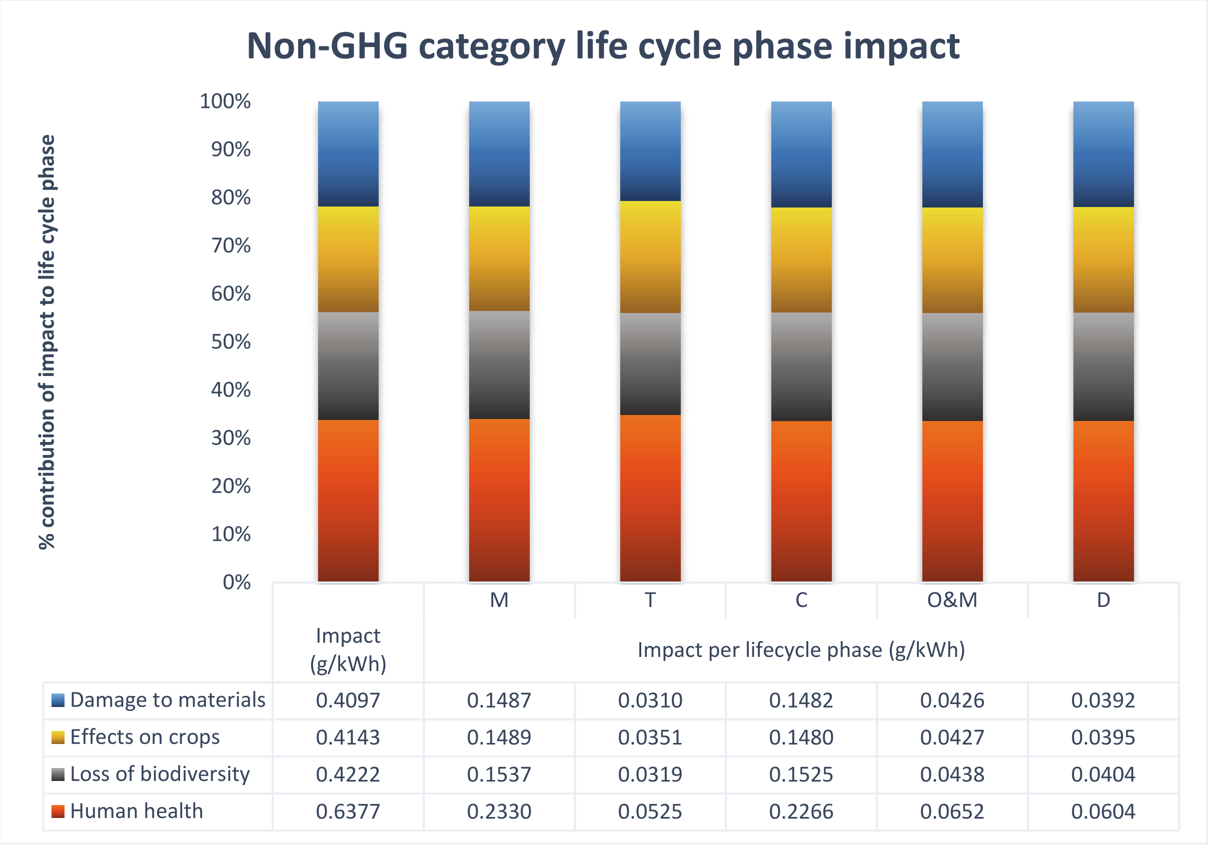


Fig. 5. Non-GHG emissions (g CO_2 eq/kWh) per life cycle impact (ZAc/kWh).

minimum and maximum cost values from Table 6), are considered. In contrast, the assessed onshore wind farm in this study estimated the total GHG impact as 26.1 gCO_2eq/kWh, with an external cost range of 0.261–9.12 €/MWh. These results fall within the range obtained from the literature.

