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Life cycle assessment of wind farm: A review on current status and future knowledge

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ABSTRACT

With rising concerns over climate change and greenhouse gas (GHG) emissions, wind power has gained attention as a clean energy source. However, Wind Power Plants (WPPs) generate emissions throughout their life cycle, from raw material extraction to decommissioning. Life Cycle Assessment (LCA) is a key tool for evaluating these environmental impacts. This paper reviews LCA studies of onshore and offshore WPPs, focusing on global warming potential (GWP) and energy payback time (EPBT) to assess their sustainability. Findings reveal that offshore WPPs generally exhibit higher GHG emissions due to complex installation and transportation but benefit from shorter EPBT due to higher wind speeds. Conversely, onshore WPPs have lower upfront emissions but experience longer EPBT due to variable wind conditions. The manufacturing and transportation phases contribute the highest emissions. Recycling and material optimization can reduce environmental impact by up to 30 %. Identified research gaps include data accuracy issues, limited offshore LCA studies, and lack of component-specific analyses. This study provides a pathway for optimizing wind power sustainability, emphasizing material efficiency, logistics improvements, and policy advancements.

1. Introduction

Global warming is a serious concern for today's world [1]. The use of fossil fuels in the power sector is responsible for 44.4 % of CO2 emissions in the natural environment, amounting to almost 36.8 billion metric tons of emissions [2]. In contrast, renewable energy sources promote a move toward zero-carbon technology [3]. Renewable energy sources are mostly environmentally friendly and secure for the future [4,5]. Not a single penny is necessary for using renewable energy sources as fuel for power plants [6], which enhances the economic viability of these systems.

Among all renewable energy sources, wind energy is recognized as the cleanest and fastest-growing energy source in the world [7]. Improvements in grid integration, energy storage, and advanced turbine design have increased the efficiency and reliability of this renewable system [8]. However, community acceptance can sometimes be negatively influenced by visual impacts, noise concerns, and other potential health effects. Despite these issues, employment opportunities and workforce development have helped to overcome negative perceptions of this technology [9].

Wind energy contributes >6 % of global electricity [10] and plays a key role in establishing the fastest-growing power technology worldwide. In the last two decades, the installed rate of wind power has increased by nearly 90 % [11]. In 2020, the world produced 1592 TWh of wind energy, which was 12 % more than in 2019. The production of wind power in 2022 was 2108 TWh, which increased by 10.3 % in 2023, reaching 2325.3 TWh. However, the 'Net Zero Emissions by 2050′ agreement requires an 18 % average annual growth in wind energy from 2021 to 2030, necessitating an annual increase in wind power capacity of about 400 GW [12,13]. Fig. 1 shows the total increase in onshore and offshore wind power generation from 2000 to 2021.

The global wind energy sector has witnessed remarkable growth in recent years. In 2023 alone, a record-breaking 117 GW of new wind power capacity was installed, marking a 50 % increase from the previous year and bringing the total cumulative capacity to over 1020 GW. This surge is largely driven by significant contributions from China, the United States, Brazil, Germany, and India. Notably, China accounted for nearly 65 % of the global wind capacity additions in 2023, installing approximately 75 GW. Looking ahead, the Middle East and Africa are projected to add 17 GW of new wind capacity between 2023 and 2027, with South Africa, Egypt, Saudi Arabia, and Morocco leading these developments. This global expansion underscores the increasing role of

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wind energy in the transition to sustainable power systems [14].

Wind power technology produces almost zero pollutant emissions during its operational phase [15], but it still generates emissions during other phases of its life cycle [16]. From material production to end-of-life, including transportation, installation, and maintenance of wind power plants (WPPs), every phase requires fuels, and these fuels emit pollutants into the environment [17]. Fig. 2 shows the emission scenarios from different life stages of a wind farm.

To analyze the environmental impact of these pollutants emitted from WPPs, Life Cycle Assessment (LCA) is the most effective tool and is widely used for managing industrial environments [18]. LCA identifies which stage of a product, service, or technology has a significant impact on the environment [19]. Moreover, LCA can provide insights into how greenhouse gas (GHG) emissions can be reduced to lower the carbon footprint [20]. Additionally, it helps determine how much time is required to generate the same amount of energy that was used for installing and running a WPP [21]. Overall, LCA is a key technique for environmental study [22].

