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Life cycle assessment of wind turbine systems: A statistical synthesis approach to address greenhouse gas emissions

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ABSTRACT

Reducing the carbon footprint and transitioning towards cost-effective, cleaner energy sources are among the most critical engineering challenges of the 21st century. Climate change modeling scenarios increasingly depend on greener technologies to limit global warming to below 2.0 °C. Wind power, along with other renewable energy technologies, plays a pivotal role in realizing these goals. This study presents a comprehensive review of the environmental impacts of wind power through the application of life cycle assessment (LCA) methodologies. It integrates findings from various LCA studies and uses statistical comparisons and graphical analysis to identify key influencing factors such as turbine size, geographical location, and methodological variations that drive differences in reported environmental impacts. These insights are essential for standardizing evaluations and assuring precise carbon footprint for global estimations, therefore informing more dependable mitigation plans. Wind power demonstrates favorable environmental outcomes compared to fossil fuels, however, emission sources, particularly during wind turbines component production, and the scale of the wind farms are identified as the key factors that influence the choice between onshore and offshore wind farms. Additionally, the study identifies key gaps in current research, including resource depletion, toxicity, and uncertainties related to component replacement and offshore operations, where environmental impacts remain poorly understood. Building upon these, the study emphasizes the necessity of enhancing LCA approaches to more effectively incorporate temporal and impact scale elements by creating more precise, unit-based measures.

1. Introduction

Wind energy is widely regarded as a sustainable solution to the dual challenges of the energy crisis and environmental concerns. As a transformative alternative to fossil fuels, it aligns with the energy-environment nexus by advancing eco-friendly technologies, promoting sustainability, and catering to the increasing demand for clean energy. [1,2]. According to the Global Wind Energy Council (GWEC), global wind energy additions currently reach 100 GW annually, with projections indicating an increase to 180 GW per year post-2025 [1,3,4]. At present, the global expansion of wind energy is contributing to the reduction of 1.1 billion tons of CO_2 emissions annually, see Fig. 1a. However, it is projected that an increase to 28 GW will mitigate the overall global challenge of CO_2 emissions and global warming, thereby maintaining levels below 2 °C (UN Climate Report). Over the last few decades, there has been a notable growth in both onshore and offshore wind farms, demonstrating their capability as one of the most cost-effective options amongst other renewable energy sources [5,6,7]. Fig. 1b underscores the economic case for renewables: their levelized cost of electricity has declined sharply from 2009 to 2024 [8]. However, renewables such as wind power and solar harvesting systems (both PV and solar thermal), remain interconnected with non-renewable resources, resulting in certain environmental impacts, including land use changes, resource consumption, and effects on local habitats and water resources. Among these, greenhouse gas (GHG) emissions remain a critical factor, as they directly contribute to climate change and serve as a key metric for assessing the overall sustainability of technologies such as wind power [9]. These, categorized as environmental loads, are linked to renewable energy systems production, which can be evaluated and measured using the life cycle assessment (LCA) methodology [10–13]. Fig. 2 depicts the greenhouse gas emission comparison amongst various energy production technologies, revealing that wind turbines exhibit one of the lowest life cycle emissions amongst other renewable resources, data taken from Ref. [14] and other sources.

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Interestingly, GHG emissions from tropical hydropower sources are quite high, mainly due to larger biomass quantities, higher average carbon content in the biomass, and warmer temperatures that accelerate the decomposition process.

The global distribution of new wind power installations between 2022 and 2024 exhibits a pronounced regional imbalance (see Fig. 3), with China maintaining a dominant position by contributing the largest annual capacity additions. In 2024, China alone installed 86.9 GW, a figure that exceeds the combined contributions of most other nations, thereby reaffirming its role as the principal driver of global wind deployment. In contrast, the United States, despite possessing a substantial pre-2021 capacity base, demonstrates a declining trajectory in recent years, with only 4.2 GW added in 2024. Emerging economies such as Brazil and India exhibit steady and incremental growth, reflecting expanding renewable energy investment and policy support in these regions. European countries, including Germany, the United Kingdom, Spain, and France, continue to add capacity at comparatively moderate levels, while contributions from smaller nations such as Sweden, Finland, and the Netherlands remain consistent yet limited in scale. Collectively, these patterns underscore the highly concentrated nature of global wind energy expansion, where China accounts for the majority of growth, while most other countries contribute relatively modest increments.

The life cycle assessment methodology delivers a comprehensive quantitative data related to the environmental impacts associated with the various stages of its life, beginning with the extraction of raw

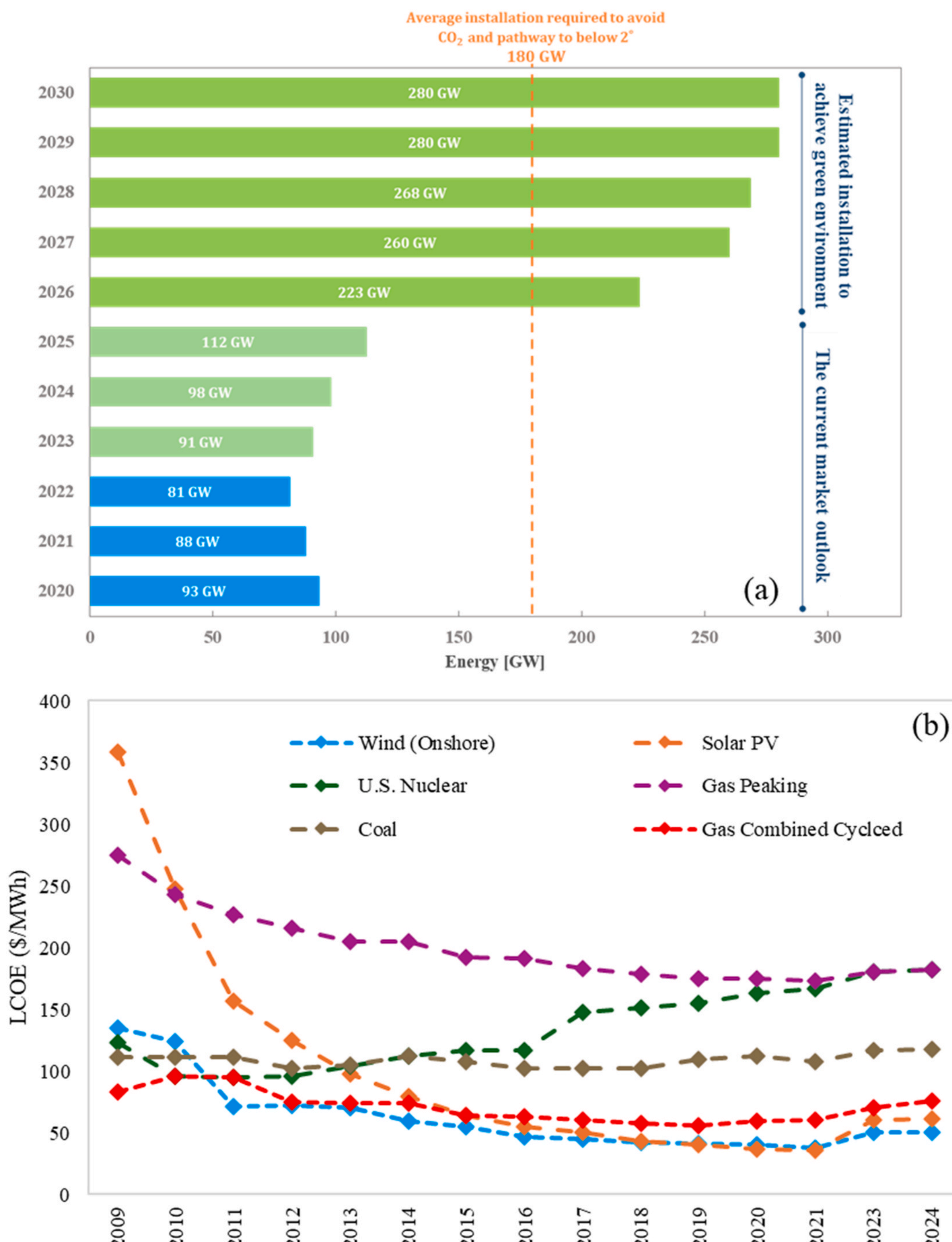

Fig. 1. (a) Clean energy requirement to reduce the CO_2 emissions [15,16]. (b) Levelized Cost of Energy consuption over the years from 2009 to 2024 [8].

materials and extending to the end-of-life phase of wind turbines and farms. This includes the processes of production, transportation, installation, operation, maintenance, and disposal at the end of their life cycle. This quantitative information serves as a prerequisite for decision makers. Additionally, it aids in assessing the effects of the brown process (fossil-based energy process or reliance on non-renewable) associated with wind power generation to enhance its cleanliness and sustainability. The International Organization for Standardization defines the ISO 14040 and ISO 14044 series, which establish the methodological framework and standards for LCA. Additionally, the International Reference Life Cycle Data (ILCD) System provides guidelines tailored for various product categories based on regional specifications worldwide. The current methodological standards for LCA consists of four distinct steps: 1) Definition of objectives and scope, 2) Assessment of inventory, 3) Evaluation of impacts, and 4) Analysis of results.

Past research on LCA of wind power includes, Lenzen and Munksgaard [17], who examined the variation in CO_2 intensity across 72 wind energy systems which were documented between 1977 and 2001. Their analyses of CO_2 intensity were conducted on multiple processes, including the manufacturing and materials used for wind turbines and their towers, as well as the overhaul system following the service life or recycling of turbines. Kubiszewski et al. [18] later built upon the research conducted by Lenzen and Munksgaard, encompasses the concept of energy return on investment. Similarly, Raadal et al. [19] proposed a further extension of the work by Lenzen and Munksgaard, which involved a comparison of the LCA of greenhouse gas (GHG) emissions between wind energy and other renewable energy sources, primarily hydro, as well as conventional energy sources, including fossil fuels and nuclear energy. Their findings indicated that additional explanation is necessary to facilitate a comparison between renewable energy sources; an analysis of greenhouse gas emissions resulting from flooded land in the context of hydropower, as well as the relationship between the size of wind turbines and prevailing wind conditions in the case of wind energy. Arvesen and Hertwich [20] incorporated qualitative discussions and a new LCA survey on prior studies that focused on cumulative environmental impacts, energy demand, GHG emissions, and specific LCA aspects such as capacity factor assumptions, modeling of recycling benefits, and techniques for calculating life cycle inventories. Martinez et al. [21] presented a comprehensive study on LCA of aging wind farms, particularly those utilizing low-power wind turbines, and the enhancement of these facilities. Their study conducted a comparison of the environmental impact between the original wind farm and the repowered wind farm. Masanet et al. [22] provided a comprehensive review of various electric power technologies utilizing LCA, encompassing all significant environmental impacts and human health considerations. Additionally, they presented quantitative results and outlined methods for enhancing LCA methodology. Mendecka and Lombardi [23] presented LCA results for both onshore and offshore wind farms. They utilized harmonization and simplified LCA models, which offer a comprehensive and general framework for evaluating the environmental impacts of wind turbine systems.