There are modest differences, the most noticeable being a 21 gCO_2eq/kWh variance (80.77 % lower than the analysed onshore wind farm), as determined by Bonou et al. [73]. The study conducted by



	Impact (g/kWh)	M	T	C	O&M	D
		Impact per lifecycle phase (g/kWh)				
🟦 Damage to materials	0.4097	0.1487	0.0310	0.1482	0.0426	0.0392
🟨 Effects on crops	0.4143	0.1489	0.0351	0.1480	0.0427	0.0395
⬛ Loss of biodiversity	0.4222	0.1537	0.0319	0.1525	0.0438	0.0404
🟥 Human health	0.6377	0.2330	0.0525	0.2266	0.0652	0.0604

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

Table 9
Onshore wind farm external costs.

	Impact (g/kWh)	External costs ZAc/kWh	M	T	C	O&M	D
Climate change (GHG eq.)	26.1	0.534 (Low)	0.225	0.066	0.158	0.044	0.042
	–	1.336 (Central)	0.562	0.164	0.395	0.111	0.105
	–	3.931 (High)	0.786	0.786	0.786	0.786	0.786
Human health	0.638	4.724	1.726	0.389	1.679	0.483	0.447
Loss of biodiversity	0.422	0.604	0.317	0.115	0.024	0.114	0.033
Effects on crops	0.414	0.053	0.028	0.010	0.002	0.010	0.003
Damage to materials	0.410	0.031	0.016	0.006	0.001	0.006	0.002
Total non GHG	1.88	5.411	2.087	0.520	1.706	0.613	0.485
Total External Cost	–	5.946 (Low)	2.312	0.586	1.864	0.657	0.527
		6.747 (Central)	2.649	0.684	2.101	0.724	0.590
		9.876 (High)	3.098	1.372	2.650	1.444	1.313

Table 10
Sensitivity analysis excluding sea and land transportation costs for non-GHG impacts.

Estimate	Original total external cost (ZAc/kWh)	Adjusted external cost (ZAc/kWh)	Percentage reduction (%)
Low	5.946	5.426	8.75 %
Central	6.747	6.227	7.71 %
High	9.876	9.356	5.27 %

Chipindula et al. [75] about the onshore wind farm analysed in this study revealed the second most significant difference of 19 gCO_2eq/kWh (73.1 % lower than the analysed wind power plant). Despite these differences, the results of the study on the onshore wind farm are consistent with the wide range of outcomes reported in the literature.

South Africa’s energy grid relies heavily on coal, leading to a higher carbon intensity compared to countries with a cleaner energy mix. Consequently, life cycle emissions associated with energy inputs in our analysis are elevated due to this grid dependency, especially in comparison with countries where wind turbine manufacturing and construction processes are powered by lower-carbon energy sources. The turbines used in this study were manufactured in Germany and transported to South Africa. This adds a significant emissions component to the life cycle environmental impact, as the logistics of long-distance shipping contribute to the overall carbon footprint. In contrast, assessments conducted in countries with local manufacturing may report lower emissions due to reduced transportation requirements. We adopted a cradle-to-grave approach, assuming no recycling at the disposal phase, as components such as turbine blades, lubricants, and magnets are still under research for recycling feasibility. This differs from studies that might assume partial recycling or extended turbine lifespans, thus impacting emissions and cost outcomes.

To compare the CO_2eq emissions of wind power with coal in South Africa, it is crucial to consider the stark difference in emissions profiles.