This paper reviews previous LCA studies of WPPs to identify their focus areas. In 2020, [23] presented a review highlighting CO2 emissions from WPPs and their energy consumption rates. This paper also focused on improving processes and evaluating whether the reuse of equipment is environmentally friendly. The results indicate that efficient technologies, new production skills, and the reuse of materials after the end-of-life of WPPs can reduce CO2 emissions. G. Mello et al. presented a review on CO2 emissions and the climate change impact of WPPs through LCA [24]. To mitigate the effect of CO2 on global climate change, this study suggests improvements in processes and advanced equipment reuse. In 2019, [25] presented a review that emphasized result harmonization and simplifying the LCA model of WPPs. The paper aimed to provide an updated review and a simplified LCA model by considering existing LCA results of WPPs for environmental improvement. The results show that this modified/simplified LCA requires fewer input parameters than traditional LCA, making it easier to predict the environmental impacts of WPPs. In 2018, [26] aimed to identify deficiencies and suspensions in the materials used for manufacturing wind turbines. Three types of rare-earth materials were considered for turbine manufacturing to assess their environmental impact. The results indicated that reusing materials for turbine manufacturing could reduce environmental effects. In 2018, [27] presented a review by considering the environmental impact and energy use of both onshore and offshore WPPs. The paper found that onshore WPPs are more environmentally friendly than offshore WPPs; however, offshore WPPs can provide more power if they reach the rated wind speed. In 2012, [28] discussed the current concept of LCA for assessing and mitigating the environmental impact of WPPs. The paper compared the energy required and the total emissions of onshore and offshore WPPs. It was found that a significant amount of emissions come from the production phase of onshore WPPs, while the substructure of offshore WPPs is more impactful. The paper also suggests that WPPs using energy around ±0.058 kWh and emitting ±13 gCO2e per kWh of electricity are good performers environmentally. In 2012, [29] presented a review paper to highlight the differences in LCA methodologies and their assumptions. The main aim was to discuss different LCA methods for WPPs. The paper identified several issues, including lack of data, unclear data, conversion errors, undesired predictions, improper recycling of materials after the end of the WPP's life, and failure to follow ISO standards for LCA operations. After reviewing the literature from the past 13–14 years, it is observed that no paper in the past 8 years has focused solely on WPPs' GHG emissions and their energy payback time (EPBT) using the LCA technique. Only [27], published in 2017, focused on the carbon footprint of wind power technology.

In this paper, an effort is made to review numerous LCA research papers and letters on WPPs from the past seven years to identify problems and suggest solutions. The main goals of this paper are: (i) to aid in identifying the most important studies and research papers in this area, (ii) to determine the total carbon emissions or GHGs from selected wind power plants (WPPs) to calculate their global warming potential, (iii) to present their energy payback time (EPBT), and (iv) to identify their respective research gaps. Additionally, (v) the overall research gaps and future research directions of WPPs' LCA are highlighted. Cost analysis is deliberately avoided here, with the philosophy of "save life, save the

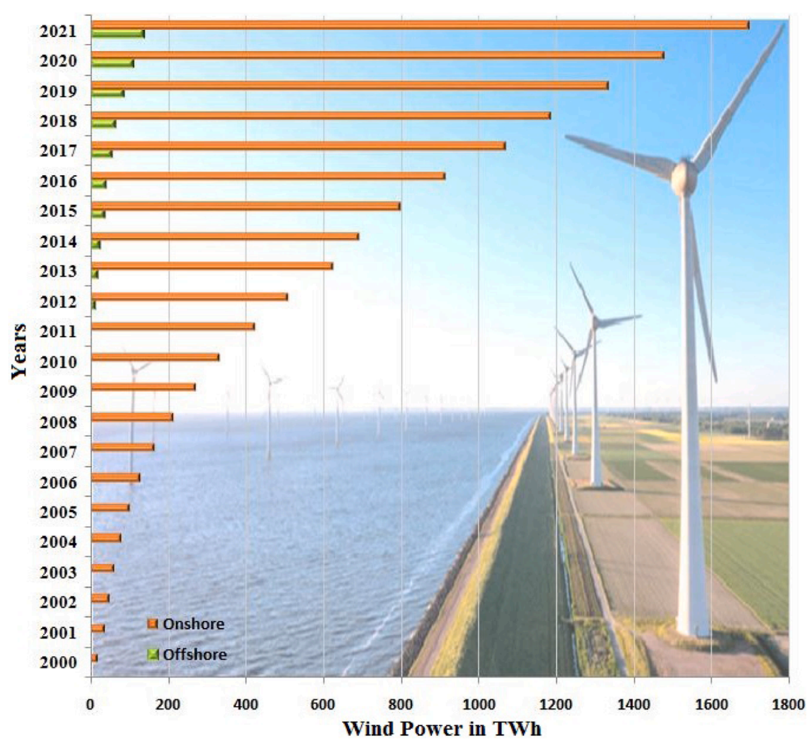

Fig. 1. Total increment of onshore and offshore wind power generation from 2000–2021 [12,13].