The importance of LCA reviews is well recognized, as they provide insight into critical factors that are often overlooked or misunderstood in LCA studies [24–26]. The objective of this study is to systematically synthesize and clarify the environmental impacts of wind energy systems through life cycle assessment. First, we compile and harmonize peer-reviewed studies covering all major life-cycle stages, including manufacturing, substructure, transport, installation, operation, maintenance, and end-of-life for both onshore and offshore turbines. Second, we integrate statistical evaluation with a methodological review of process-based, EEIO, and hybrid approaches to identify and rank the principal determinants of variability. Third, we assess how methodological choices, system boundaries, and inventory assumptions propagate uncertainty and contribute to variation in reported results. Fourth, we establish an evidence base to harmonize LCA practices, improve cross-study comparability, and strengthen global-scale carbon footprint estimates. Finally, we put forward recommendations for future policy to support more trustworthy assessments and guide sustainable deployment of wind energy systems.

The following section briefly discusses the critical background about LCA and the two fundamental methodological approaches to apply the life cycle inventory assessment. Next, we synthesize the published LCA literature that construct the basis of review. Sections 4 and 5 cover the scope, assumptions, and methodologies of wind-power LCAs and present stressor and impact indicators with critical discussion. Section 6 details emissions across inventories, component manufacturing, and project processes; Section 7 briefly addresses non-emission environmental effects; and Sections 8–10 present future prospective, conclusions, and outline the recommendations for policy (see Fig. 4).

2. Brief details of LCA and calculation techniques

LCA methodologies for wind energy assess the environmental impact associated with the production of one unit of electricity generated by

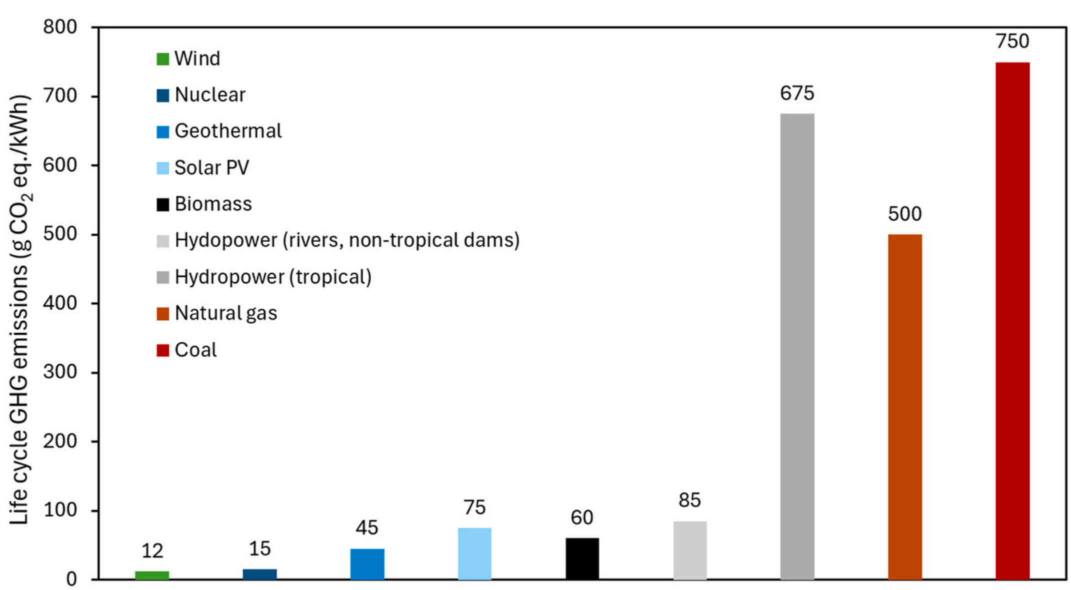

Fig. 2. CO_2 emission comparison of different energy sources [14].

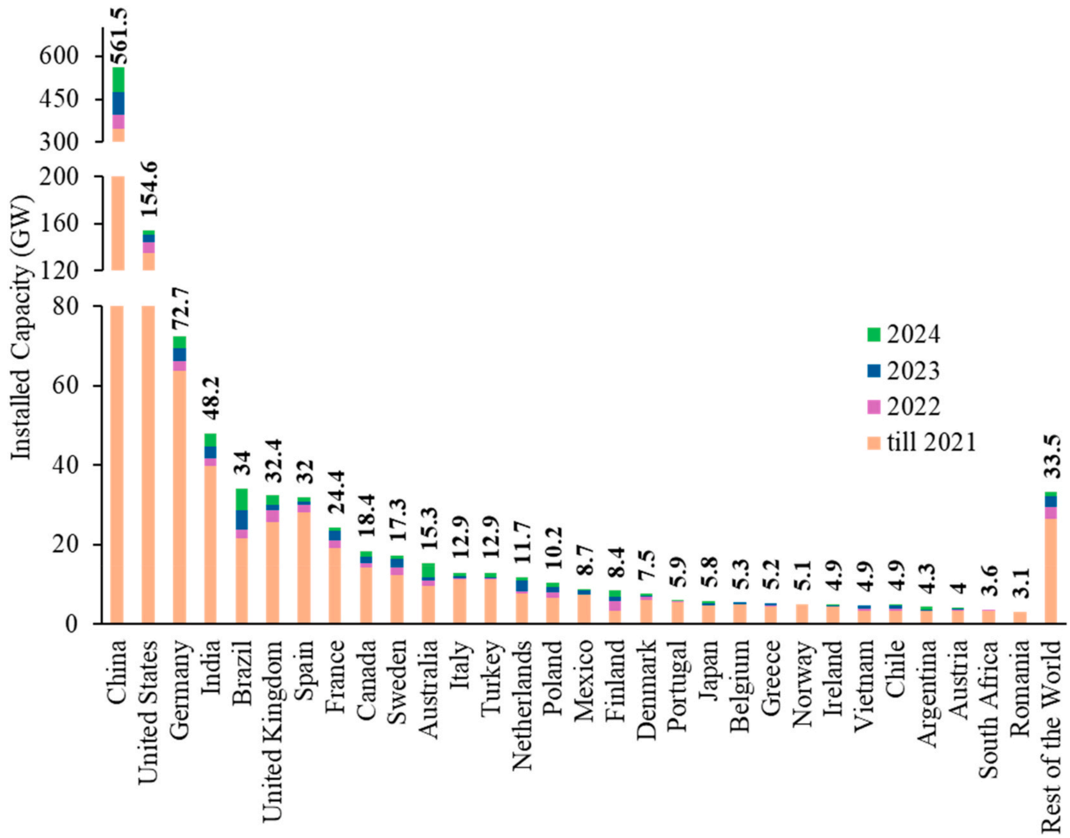

Fig. 3. Country/Region wise installed capacity of wind power plant in GW.

wind. This assessment encompasses the entire lifecycle, starting with the materials and manufacturing processes of wind turbines, progressing through the development of wind farms, including logistics and land allocation - continuing into operational phases that involve maintenance and troubleshooting, and concluding with the end-of-life considerations. This systematic approach allows LCA to deliver comprehensive data regarding the environmental impacts associated with the use of wind turbines for electricity generation.

Two fundamental methodologies have been identified for the application of LCA. The process-based LCA methodology begins by detailing the inputs, such as materials and energy requirements, as well as the outputs, which includes waste and emissions to the environment based on specific operational data involved in production. This method primarily relies on physical process that yields highly detailed and accurate results. However, two key limitations are associated with process-based LCA methods [27–29]. The first relates to the initial definition of system boundaries and assumptions, which determine which elements are included or excluded from the assessment [30]. The consideration of circularity effects can result in the omission of certain upstream processes or auxiliary inputs that are essential for generating complete life cycle inventories. This exclusion can restrict the scope of the analysis and potentially ignore contributors whose cumulative or synergistic environmental effects may be significant [31].

The second LCA approaches, known as EEIO (environmentally extended input-output) analysis, operates at a macroeconomic level. It uses input-output tables augmented with environmental data to estimate resource use and emissions across entire economies or supply chains [32]. While EEIO functions at a high level of aggregation and typically lacks the sectoral resolution needed for product-specific assessments, it offers the advantage of including indirect environmental effects that process-based LCA may miss due to boundary cut-offs. Therefore, EEIO complements process-based LCA by capturing upstream and background system impacts that are difficult to quantify through direct process modeling. Consequently, the sector resolution is often insufficient for the application of LCA in product analysis [33].

The hybridization of these two approaches can overcome the individual limitations of each, providing a more holistic and robust assessment of environmental impacts across the entire product life cycle [34]. Process-based LCA captures major, well-defined operations with high precision, while EEIO covers the broader system-level contributions that might otherwise be excluded. As a result, hybrid LCA combines the specificity of process data with the completeness of EEIO analysis. However, the effectiveness of this integration is highly dependent on data quality and the chosen hybridization methodology [34–36]. Demir et al. [37] proposed a novel approach for wind farms that combined LCA with the Analytical Hierarchy Process to assess the environmental impact in conjunction with conventional site selection factors, such as wind speeds.

Bush et al. [38] conducted LCA utilizing two distinct process-based and hybrid methodologies. The enhanced structural detail of the hybrid LCA method resulted in more precise emission predictions, yielding higher values. Techniques like the integrated hybrid LCA possess the ability to capture impacts that would typically be obscured by the truncation error associated within the process of LCA. Weidmann et al. [39] conducted an LCA employing two hybrid methodologies: an I/O-based method and an integrated hybrid method. The Integrated Hybrid Life LCA and I/O-based LCA methodologies should theoretically produce identical outcomes; however, the I/O-based hybrid approach quantifies all elements in a monetary sense, whereas the integrated hybrid methodology utilizes physical units.