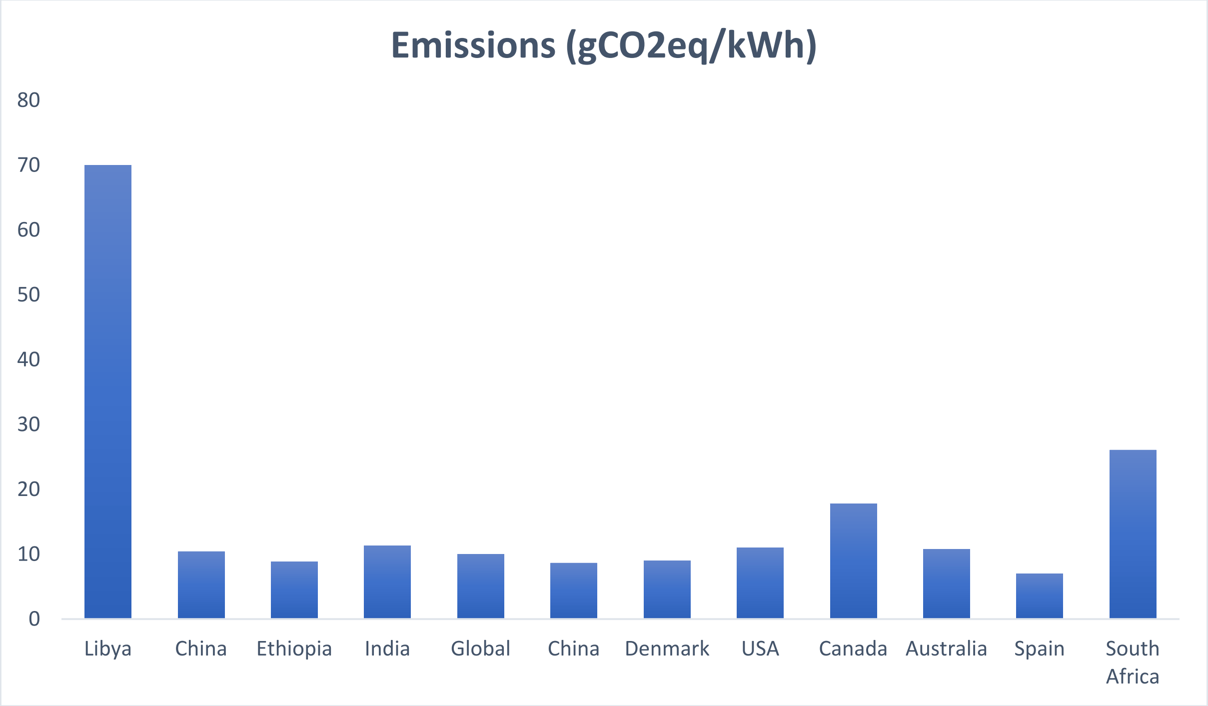


Fig. 7. GHG impacts comparison with the current study and the literature.

The life cycle assessment (LCA) of the 138 MW wind farm in this study estimates climate change impacts at 26.1 gCO_2eq/kWh. This is significantly lower than the CO_2 emissions from coal-fired power plants in South Africa, where typical emissions range from 925 to 1262 gCO_2eq/kWh [89]. Coal plants, particularly in South Africa, are a major source of emission due to the country's reliance on coal as its primary energy source. The high emissions associated with coal power not only contribute to climate change but also result in severe environmental and health impacts. In contrast, wind power's CO_2eq emissions are primarily linked to the manufacturing and construction phases, which are much lower in comparison, making wind energy a far cleaner option for reducing carbon emissions and supporting South Africa's transition to a low-carbon economy.

An assessment of the GHG emissions relevant to onshore wind farms was established in the literature with distributed generation (DG) being one of the strategies adopted by wind power plants to reduce costs and environmental impacts [87]. It was obtained that there may be differences in the results between the harmonisation technique and the standard way of performing an LCA because of several factors.

By leveraging actual data from an onshore wind farm and making use of global data maturity, onshore wind studies can disclose the observed discrepancies in both the present study and previous research. The obtained results from the onshore wind farm closely match the range reported in the literature, suggesting little variances even with possible small 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 case study research design, focusing on a unique case, introduces potential differences in results based on plant capacity, life cycle boundary assumptions, and author perspectives. Variations in results with overall literature studies can be attributed not only to these factors but also to different transportation requirements, modeling, and the use of diverse analysis tools. The influence of these factors on the overall impact results obtained by the harmonisation method emphasises the need for a comprehensive understanding of the intricacies involved in onshore wind farm studies.