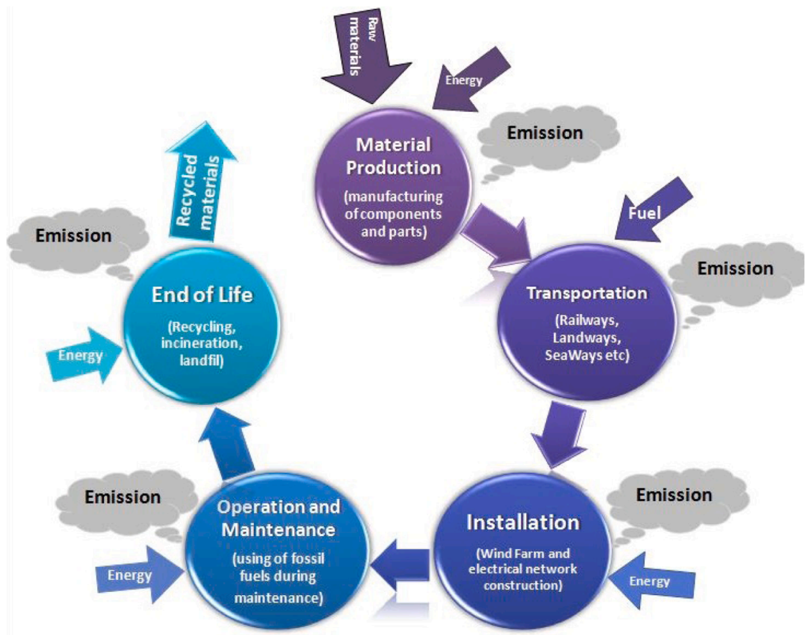

Fig. 2. Emission scenarios from different life-stage of Wind Farm.

environment." Furthermore, this paper focuses on scientific research from the last eight years (with priority given to SCI, SCIE, ESCI, and Scopus-indexed journals) to provide a pathway for clean future technology. The novelty of this article lies in its unique focus on assessing the GHG emissions and EPBT of WPPs. While many studies have explored the environmental impacts of WPPs, this paper specifically addresses recent gaps in the analysis of GHG emissions and the time required for energy payback. This focus enables a more precise evaluation of wind turbines' efficiency and environmental footprint. Altogether, this paper advances the state of the art by highlighting gaps in GHG and EPBT analysis, emphasizing recent research, and providing a roadmap for future investigations into the environmental impacts of WPPs.

The background and importance of LCA for WPPs are presented in this section, along with the paper's objectives. Section 2 discusses why greenhouse gas (GHG) emissions and energy payback time (EPBT) are important for WPPs' LCA. The method for selecting the papers and the analysis of WPP studies on LCA are presented in Section 3. Section 4 provides an overall summary, including the research gaps and future research directions of the theme. Section 5 concludes the paper.

2. Why GHG and EPBT are important for WPP

Wind power technology is considered one of the cleanest technologies in the world due to its ability to generate electricity without direct GHG emissions during operation. However, the full life cycle of wind power plants (WPPs) includes several stages—installation, operation, maintenance, and end-of-life—that do contribute to GHG emissions [30]. Understanding and calculating these emissions is crucial for several reasons.

Firstly, to estimate the total environmental impact of WPPs through life cycle assessment (LCA), GHG emissions play a vital role because they significantly affect the environment. LCA is a comprehensive method that evaluates the environmental impacts of all stages of a product's life, from cradle to grave. For WPPs, this includes the manufacturing of components, transportation, installation, operation, maintenance, and decommissioning. GHG emissions are a key metric in LCA because they contribute to global warming and climate change. By accurately calculating these emissions, we can better understand the overall environmental footprint of wind power [31].

Secondly, identifying the specific sources of GHG emissions within the life cycle of WPPs is essential for targeting reductions. During the installation phase, emissions primarily come from the production and transportation of materials such as steel, concrete, and fiberglass used in the turbine towers and blades. During operation, although the turbines themselves do not emit GHGs, maintenance activities can involve the use of vehicles and machinery that burn fossil fuels. At the end-of-life stage, dismantling and recycling turbine components also result in emissions. By pinpointing these sources, we can focus on reducing or replacing high-emission processes and materials. For example, using low-carbon concrete or improving logistics to reduce transportation emissions can make future WPP installations more sustainable [32].

Thirdly, GHG calculations help researchers and engineers identify the drawbacks of current technologies and components used in WPPs, facilitating the development of zero-carbon technologies [33]. Understanding the GHG footprint of each component and process allows for targeted improvements. This iterative process of identifying gaps and making advancements is crucial for technological development. As the saying goes, "no gap, no development." By addressing these gaps, we can innovate and create more efficient and environmentally friendly wind power technologies.