Martinez et al. [40] evaluated LCAs for wind turbines utilizing multiple software tools, uncovering substantial discrepancies in results across specific effect categories based on the software used. The data for Acidification and Eutrophication were categorized into two unique groups: one consisting of outputs from CML, Ecopoints, EDIP, EPS, and TRACI, and the other from Eco-indicator 99 and IMPACT2002. Within the aspect of Abiotic Depletion, the majority of results were found to be consistent, with the exception of EPS, which indicated negative values. Likewise, in the context of Ozone Layer Depletion, the outcomes using Ecopoints 97 significantly diverged from those of alternative methodologies. The authors also reported a significant variance in the results of all examined LCIA methodologies for Human Toxicity and Ecotoxicity.

LCA is utilized to identify sensitive parameters and inconsistent methods effectively. Subsequently, modifications of the assumptions may result in reduced uncertainty, facilitating the adjustment of results for alternative conditions [41]. Improved LCA models provide a straightforward and effective method for predicting environmental impacts, rather than presenting a complex approach. The findings of the LCA are organized into categories known as indicators, which can be classified into 'midpoint' or 'endpoint' levels of aggregation concerning environmental impact. Midpoint indicators aggregate various stressors into a single impact category while endpoint indicators estimate impact at the end of the cause-effect chain, typically human health, ecosystem integrity, and natural resource sustainability. However, certain methodologies focus on singular indicator for environmental damage [42,43].

3. Literature survey

The principles for evaluating the energy performance of products were established in the 1970s during a conference held by the International Federation of Institutes for Advanced Studies, which introduced the 'energy analysis' method. Consequently, LCA represents a contemporary approach to energy analysis, extending beyond mere energy evaluation. LCA was introduced in the late 1980s and underwent significant evolution during the 1990s, coinciding with improved access to scientific publications. Subsequently, various approaches and guidelines emerged. The recent developments have been comprehensively summarized by Finnveden et al. [44] and Guinee et al. [45].

The life cycle assessment of wind turbines typically encompasses two primary objectives: 1) the comparison of two or more wind turbines, focusing on aspects such as size, performance, and environmental impacts, which are often subject to subjective analysis; 2) the assessment of sensitive parameters related to wind turbines, primarily based on environmental impacts, including factors like transport distance and energy requirements for dismantling. Two meta-analyses are present in the literature. Additionally, Cleary et al. [46] concentrated solely on the LCA of various infrastructure components (such as concrete towers, steel towers, and tower foundations) within wind turbine systems, with a particular emphasis on the comparison between onshore and offshore wind turbines. Jorge and Hertwich [47]. exclusively provided the LCA for the power transmission system linked to wind turbines. Berndt [48] conducted an analysis focused solely on the impact of concrete in the construction of foundations for large wind turbines. They concluded that the reduction of CO_2 is contingent upon the strength class of the cement. Arbabzadeh et al. [49] performed a LCA study on energy storage batteries linked to wind turbines. Jin et al. [50] conducted a comparison of wind turbine production utilizing rare earth elements versus those that do not, employing LCA methodology. Jiang et al. focused on the environmental impact of wind turbine gearboxes.

Several LCA articles described the impact indicators predicated on various situations. Benitez et al. [51] performed a prospective life cycle assessment (pLCA) concentrating on a 9.5-MW offshore wind farm, with two life forecasts stretching to 2030 and 2050. It was noted that, while considering the lifespan till 2050, maintenance and operation significantly influence stressors. Moreover, they also predicted LCA using three scenarios Pessimistic, Moderate and Optimistic representing different estimations of water depth, wind speed, and rotor diameters. Struthers et al. [52] conducted a Life Cycle Assessment study on four major categories of wind turbines, focusing on the analysis of stressor impacts based on the geographical location (North, East, and Northeast). Geographical locations can significantly influence the capacity factor, resulting in varying patterns of stressors and considerably altering transportation emissions. Moreover, the Life Cycle LCA conducted on two different turbine sizes by Turkmen and Babuna [53] revealed different lifespans of fixed components (40 years) and moving components (20 years), leading to a decreased negative environmental impact.

For the current review, peer-reviewed articles published within the last two decades (2010–2024) have been selected. Additionally, official environmental reports from government and industry pertaining to the life cycle assessment of wind power technology were included in this review. The literature survey indicates that the past decade has experienced substantial advancements in wind energy systems. Consequently, a concise and critical review of these systems will assist in identifying the primary indicators of greenhouse gas emissions. The objective of this article is to present robust LCA databases, methodologies, and economic characteristics from recent decades. Additionally, a review of other studies was conducted to establish a connection between the background and recent developments, providing valuable insights.

4. Scope, assumptions and boundaries

4.1. System scope and end-of-life modelling

LCA literature encompasses the entire spectrum of wind turbine sizes, ranging from watt-scale units to multi-megawatt turbines, applicable in both offshore and onshore settings [54,55]. The sources listed in Table S1 clarify that the majority of the assessments pertain to onshore wind farms, with a notable predominance of studies referencing European nations [56,57]. Numerous analyses of oceanic systems are also evident [58]. The life cycle assessments of offshore wind farms focus on bottom-installed wind turbines, primarily situated in shallow waters, with a few outliers [35]. Two studies investigate a hypothetical wind farm consisting of floating units and an operational wind farm at a water depth of 30 m, respectively [59].

The sole life cycle stage common to all assessments is the production of wind turbines. The assessments of wind turbines with capacities of hundreds of kilowatts and above are predicated by the majority model power lines, which encompass internal and external cabling, and occasionally transformer stations, required to link the wind farm to the existing grid, as well as the building of foundations. Transportation operations, together with the operation and maintenance of systems, are generally included in most studies, however, to varying degrees. Numerous reviews explore integrated systems that enhance energy storage by incorporating energy converters with additional power generation technologies [60,61].

The end-of-life phase is represented in several ways. Some studies incorporate assumptions to estimate transit and disposal of waste, whilst others exclude this aspect. The end-of-life phase could reduce emissions and resource consumption, rendering it distinct amongst the life cycle stages. When analysts subtract indicator values deemed undesirable, negative contributions arise, particularly when system components are cremated or recycled after their operational lifespan to yield valued outputs. In LCA literature, this is referred to as substitution by system expansion or the avoidable burden technique, wherein the system receives credit for reintroducing useable resources (e.g., recyclable steel) into the technosphere. Although LCA studies utilizing the avoided load method are fewer in number, they constitute a considerable proportion. The installation and decommissioning of wind farms is also modelled in a similar manner.

Most wind-energy LCAs use cradle-to-grave boundaries (extraction → manufacturing/transport → installation → operation/maintenance → end-of-life), providing a complete impact profile. Fewer adopt cradle-to-gate (to the factory gate, sometimes including transport) or cradle-to-use; in our dataset, two studies (Table S1) applied cradle-to-gate with transport. The dominance of cradle-to-grave reflects the need to capture operational and decommissioning effects for robust comparison, policy design, and technology improvement. For more sources, cited in

Table S1 see Refs. [62–69].

4.2. Capacity factor

Life Cycle Assessments for both onshore and offshore wind farms typically estimate operational lifespans of approximately 20–25 years. The capacity factor (the ratio of actual energy output to the maximum possible output over a specific period) is used as a key performance metric. In Fig. 5, the capacity factors of different turbine types are plotted against their rated power, which refers to the maximum electrical output a turbine can produce. In accordance with predictions and established knowledge, three overarching tendencies may be discerned in Fig. 5 [70]: 1) Enhancing the nominal capacity of wind turbines leads to an improvement in their capacity factor; 2) Energy extraction in offshore wind farms surpasses that of onshore farms; 3) Onshore locations exhibit lower capacity factors than offshore locations for a given power rating. The mean assumed capacity factor (± standard deviation) across all areas is 29 % (±8.64 %). For onshore turbines with a capacity below 100 kW, the capacity factor is 25.4 % (±9.1 %), for 100 kW to 1 MW turbines it is 22.67 % (±4.5 %) and for larger than 1 MW turbines it is 30 % (±8.5 %).

When the capacity factor is elevated, the use of energy will significantly decrease, a phenomenon that occurs with nearly every stressor. However, certain stressors exhibit an inconsistent pattern for the lifespan of wind turbines; an extended lifespan escalates maintenance and operational costs, resulting in elevated emissions. This is similar to the methodology employed for calculating generation costs (expressed in units of $/kWh or comparable). Offshore wind turbines possess higher capacity factors due to their exposure to stronger, more consistent winds and reduced turbulence relative to onshore sites [71]. Their increased turbine dimensions and optimal spacings further augment efficiency and energy production. Moreover, offshore locations have less operational constraints, facilitating prolonged and more efficient functioning. The LCA analysis conducted by Wang et al. [72] presented a favorable comparison of the capacity factor between onshore and offshore power ratings of 2.0 MW. They demonstrated that the offshore locations had a 43 % higher capacity factor, yielding an additional 2.5 TWh compared to the onshore site. However, the offshore site generated higher emissions due to substructure requirements, transportation, and increased material usage for wind turbine production. The study conducted by Noori et al. [73] examined the capacity factor comparison of two wind turbines (2.0 and 3.0 MW) for various geographical regions of the USA, focusing on both onshore and offshore installations. The capacity factor for offshore installation was found to be superior (0.462 for the 2 MW turbines and 0.537 for the 3 MW turbines) compared to onshore installations (0.322 for the 2 MW turbines and 0.3 for the 3 MW turbines).

The capacity factor comparison for various sizes was also presented by Teffera et al. [74], which examined one medium turbine (0.1 MW) and three large turbines (1.5, 1.5, and 1.67 MWs). The capacity factor for medium-sized turbines was determined to be 0.17, whereas for large turbines, it ranged from 0.24 to 0.34. Similarly, Cucurachi et al. [75] demonstrate LCA across various turbine sizes, revealing a capacity factor trend of 0.17–0.25 for medium-sized turbines and 0.16–0.24 for larger turbines. Generally, larger wind turbines have higher capacity factors due to their elevated towers and extended blades, which enables them to harness stronger and more consistent winds at greater altitudes. They possess sophisticated technology to harness energy more efficiently, even at reduced wind speeds. Furthermore, their expanded swept area enhances the overall wind energy captured, resulting in a more reliable and elevated energy output.