5. Conclusion

This study provides a comprehensive life cycle assessment (LCA) of a 138 MW onshore wind farm in South Africa, focusing on the external costs associated with its development, construction, operation, and disposal. A critical gap in the literature is filled by quantifying the environmental, health, biodiversity, and material impacts of wind power, offering valuable data for policymakers and stakeholders. The findings from this study are significant for the broader context of renewable energy development, as they inform cost assessments and policy decisions related to onshore wind projects. The detailed analysis of external costs provides a more accurate representation of the true costs of wind power, which is crucial for promoting informed decision-making and sustainable energy transitions. The novelty of this study is in its comprehensive assessment of both GHG and non-GHG external costs associated with an onshore wind farm in South Africa, a first for this region. By integrating LCA methodology, external costs across various life cycle phases were quantified. These results underscore the need for detailed evaluations to support sustainable energy transitions, highlighting the significance of the findings in guiding renewable energy policy and development.

The LCA results from the study in Table 9 illustrated that the external cost for the onshore wind farm was within a range of 5.946 to 9.876 ZA c/kWh, with a median estimate of 6.747 ZAc/kWh. The results also indicated that climate change and human health jointly account for 89.4 % of the median estimate of the external costs, with these impacts primarily associated with the manufacturing and construction life cycle phases. The significant contribution to almost all subcategories was identified in the manufacturing phase, attributed to the energy needed for producing the components of the onshore wind farm. The construction phase emerges as the second most significant phase in the climate change subcategory. This is primarily attributed to the transportation demands associated with onshore wind turbine components (including gearbox, tower, blades, concrete, wires, and nacelle), along with the energy needs for cranes and the assembly process. The transportation phase is specifically accountable for conveying turbine components and essential materials for establishing onshore wind farms. On the other hand, the O&M and disposal phase plays a minor role in the overall impact, as the energy consumption for plant operation and disposal is comparatively low. The extraction of materials and the manufacture of major components from overseas contribute significantly to external costs in most subcategories, primarily due to emissions of nitrogen oxides, ammonia, and sulphur dioxide during the manufacturing phase. While onshore wind turbines have notable effects on biodiversity, particularly on bats and various bird species, emphasising the adverse effects of these turbines, the impact on birds in the South African context is minimal. This is attributed to the strategic placement of onshore wind farms in areas that do not intersect with common bird migration paths.

The manufacturing phase constitutes the highest share of the total external costs, accounting for 35.71 %. Subsequently, the construction phase follows, contributing 29.3 %, primarily linked to the transportation demands related to onshore wind turbine components (such as gearbox, tower, blades, concrete, wires, and nacelle), as well as the energy requirements for cranes and the assembly process. The transportation, O&M, and disposal phases, characterised by low operating energy needs, exhibit the lowest external cost contributions at 11.71 %, 12.52 %, and 10.77 %, within the overall central estimate of the external cost. The comparison analysis of GHG emissions during the LCA of the 138 MW Jeffreys Bay Wind Farm indicates results consistent with those found in other literature studies, ranging from 5 to 33.6 gCO_2eq/kWh (resulting in an external cost of 0.05–11.76 €/MWh). Slight variations may be attributed to differences in modeling requirements. In the South African onshore wind turbine manufacturing sector, dependence on imported components from developed countries like Germany, the USA, South Korea, and Spain is notable. These countries manufacture components locally, mitigating the impacts of transport activities. The study's significant contribution lies in its ability to compare external costs with the internal costs of onshore wind turbines in South Africa. With a fixed rate of approximately 0.495 R/kWh set by the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) in 2022, it is shown that approximately 15.7 % of this cost is attributed to the median external cost, which is 6.747 ZAc/kWh as indicated in Table 9. The minimum and maximum external costs represent 13.86 % and 23 % of the internal cost. It is noteworthy that the external costs of onshore wind power fall within the range of estimates discussed in section 2 of the study. This underscores the growing significance of external costs in the overall assessment of wind power costs, driven by the decreasing cost of onshore wind power technology.

There is a global initiative to decrease GHG emissions. The substantial reduction in GHGs is largely attributed to the generation of electricity from renewable sources. Even technologies relying on renewable energy can result in unaccounted impacts and externalities. Real insights into the actual costs and emissions associated with electricity production for different technologies are revealed through externality studies. Various research studies, including the current one, indicate that onshore wind farms can produce electricity with lower GHG emissions compared to those generated by fossil fuels. Wind turbine-generated power is commonly stored in batteries, effectively addressing the intermittency challenges often associated with renewable energy sources. The careful consideration of plant locations is crucial for minimising the impact on crop damage and biodiversity loss, while the manufacture of wind turbine components will reduce the effect on human health as indicated in the results and discussion section. This study reveals that high emissions are attributed to the transportation of key components in onshore wind farms.

To optimise benefits for the local community, environment, and economy, there is potential in localising the manufacturing of these components, thereby reducing emissions from transportation activities. Challenges exist in expanding local manufacturing due to the need for a substantial initial investment in infrastructure and the development of a skilled workforce amidst open markets and declining costs of wind turbine components. Prioritising the manufacturing of superior components not only fosters innovation but also stimulates research and development (R&D) within the national context. Conducting an LCA for an onshore wind farm, the study determined external costs associated with the technology. The policy recommendations for mitigating the external costs of onshore wind power include incentivising local manufacturing of turbine components, enhancing quality standards, investing in workforce development, supporting research and innovation, and improving infrastructure. Also, Nevertheless, a degree of uncertainty persists, potentially resulting in either minor overestimations or underestimations of the impacts or external costs. These onshore wind farms in South Africa are relatively new, relying on assumptions drawn from analogous international studies.

The major challenge encountered during the study was the variability and uncertainty in data, particularly concerning emissions and materials during different life cycle phases. Given the inherent uncertainty in applying an abatement cost approach to non-GHG externalities, an initial recommendation for future investigations will be to use a bottom-up impact pathway approach. This would involve conducting an LCA using primary emission data from plants and transport sources to estimate localised impacts on human health, biodiversity, crops, and materials. Such an approach would better account for regional variations in pollutant dispersion and associated external costs, reducing reliance on generalised cost estimates. An additional recommendation for further study would be integrating the life cycle analysis with a techno-economic assessment, which would help stakeholders attain a more comprehensive understanding of wind power's true costs and sustainability implications. This approach will facilitate informed decision-making and contribute to the promotion of sustainable practices within the wind energy sector. Considering the significant off-shore wind availability off the Southern African coast, an external cost LCA for an off-shore wind farm off the Southern African coast is an added recommendation since no study currently exists on it. Integrating socio-economic factors and stakeholder perspectives will enhance the assessment of external costs. Focusing on the cumulative impacts of multiple renewable projects and their interactions with infrastructure and ecosystems will refine cost assessments, supporting more sustainable energy planning and policymaking.

CRediT authorship contribution statement

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

Declaration of competing interest

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

Appendix A

Table A1
Ecoinvent and material data [73,88].

Inventory materials for the wind farm	Quantity
Steel	57.08×10^3 kg
Reinforcing steel	155×10^3 kg
Cast iron	72.6×10^3 kg
Concrete	1630×10^3 kg
Copper	10.64×10^3 kg
Fibreglass	14.2×10^3 kg
Aluminum	2.7×10^3 kg
Epoxy resin	12.7×10^3 kg
Polyethylene	4.17×10^3 kg
Lubricating oil	10.1×10^3 kg
Aluminum, cast alloy	4.16×10^3 kg
Concrete	6.19×10^2 m^3
Excavation, hydraulic digger	3.14×10^2 m^3
Polyethylene, high density, granulate	3.09×10^3 kg
Steel, chromium steel	1.14×10^3 kg
Wire drawing, copper (process)	1.06×10^3 kg
Diesel, burned in building machine	5.79 MJ
Gravel, crushed	18.4 kg
Electricity, medium voltage	0.106 kWh
Waste glass	7.1×10^3 kg
Scrap steel	5.46×10^3 kg
Scrap copper	1.06×10^4 kg
Iron scrap, unsorted	7.26×10^4 kg
Electronics scrap from control units	4.4×10^2 kg

Data availability

Data will be made available on request.

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