According to published LCA studies, the average capacity factor for wind turbines in Africa is 0.36 (±0.14), 0.29 (±0.06) for Asia-Pacific, 0.39 (±0.14) for Europe, 0.25 (±0.04) for North America, 0.38 (±0.09) for the UK, and 0.28 (±0.10) for the USA. A larger average capacity factor is observed in Europe; nevertheless, the standard deviation is also elevated. The prediction appears more suitable for the Asia region due to its value being near the global average of 0.33 with a lower standard deviation.

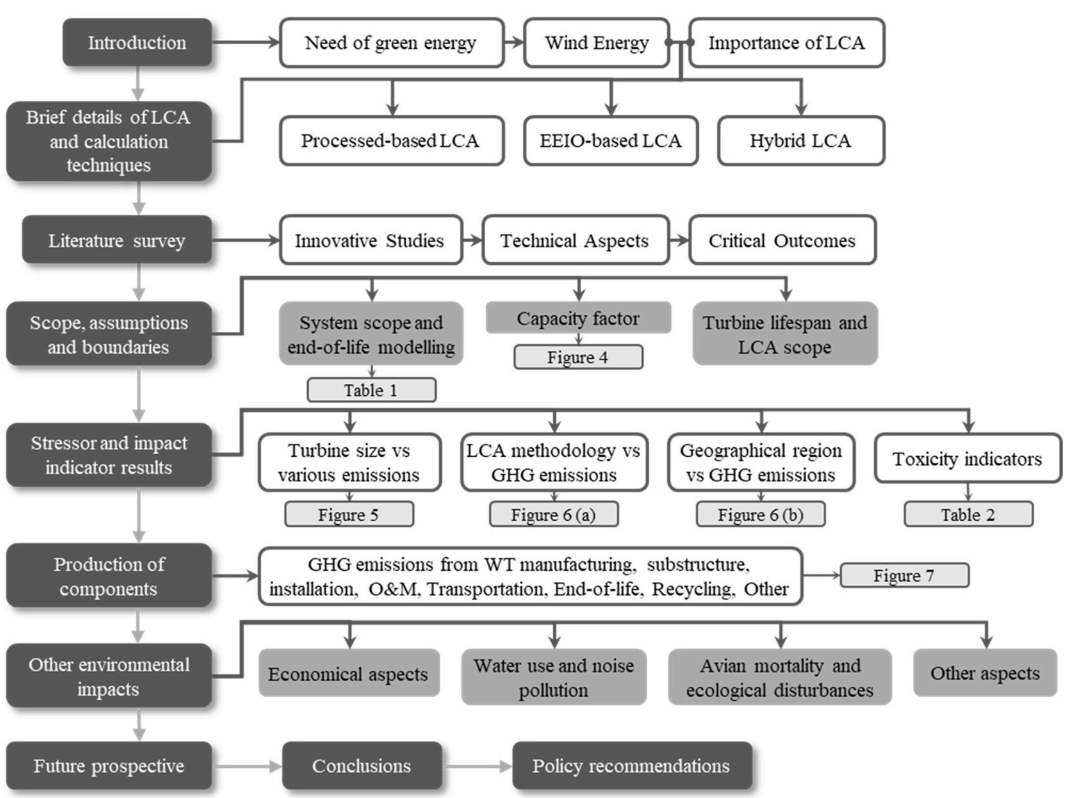

Fig. 4. Overview flowchart of the review's structure and sections.

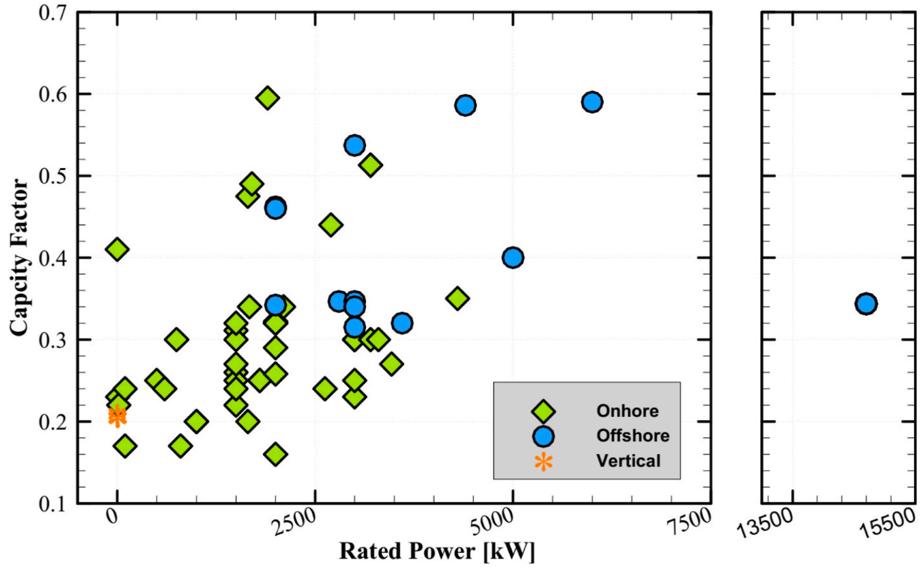

Fig. 5. Capacity factor of vertical, onshore and offshore wind turbines as a function of power rating. (This data is gathered from cited papers of Table 1 and Table S1).

4.3. Turbine lifespan and LCA scope

In contrast to the capacity factor, the actual data related to the lifespan of modern wind turbines is limited; hence, lifetime estimates must rely on evaluations from wind turbine specialists and design lifetimes set by manufacturers. Life cycle assessments typically presume a 20-year lifespan for both onshore and offshore systems. Contemporary economic assessments of wind energy typically attribute lifespans of 20 years for onshore installations and 25–30 years for offshore ones. Based on this data, it appears that the longevity assumptions in the LCA literature are less advantageous for offshore wind farms compared to the analogous assumptions in economic calculations.

Traditionally, LCA research on wind power has been concentrated on energy consumption and greenhouse gas (GHG) emissions; subsequent literature continues to be predominantly influenced by these factors for impact assessments. Table S1 presents a comparison of the sample sizes for energy, CO2, and GHG in relation to other air pollutants depicted in Fig. 6. Typically, contributions from CO2, CH4 and SO2 are regarded when assessing climate change indicator values; however, in certain instances, fluorinated GHG (SF6, HFC, and PFC) are also taken into account. More than half of the research presented in Table S1 incorporates impact categories beyond GHG and energy. Air pollutants associated with the production and burning of fossil fuels (CO2, CH4, CFC, NOx, PM and SO2) are the environmental stressors that generally receive significant attention [17]. These contaminants significantly influence studies and evaluations related to climate change, eutrophication, photochemical oxidation (smog), and acidification. Minimal focus is directed towards pollution types beyond fossil fuel-related air emissions; Table S1 cites just 18 research studies to quantify defined toxicity indicator data [76]. The decline of non-renewable resources and the associated resource requirements are also briefly discussed. Life cycle inventory for specific mineral resources is presented in several publications without doing any impact assessments, while a limited number of studies examine non-renewable resource depletion, for example [77] examined the direct and indirect land use associated with power producing systems, including wind energy. While not elaborated upon, certain studies quantify water usage throughout the life cycle, for example, Fthenakis and Kim [78] conducted a review of prior studies utilizing various technologies about the life cycle water usage in power generation. Hybrid LCA appears in few studies, with the literature dominated by process-based LCAs (Table S1); while future-oriented LCA variants are emerging, they are not yet mainstream.

5. Stressor and impact indicator results

The visual representation of findings from the literature review are shown in Fig. 6, which focuses on the total emissions and impact indicator values. As depicted in Fig. 6, the turbine types are categorized as small, medium, large, vertical-axis, and offshore. The small, medium, large, and vertical-axis turbines all represent onshore wind turbines. The offshore category includes only large-scale turbines (because of data availability). Additionally, a sixth category, labeled "Total," is included in Fig. 6 to represent the combined dataset from all five turbine types. This aggregation provides an overview of the overall variability in emission and energy demand values reported across the full spectrum of wind turbine systems, offering a reference point for comparing individual turbine categories. Based on this classification, the average energy demand to produce onshore wind power is 0.1854 kWh/kWh, with a standard deviation of ±0.24874, while for offshore wind turbines, the average energy demand is 0.1208 kWh/kWh, with a standard deviation of ±0.04891. When comparing onshore and offshore emissions, the average GHG emissions are 32.33 (±52.86) g CO_2 eq-/kWh and 29.0081 (±11.64) g CO_2 eq-/kWh, respectively. The significant large standard deviations and wide ranges that appear in each of the categories (as depicted in Fig. 6 and 7) are evidence of the significant variability that exists in the results. The levels of energy intensity that have been reported for all categories of wind generating systems range vary from 0.00146 to 0.98 kWh/kWh. This significant discrepancy is because vertical turbines have rated capacities that are significantly lower than those of small turbines. Offshore data, on the other hand, displays a substantially smaller normal distribution, and all of these turbines are classified in the large turbine category.

In addition, some offshore turbines have rated output more than 10 MW. Due to the exclusion of vertical wind turbines and those with a capacity of less than 100 kW from the analysis, the spread of the normal distribution is reduced, resulting in a mean and standard deviation of 0.12137 (±0.13) and 0.08955 (±0.098) kWh/kWh for energy consumption, respectively. It is observed that smaller turbines have higher indicator values. When compared to large onshore wind turbines, offshore turbines appear to be greener since they exhibit a narrower range of indicator values. This implies that offshore turbines are more environmentally friendly, as shown in Fig. 6. This is due to the increased offshore rated capacity and capacity factor, as well as the decreased land resource requirements for offshore wind power plants. As can be seen in Fig. 6, the mean values constantly surpass the median values. The last

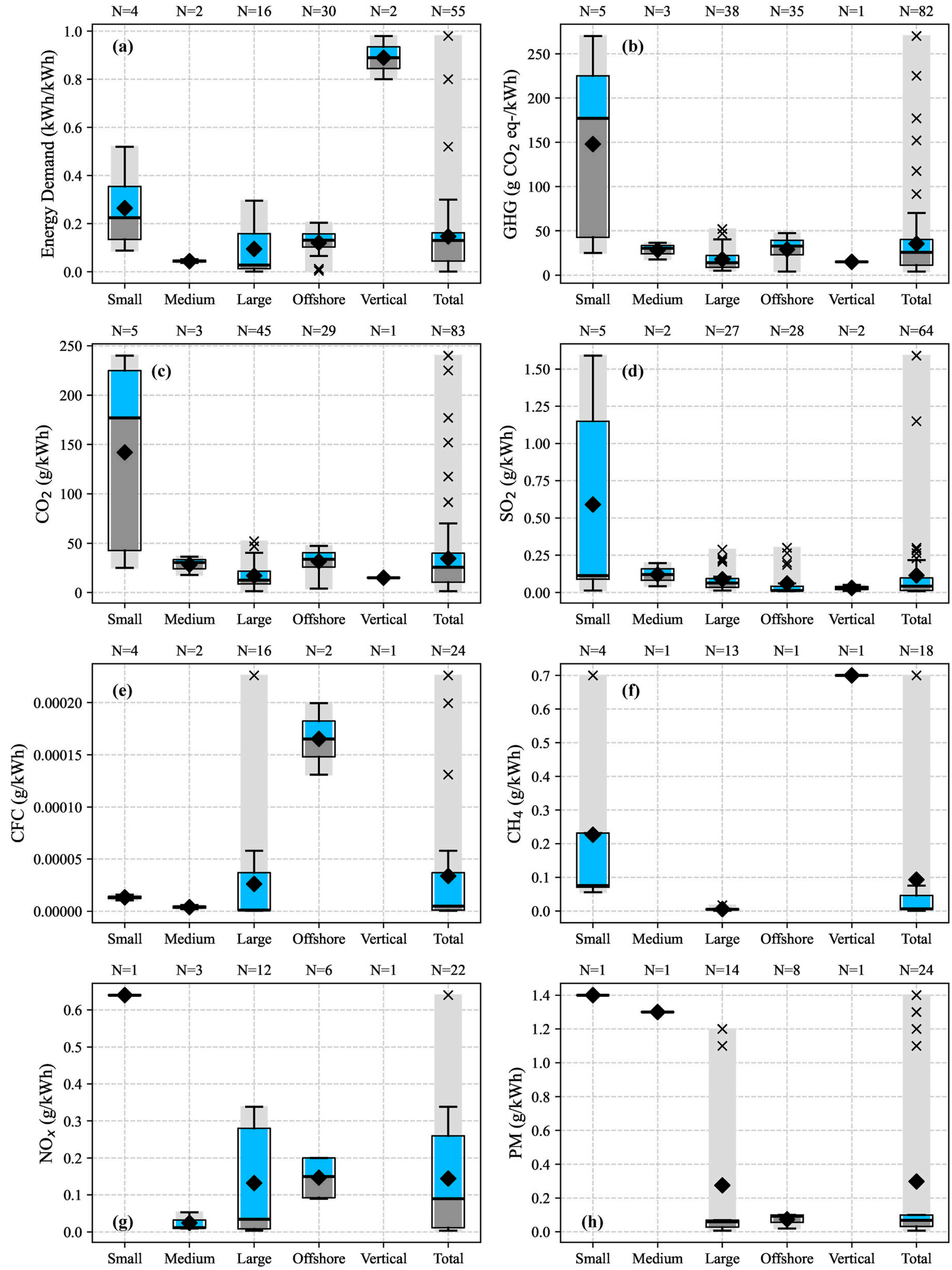

Fig. 6. Stressors and impact indicators are categorized into five wind systems: small, medium, large, offshore, and vertical, as illustrated in Table S1, along with eight impact categories: (a) energy demand, (b) GHG, (c) CFC, (d) CO_2, (e) SO_2, (f) PM (g) NO_x and (h) CH_4. The bottom gray box signifies the 0–25 % first quartile, the dark gray box denotes the range from the first 25 % to the 50 % second quartile, the blue box represents the 50–75 % third quartile, and the upper gray box indicates the 75–100 % fourth quartile. The horizontal bar within the box represents the median value; the diamond markers denote the mean value; the upper and lower fences (whiskers) indicate the maximum and minimum values, respectively. (This data is gathered from cited papers of Table 1 and Table S1). The symbol 'N' above candles indicates the sample size. Data taken from sources as listed in Supplementary Table S2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Summary of toxicity indicator resulted by three impact categories, as quantified by 11 studies. HT = Human toxicity. FE = Freshwater ecotoxicity. TE = Terrestrial ecotoxicity. DCB eq = 1,4-dichlorobenzene equivalents. Site: On = Onshore; Off = Offshore.

Ref.	Site	Power Rating (MW)	Toxicity (g 1,4-dichlorobenzene equivalent per kilowatt-hour (1,4-DCB eq./kWh))		
			HT	FT	TT
[90]	Off	5.0	24.5	412	0.295
[91]	On	2.0	0.421	0.058.11	0.021
		2.0	0.580	0.80.00	0.020
[73]	On	2.0	1880	265.3	–
		3.0	1870	250	
	Off	2.0	1040	113.7	–
		3.0	620	100	
[92]	On	0.5	154	121	0.0073
		0.6	59.2	51.1	0.0055
		0.8	321	291	0.0292
		1.5	44.5	41.5	0.0036
		1.65	73.7	68.7	0.006
		2.0	44.1	39.7	0.0092
		3.0	68	46.5	0.002
[93]	On	1.5 (Five different configurations of same wind turbines)	53.8	19.5	0.224
			53.5	19.5	0.223
			50.8	16.6	0.161
			25.1	10.4	0.151
			23.1	8.10	0.0872
[94]	On	1	503	186	1.21
		3	357	133	0.92
[95]	On	0.75	54.5	33.3	13.0
		1.5			
[96]	On	1.5	32	–	–
[72]	On	3.3	12.94	–	–
		3.2	10.25		
		3.0	19.79		
[74]	On	3.0	23.19	104.9	–
[97]	Off	3.0	–	0.067	–
[98]	Off	14.7 MW		0.0016	
[52]	Off	15 MW	7.2	0.0135	
			7.7	0.0131	
			7.8	0.0176	
			11.5	0.034	
				18.6	
				16.5	
				28.2	
				65.9	
[37]	On	3.2 MW	20.06	1.18	0.0356
[99]	On	4.3 MW			0.0108
[53]	On	3.6 MW	20.067	0.002412	0.63919
		4.8 MW	12.635		0.398156
[51]	Off	9.5 MW		1.7074	1.1963
				3.4412	1.1243
[100]	Off	2.8 GW		2.08E+01	
		3 MW			

four subplots in Fig. 6 demonstrate that even larger turbines had a similarly high degree of variation due to significant dispersion in data. This can be attributed to insufficient research of these stressors, and the assessment of these stressors may differ considerably. There are few other stressors (e.g. NMVOC, N_2O, NH_3) which are not presented in Fig. 6, due to limited data [79,80].

Method choices alone can shift results substantially. Impact assessment methods (ReCiPe, EF, TRACI) use different characterization factors, so the same inventory (e.g., steel, transport, resin) can yield different midpoint totals; GWP metric choices (IPCC AR5 vs AR6; 100-year vs 20-year) alter climate results and rank orders. Allocation and end-of-life modeling (cut-off vs substitution/system expansion; recycling credits vs no credits) can move metal-heavy systems by tens of percent. Functional unit definitions (gross vs net kWh; inclusion of curtailment/auxiliaries) change the denominator and inflate/deflate intensities.

Fig. 7 (a) indicates the GHG emissions from wind power plants using different methods, further categorized by their sizes. It can be seen that modeling frameworks results can diverge even with the same inventory. Process-based LCA offers high component resolution but suffers truncation (missing indirect services/capital goods), typically underestimating totals when boundaries are tight. I/O-based LCA captures the entire supply chain (including services/capital) but at coarse sectoral averages and in monetary units, introducing aggregation error and sensitivity to price/deflators. Hybrid LCA reduces both errors, for example, tiered or integrated matrix augmentation, physical linkages are reconciled; choices of concordance, cut-offs, and linking coefficients materially shift results. Lastly, whether the LCA is attributional or consequential, and static or prospective/dynamic (with time-varying grid mixes and learning effects), determines which effects are included, thereby shifting gCO_2e/kWh values.

Fig. 7 (b) depicts the GHG emissions for different regions. As observed in Fig. 6, most of the variation originates from the small-size category, and a similar pattern is reflected in Fig. 7. Higher standard deviations are observed for the Asia region (69.07 g CO_2/kWh ± 83.57) and for the I/O-based method (54.78 g CO_2/kWh ± 63.71). This greater variability in input–output–based LCAs arises from their reliance on aggregated industry-level datasets rather than detailed engineering inventories. Such datasets often span heterogeneous products and outdated temporal baselines, causing mismatches with current wind turbine technologies and supply chains. Differences in sector mapping, regional adjustments, and database selection further amplify uncertainty, leading to larger deviations in reported environmental impacts.

Furthermore, regional policy frameworks directly shape key LCA inputs such as capacity factor, the carbon footprint of grid-mix, transport/supply-chain distances, and end-of-life options, therefore, these factors provide reason behind this cross-regional difference in results. In the EU, the recast Renewable Energy Directive (EU) 2023/2413 (in force since 20 Nov 2023) raises the 2030 renewables target to ≥42.5 % (45 % aspiration) and is complemented by fast-track permitting under Council Regulation (EU) 2022/2577, as amended by (EU) 2024/223; together these measures support higher capacity factor wind farm (especially offshore) and lower embodied emissions per kWh via a cleaner grid and shorter lead times [81,82]. In China, the 14th Five-Year Plan for Renewable Energy Development (2021–2025) targets a non-fossil electricity share of ~39 % by 2025. Moreover, China's rapid wind deployment has been matched with policies to cut curtailment and the build-out of ultra-high-voltage transmission, reducing national wind curtailment to ~2.7 % in 2023 (i.e., >96 % of potential generation was utilized) [83–86]. However, integration pressures vary by province that directly affect LCA intensity per kWh. In the United States, the Inflation Reduction Act (2022) preserves PTC/ITC ($45/$48) and introduces tech-neutral credits ($45Y/$48E) beginning 2025, which influence turbine sizing and domestic-content choices, while recent BOEM (Bureau of Ocean Energy Management) approvals (e.g., New England Wind and Atlantic Shores South in 2024) shape offshore deployment timelines and logistics assumptions used in LCA [87,88].

Table 1 provides information regarding the toxicity levels in humans and various environments, specifically freshwater and terrestrial ecosystems, during production and reported lifespans. Additional toxicity indicators exist in research; however, summarizing them for comparison is challenging due to insufficient clarity on calculation methodologies and assumptions. For instance, the marine aquatic ecotoxicity documented in the study by Struthers et al. [52] indicated a total impact ranging from 15.5 to 110.4 kg 1,4-DCB eq./kWh across various wind power plant locations, while Turkmen and Babuna [53] reported total impacts of 59 and 37 kg 1,4-DCB eq./kWh for turbine capacities of 3.6 and 4.8 MWs, respectively. Another study categorizes human toxicity into carcinogenic and non-carcinogenic types; however, this study exclusively discusses the maintenance and operational emissions of floating wind turbines [89]. Table 1 illustrates a substantial variety in the provided data, exemplified by the disparity in human toxicity between references [90,91]. The cause of this variation is unclear but may

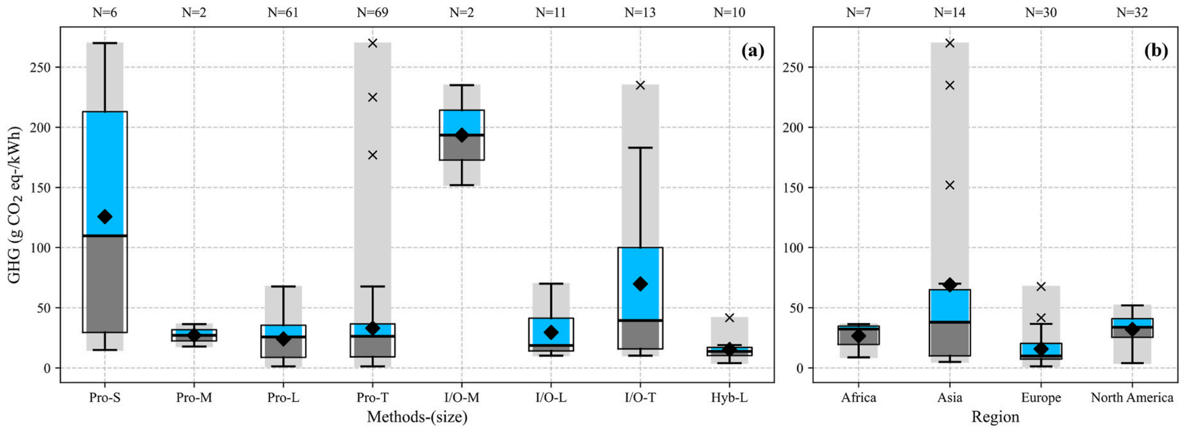

Fig. 7. (a) GHG emissions (CO_2-eq) is categorized based on 3 LCA methods (Pro, I/O and Hyb denote Process-LCA, Input/Output-based LCA and Hybrid LCA) and turbine sizes (small, medium and large). (b) GHG emissions (CO_2-eq) is geographically categorized. Description of box-whisker graph is same as mentioned in Fig. 5. Data taken from sources as listed in Supplementary Table S2.

be attributable to varying impact characterization approaches.

Fig. 8 illustrates the contributions of various stages (wind turbine production, substructure, installation, operation and maintenance, transportation, end-of-life, and recycling) in wind power plants. In Fig. 8, the "wind turbine" category specifically represents the energy and environmental impacts associated with the materials and manufacturing of the turbine itself. Other lifecycle stages such as substructure, installation, transportation, operation and maintenance, end-of-life, Recycling and others, are categorized separately. Various distinct methodologies have been employed in the literature to demonstrate the contribution analysis. The production of wind turbines can be further categorized into components such as rotor, blade, hub, nacelle, and frame, with their emission values aggregated as that of a wind turbine. Some studies recorded contributions from cabling, while others noted connections to the grid; similarly, internal cabling is included to mitigate complications, resulting in a combination of both signs during installation. Fig. 8 exhibits some ambiguity because certain studies have amalgamated two categories, while others reported a distinct category, which this study designates as 'Others.' Assumptions regarding lifespan can alter patterns, leading to increased maintenance and operational costs, which consequently result in higher energy use and emissions. The lowest emissions have been associated to transportation; nonetheless, research indicates that vertical turbines exhibit higher transportation emissions [101]. The highest emissions are associated with the production of wind turbines, as shown by all studies. This study [72] conducted a comparative analysis of LCA for onshore and offshore scenarios, revealing that offshore scenarios exhibited greater emissions related to installation and end-of-life, while onshore scenarios show higher emissions associated with operation and maintenance. The application of the avoided burden technique generally results in significant emissions reductions during the end-of-life phase. Recycling credits approximately reduce the energy or greenhouse gas emissions associated with the wind turbine by 50 % and diminish overall indicator values.

Fig. 9 depicts the energy consumption, GHG emissions, and SO_2 emissions relative to the rated power of the wind turbine. The data

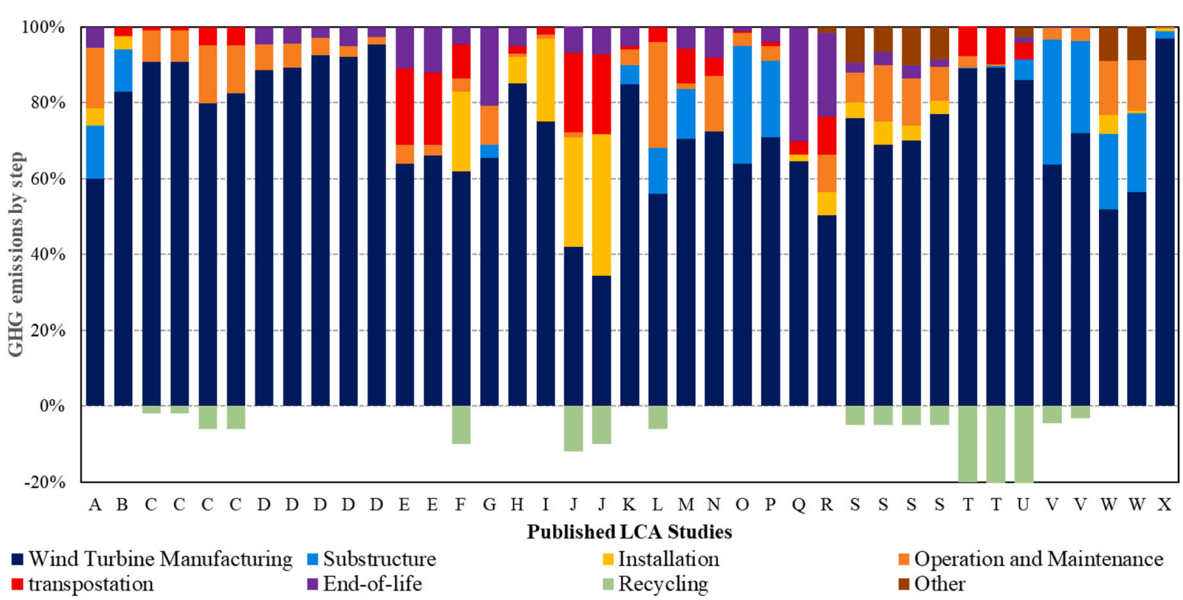

Fig. 8. Percentage of primary components or life cycle phases for the assessment of greenhouse gas emission in the referenced 24 studies. In several instances, it was essential to analyze results and/or interpret charts in the referenced articles. A study indicates that an analysis including many units of wind turbines exceeds a singular reference point. Reference for included studies in chart A – [90], B - [102], C - [103], D - [104], E – [101],F - [105], G - [93], H - [95], I – [96], J - [72], K - [74], L - [106], M – [107], N - [97], O - [108], P [60], Q - [80], R - [98], S - [52], T - [109], U - [99], V - [53], W - [51], and X - [37]. Data taken from sources as listed in Supplementary Table S3.

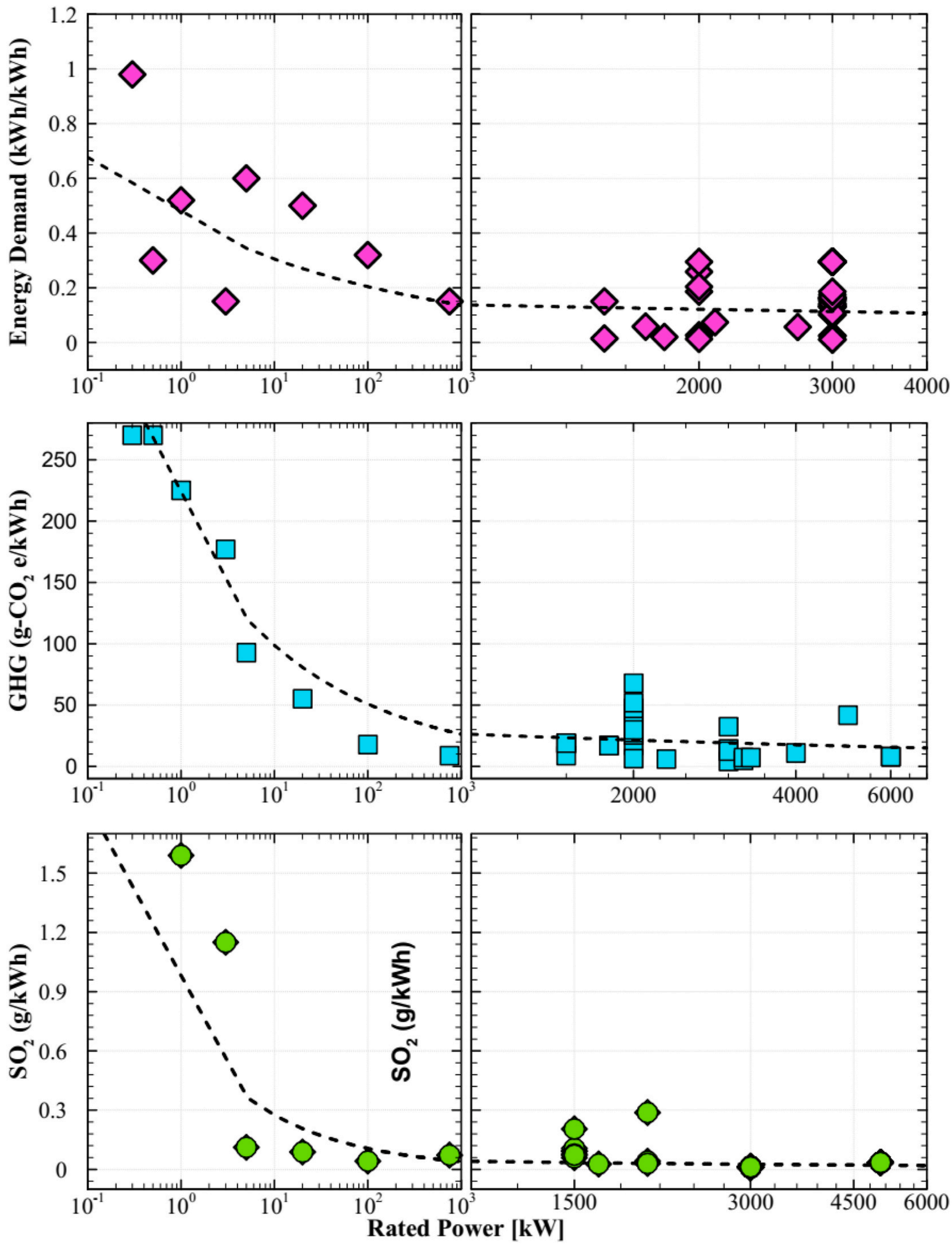

Fig. 9. Energy demand and overall emissions of CO_2 and SO_2 as a function of power rating (/kWh). (This data is gathered from cited papers of Table 1 and Table S1).

demonstrates that larger capacity wind turbines substantially reduce energy consumption and emissions. Numerous studies have supported this tendency through comparisons of turbine sizes. Kabir et al. [110] conducted a comparison of three turbine sizes: 5 kW, 20 kW, and 100 kW, focusing on energy consumption, GHG emissions, and SO_2 output. They reported that the largest 100 kW turbine consumed 69 % and 41 % less energy than the 5 kW and 20 kW turbines, respectively for their wind turbine facility. Likewise, GHG and SO_2 emissions for the 100 kW turbine were substantially lower than those for the smaller turbines, 58–29 % and 67–53 %, respectively. Another study [53] compared 3.6 MW and 4.8 MW turbines, revealing that energy consumption doubled for the lower capacity turbines. Additional stressors are reportedly also diminished, including GHG emissions by 6 %, CH_4 by 30 %, PM by 26 %, and SO_2 by 24 % [53]. Bi et al. [60] reported on six sizes of wind turbines (0.66, 0.85, 1.25, 1.5, 2, and 3 MW) and compared their greenhouse gas emissions ratings. Their findings indicated that the 1.5 MW turbine exhibited the highest emission index, as larger turbines significantly increase the consumption of heavy and rare-earth metals, reflecting this trend.

While it is possible to compare turbines of the same size using different LCA methods, only a few studies exist that compare the LCA approaches themselves. Challenges also remain in accounting for the geographical location of the site and the capacity factor. The LCA study by Xu et al. [105] (utilizing a process-based method) and Wang et al. [93] (employing a hybrid method) presented the LCA for a 1.5 MW turbine size, with both sites located in China, exhibiting capacity factors of 0.3 and 0.25, respectively. Although the capacity factor declined by just 17 %, greenhouse gas emissions were recorded at 19 and 8.65 (g CO_2 eq-/kWh), with methane emissions of 0.0636 and 0.017 (g CO_2/kWh). The disparity between the reported values exceeds double; one potential reason for this variance may be the impact of transportation. Moreover, the process-based and hybrid LCA methods exhibit distinct scopes and methodologies; the hybrid technique additionally encompasses indirect effects and extensive system-wide implications, hence mitigating truncation error. A separate study [60] for China employing the I/O technology indicates more greenhouse gas emissions than both process-based [105] and hybrid [93] approaches for 1.5 MW turbines.

The energy demand and GHG emissions throughout the life cycle of wind generating plants have been thoroughly examined in the literature. Furthermore, a significant amount of research quantifies the air pollutants typically associated with fossil fuel combustion, including NO_x and SO_2, along with their environmental impacts, such as acidification, eutrophication, photochemical oxidant formation, and, to a lesser degree, particulate matter formation. Nonetheless, the material-intensive characteristics of wind power in contrast to fossil fuel alternatives underscore a significant knowledge deficiency, the inadequate comprehension of harmful emissions across the whole life cycle of wind power installations. Toxic emissions predominantly arise during the material manufacturing phase, highlighting the necessity for comprehensive analysis in this domain [111].

Assessing harmful effects in LCA remains difficult due to sparse emissions data for hazardous substances and inconsistent toxicity characterization models. These limitations, present across LCAs, are especially acute for offshore wind where methods to quantify marine impacts are still maturing and the long-term consequences of metal releases and particulate pollutants remain uncertain [112,113]. A parallel gap concerns abiotic resource use: demand for non-renewable materials is often underexamined and methodological consensus is lacking. This is important for rare-earth elements e.g., neodymium used in permanent-magnet generators where supply risks have been noted, even as new deposits and recycling advances offer mitigation. [114]. Overall, more rigorous and standardized methods are needed to close these gaps and enable comprehensive environmental appraisals of wind power systems.

6. Production of components

The manufacturing of system components is a critical element of any LCA for wind energy systems. Variability in the embodied energy and related emissions of materials frequently results in inconsistencies in impact indicator results. This diversity may stem from divergent assumptions about the energy mix utilized in industrial processes [95, 115], as also indicated in previous studies. Furthermore, discrepancies may arise from dependence on various LCA databases or the application of differing assumptions regarding material composition, especially when the precise specifications of the materials utilized in components are unclear (e.g., steel alloys).

Contribution analysis indicates that the production of wind turbines accounts for a significant 73 % of total emissions, with a minimal standard variation of ±15. Other components and processes exhibit significant standard deviations; for instance, the substructure contributes 6.5 % with a standard deviation of ±9.7 %, installation contributes 5.3 % with ±9.3 %, operation and maintenance account for 5.6 % of total emissions with ±6.9 %, transportation also contributes 5.6 % (±6.6 %), and recycling has a mean contribution of 4.3 % (±4.2 %), which is lower than the other processes.

Given that the production of wind turbines (including towers, blades, nacelles, etc.) accounts for over 73 % (±15 %) of total emissions, it is imperative to investigate this aspect more thoroughly than other components or processes. Chiesura et al. [116] examined the impact of emissions by comparing various materials utilized in the production of wind turbine blades. They determined that 71 % of CO_2 emissions are attributable to blade manufacture, whereas 29 % are associated with other components of the wind turbine in the absence of recycling. Implementing a 90 % recycling rate with a resin system can lead to a 28 % reduction in emissions. Guezurage et al. [117] conducted a LCA on 1.8 and 2 MW with gearless and geared wind turbines, respectively. They reported that the production of wind turbines constitutes 84.4 % of overall emissions, while the fabrication of towers represents 55 % of total emissions related with manufacturing. Moreover, gearless wind turbines exhibited nearly half the life cycle emissions in comparison to geared turbines.

Discrepancies in components may occur due to the database; for instance, the study by Rajaei and Tinjum [102] on 1.8 MW wind turbines utilizing Ecoinvent v.2 revealed that steel emitted 1.708 kg CO_2 eq/kg, cast iron 1.467 kg CO_2 eq/kg, and aluminum 11.426 kg CO_2 eq/kg. Nonetheless, the research conducted by Ozoemena et al. [118] indicated average values of 2.56 kg CO_2 eq/kg for steel, 1.9 kg CO_2 eq/kg for cast iron, and 1.98 kg CO_2 eq/kg for aluminum, derived from the consolidated inventory data in National Renewable Energy Laboratory.

Jorge and Hertwich [47] examined the environmental impact of various cable materials and configurations, including overhead lines, land cabling, underwater cabling, transformation, grounding, and substation cabling. It was reported that the raw material for cabling contributed 0.97 g CO_2-eq/kWh, representing 53.3 % of the cabling components, whereas power losses provided the second largest contribution at 0.68 g CO_2-eq/kWh, accounting for 37.2 %. The remaining contributions were attributed to maintenance and operations at 0.11 g CO_2-eq/kWh (6 %) and manufacture and installation at 0.06 g CO_2-eq/kWh (3.5 %). Arvesen et al. [90] examined the emissions associated with the installation processes of offshore wind turbines, with particular emphasis on foundational activities including excavation, seabed preparation, barge operations, excavator transport, seabed material disposal, vessel utilization, and the transport of rock for stone beds and protection. Raadal et al. [119] conducted the LCA on various foundations employed for offshore wind turbines, including Umaine Spar, MITTLB, SWAY Floating, Umaine Semi-S, Umaine TLP, and OC4Jacket Bottom fixed. Umain-Semi-S exhibited the highest CO_2 emissions, whilst MITTLB demonstrated lower emissions. Moreover, they determined that emissions associated with foundations predominantly depend on steel mass. Similarly, the LCA report by Berndt [48] demonstrated varying foundation configurations for onshore wind turbines. Their research indicated that utilizing 32 MPa class concrete instead of 40 MPa can diminish concrete-related pollutants by a minimum of 11 %. The most significant reduction in emissions for the analyzed mixtures occurred in concrete with a 65 % substitution of cement with blast furnace slag, yielding reductions of 42.7 %–44.8 %, contingent upon the strength class. Akram et al. [120] conducted a LCA on various wind turbine lubricants, including those infused with nanoparticles.

Several studies attribute emissions reductions to end-of-life recycling through the avoided burden methodology (refer to Table S1). Nonetheless, the implementation of this strategy frequently entails methodological inaccuracies and insufficient transparency. The principal problem stems from the inadequate acknowledgment that: (1) integrating recycled content as input materials in the production process, and (2) attributing the system with mitigated environmental impacts at the end of life, cannot be considered in isolation. In materials utilizing the avoided burden approach, the proportion of secondary inputs in production must consistently be zero. This technique would inconsistently model recycling benefits, once during the production phase and again at the end-of-life phase, leading to double-counting. The fundamental question is whether the advantages of recycling should be attributed to systems that employ recycled materials (as suggested when secondary inputs are incorporated in a life cycle assessment) or to systems that produce recyclable materials (as indicated when the avoided burden technique is utilized). These two viewpoints should remain distinct.

7. Other environmental impacts

7.1. Economical aspects

Life Cycle Assessment of wind turbines not only supports the transition toward alternative and green sources of electricity generation but also highlights the importance of economic considerations in their adoption. Several studies have integrated economic analysis alongside LCA to provide a holistic evaluation of wind power plants. These analyses generally reveal that approximately 99 % of the total cost is concentrated in the early phases of a wind project, primarily in the purchase of wind turbines and the construction of the wind farm [121].

Although wind energy is often considered economically competitive, its high upfront capital expenditure can translate into financial losses if electricity prices fall. For comparison, electricity costs from fossil fuel-based power plants are largely driven by fluctuating fuel prices, making their cost structure different from that of wind energy. Another critical factor influencing the economic viability of wind power is government subsidies. While subsidies are designed to promote renewable energy adoption, they do not necessarily guarantee direct profitability and can indirectly impose financial burdens on other sectors [122].

Li et al. [123] examined six scenarios for wind farm costs, accounting for variables such as turbine procurement from different regions, shipping and transportation costs, and varying management expenses. For example, a 40 MW wind farm with different turbine sizes under distinct scenarios exhibited substantial variation in associated costs and capacity factors. Projects with lower annual generation rates are generally less profitable than those with higher energy yields. Chomac-Pierzecka [124] reported that adding 1 GW of wind power capacity to Poland's energy mix could reduce electricity prices by EUR 6/MWh.

Peacock et al. [125] conducted an economic assessment of micro-wind systems ranging from 0.4 kW to 2.5 kW capacity. Four parameters were evaluated over a 20-year lifespan at a 3.5 % discount rate, with and without grants: net savings, discounted payback period, emission savings, and emission savings-to-investment ratio. Results showed substantial increases in both cost savings and emission reductions with larger systems. For instance, net savings increased from EUR 56.1 to EUR 399.0, and the emission savings-to-investment ratio rose from 244 to 2098 kg CO_2/EUR p. a. However, absolute emission savings (kg CO_2/EUR) decreased from 35.3 (with grant) and 50.5 (without grant) for the 0.4 kW system to 31.4 and 44.8 for the 2.5 kW system.

Similarly, Kabir et al. [110] analyzed the economics of small (5 kW and 20 kW) and medium-scale (100 kW) wind turbines, considering electricity price and simple payback period with an internal rate of return (IRR) of 10 %. Small turbines exhibited significantly higher electricity prices and longer payback periods, for example, 0.61 and 0.25 USD/kWh with payback periods of 9.68 and 9.53 years, respectively, compared to medium turbines, which had lower costs (0.21 USD/kWh) and shorter payback periods (7.82 years).

7.2. Water use and noise pollution

Certain research examined additional vital factors associated with environmental change; for instance, the LCA report by Feng et al. [61] indicates that incorporating renewable energy up to 40 % in total power production can reduce water use for electricity generation by 50 %. Their analysis of various renewable energy sources indicated that wind turbines have the lowest water use, using less than 1 L per kWh during their entire life cycle. Noise pollution from wind turbines is seen as highly harmful, as elucidated by Schmidt and Klokker [126] regarding the drawbacks of wind turbine noise. Subjects suspected of exposure to wind turbine noise have reported various symptoms, including sleep disturbances, headaches, tinnitus, and vertigo. This phenomenon pertains not only to humans; wildlife is also considerably impacted by noise generated by wind turbines. The flight patterns of birds are considerably influenced by this noise, as geese, ducks, cranes, and gulls exhibit broader geographical avoidance radii around large wind turbines compared to highways and municipal roads [127].

7.3. Avian mortality and ecological disturbances

Other environmental impacts, such as bird fatalities caused by wind power, may be minimal but cannot be disregarded. Wang et al. [128] highlighted the various scenarios that may lead to avian mortality. The overall number of bird casualties in the European region is 829, with many being eliminated prior to detection by researchers. Their study compiled six hypotheses concerning flying conditions, turbine illumination, avian behavior, geographical location and topography of wind power sites, turbine design attributes and wind farm configuration, as well as habitat disruption, to elucidate the mechanisms by which birds are killed at wind energy facilities. Nilson et al. [129] conducted an experiment utilizing dummy birds to obtain more precise conclusions, which were implemented in a medium-sized wind turbine farm. During migration times, the wind farm was inspected weekly by carcass survey teams utilizing trained dogs to locate deceased birds. The dogs in the corpse surveys had greater success in detecting large fake birds compared to tiny ones (60–200 g), successfully finding 74 % of the large dummy birds. Identifying the smaller group (5–24 g) was more challenging, with the dogs locating only 17 % of the little dummy birds. A regression model was developed by the authors to estimate the actual count, which was determined to be between 1 and 5 birds every day.

7.4. Other aspects

In addition to environmental impacts, wind turbines pose certain safety and structural risks, particularly in the event of mechanical failure. While such occurrences are rare, understanding their implications is important for comprehensive life cycle evaluation [130]. A Central Electricity Generating Board study assessed the risks associated with wind turbine blade failure, finding the highest danger within one blade diameter of the tower. Beyond this range, the annual probability of impact is extremely low ($\sim 10^{-7}$). Blade throw distances typically range up to 800 m, with rare cases possibly exceeding 2 km, though associated risks remain minimal due to wide dispersion [131].

Wind turbines can cause stroboscopic or shadow flicker effects when the rotating blades periodically block sunlight, casting rhythmic shadows on nearby residences or roads. This visual disturbance is most prominent during sunrise or sunset that can lead to annoyance, distraction, and in rare instances, health concerns such as headaches or increased stress. While the rotational frequency of turbine blades is generally below the threshold for photosensitive epileptic seizures, proper turbine siting, orientation, and mitigation strategies are essential to minimize this effect [132–134]. In addition to shadow flicker, nighttime light pollution from wind turbine obstruction lights can significantly affect the nocturnal landscape and visibility of starry skies. A study by Bara and Lime [135] shows that medium-intensity turbine lights may appear brighter than Venus or the brightest stars up to several kilometers away, making their visual impact at night considerably greater than during the day.

Furthermore, wind turbines can cause electromagnetic interference (EMI) due to their large rotating blades, electrical generators, and associated power electronics, which can affect radio, television, radar, and communication systems. The degree of interference is influenced by turbine design, electromagnetic emissions, and proximity to sensitive equipment. EMI is a recognized concern, particularly near aeronautical and meteorological radar installations, and must be considered during the siting and permitting stages of wind farm development [136].

8. Future prospective

This review highlights several actionable insights relevant to the renewable energy sector, particularly in guiding future technology design, manufacturing, and deployment. Larger turbines, especially those rated above 2 MW (used in offshore applications) demonstrate higher capacity factors and improved life cycle environmental performance per unit of energy generated. Among the various turbine components, the tower and nacelle contribute the most to overall emissions due to the intensive use of steel, aluminum, and composite materials. In offshore installations, the substructure system emerges as another major contributor to environmental impact, owing to the scale and complexity of underwater structures. Traditional steel monopile or jacket foundations, while structurally robust, involve high embodied energy and emissions. Emerging alternatives such as ceramic-reinforced composites, hybrid concrete–ceramic systems, or floating foundations offer promising reductions in both weight and environmental footprint, especially for deep-sea applications.

From a manufacturing and supply chain perspective, localized production, low-carbon material substitution, and renewable energy sourcing in fabrication can significantly reduce upstream impacts. Technologies prioritizing lightweight modular designs, recyclable components, and efficient logistics (e.g., minimizing long-haul transport) also show clear potential in reducing the overall life cycle burden. Incorporating such strategies into the design, procurement, and policy frameworks could greatly enhance the sustainability of future wind power infrastructure.

9. Conclusions

The current LCA research contributes to our comprehension of the life cycle environmental implications of wind power concerning total fossil fuel usage and its associated pollution. The research discrepancy arises from a confluence of real-time variances (e.g., the scale of wind turbines, whether small or large), fundamental assumptions (e.g., lifespan and projected/calculated capacity factor), database inconsistencies (e.g., emission intensity due to materials), and methodological divergences (e.g., process-based LCA versus EEIO-LCA, end credits benefits). Published LCA studies have revealed a significant disparity between low and high values that hinders its application to policy decision-making. However, adhering to established methodologies and assumptions in the future analyses may mitigate this issue.

It is essential to rectify the concerns stemming from varied outcomes, operational network complications, and underlying assumptions. This can be corrected by adhering to the principle of transparency in LCA by incorporating process-level inventory input data into all LCA publications. This can assist us in comprehending the causes of data discrepancies and enhance our comprehension of result generation.

This analysis indicates that past research has primarily focused on onshore and offshore wind turbines globally, with particular emphasis on the production life cycle stage. Future studies, thus, may concentrate on system types or life cycle stages that need sufficient investigations and/or appropriate evaluations, such as:

- Region-specific manufactured systems and operational circumstances.
- Wind turbines of a capacity more than 3 MW, particularly offshore wind farms located far from the coast or in deep waters.
- Particularly, the substructure, installation, operation, and maintenance phases of offshore wind farms

10. Policy recommendations

Life Cycle Assessments of wind power typically utilize a modest unit of 1 kWh of electricity to evaluate environmental impacts, concentrating on fossil fuel emissions, and often employ the process-LCA approach. These evaluations were essential in the past and are likely to continue being so in the future. However, given the extensive number of studies conducted in this field, the expected outcome should be more significant advancements in diverse analyses and complex methodologies. Consequently, it is recommended that the future policies should consider the following:

- Prioritize high-capacity turbines in planning and permitting processes (especially offshore) since larger turbines generally exhibit lower environmental impacts per kWh over their life cycle.
- Promote low-impact material innovation in turbine components (e.g., nacelles, towers, foundations), such as low-carbon steel, ceramics, or hybrid composites, to reduce upstream emissions from material extraction and manufacturing.
- Support R&D for advanced foundation systems (e.g., floating or modular foundations) in offshore installations, particularly for deep-water sites where traditional foundations show higher environmental intensity.
- Adopt hybrid LCA approaches that combine process-based and environmentally extended input-output methods to ensure comprehensive coverage of both direct and indirect environmental impacts in policy and permitting assessments.
- Expand the scope of environmental impact categories to include less-addressed but critical areas such as toxicity of industrial waste, depletion of rare earth elements, and long-term vs. short-term effects of wind energy systems.
- Integrate scenario-based assessments into LCA modeling to evaluate how technological advancements, regional/global deployment scales, and evolving life cycle inventories affect overall environmental performance.
- Account for emission penalties due to intermittency, which can arise from increased reliance on backup or balancing systems in grid operations influenced by wind energy variability.
- Improve consistency in recycling assumptions and models, as past studies have shown that divergent assumptions lead to substantial variation in LCA outcomes. Standardization and transparent modeling of end-of-life scenarios should be encouraged.
- Incorporate regional factors such as grid carbon intensity, transportation logistics, and local manufacturing energy mixes, into planning tools to reflect the location-specific environmental impacts of wind projects.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2025.116429.

Data availability

Data will be made available on request.

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