Energy payback time (EPBT) is another important metric that evaluates the sustainability of WPPs. EPBT is the time required for a WPP to generate the same amount of energy that was consumed during its installation. This includes the energy used in manufacturing the turbine components, transportation, installation, and commissioning [34]. Several factors are critical when calculating EPBT:

1. **Total Energy Required for Installation**: This includes all the energy inputs from manufacturing to the final setup of the WPP. Accurate data on the energy consumed in producing materials (e.g., steel for the tower, composites for the blades), as well as the energy used in transportation and construction activities, is essential.
2. **Installation Finishing Time and Energy Generation Start Time**: The timeline from the start of installation to the commencement of energy production must be precisely documented. This timeline affects the EPBT calculation, as any delays or extended installation periods increase the overall energy required before the WPP starts generating electricity.
3. **Energy Generation Data**: Accurate and complete data on the energy produced by the WPP once it starts operating is very important. This

includes the average power output, capacity factor (which accounts for variations in wind speed), and operational efficiency [35].

GHG emissions and EPBT are inversely related. As wind speed increases, the energy output of a WPP increases. Higher energy output means the WPP reaches its energy payback point more quickly, thus reducing the EPBT. However, increased energy output also leads to more frequent maintenance, which can involve activities that emit GHGs, such as transportation and the use of maintenance equipment [36]. Therefore, while higher wind speeds and increased energy generation shorten the EPBT, they can also result in higher overall GHG emissions due to increased maintenance demands. The mathematical expression for calculating EPBT can state as:

$$EPBT = E_{input}/E_{annual\_output}$$

Here, E_{input} is total primary energy consumed over the wind farm's life cycle and E_{annual_output} is the annual energy production of the wind farm [37]. Now, E_{input} is the cumulative energy used at each stage of the life cycle of power plant.

$$E_{input} = E_{manu} + E_{trans} + E_{instal} + E_{o\&m} + E_{end}$$

Here, E_{manu} is the total energy used for manufacturing of each components of the plant, E_{trans} is the total energy used for transporting of each components of the plant, E_{instal} is the total energy used for installing each components of the plant, $E_{o\&m}$ is the total energy required for operation and maintenance of the power plant, E_{end} is the total energy input for the end of life of the plant [33,37,]. Now, the emission factor for per unit energy production ($EF_{GHG/unit}$) by WPP can be calculated as:

$$EF_{GHG/unit} = \frac{EF * P}{\sum_{N=1}^{20} E}$$

Here, EF represents GHG emission factor, P is the capacity factor of the WPP, n is the number of life of the WPP, and E is the total energy electricity yield annually by the WPP.

While wind power technology is inherently cleaner than fossil fuel-based energy generation, there are still GHG emissions associated with its life cycle. Calculating these emissions and understanding their sources is crucial for improving the sustainability of WPPs. EPBT provides a useful measure of the time required for a WPP to offset the energy consumed during its installation, and understanding the interplay between GHG emissions and EPBT helps identify areas for improvement in wind power technology [38]. By focusing on reduced emissions and improved energy payback times, we can advance toward more sustainable and efficient wind energy solutions.

After studying various practical-based WPP LCA research articles from the link given in reference [39], a graphical relationship between GHG emissions and EPBT with wind speed is shown in Fig. 3. It indicates

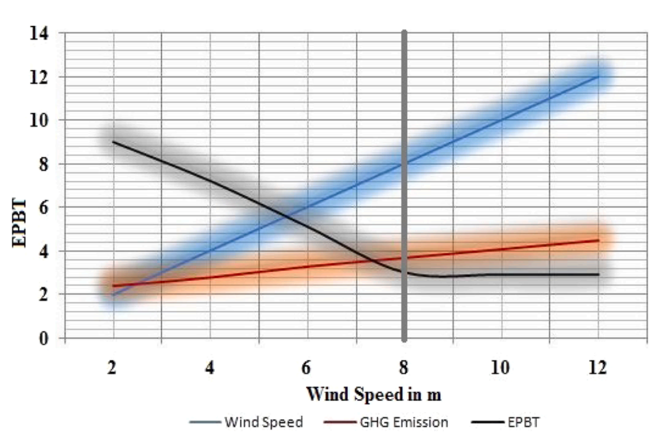

Fig. 3. Graphical representation of relation of GHG and EPBT with wind speed.

that if the rated wind speed of an area where induction-type wind turbines are installed is 8 m/s, GHG emissions will increase with the increasing wind speed during the operational period of the WPP [36]. (GHG emissions are considered constant during the installation, transportation, and end-of-life phases of the WPP.) These GHG emissions will continue to rise to some extent even after surpassing the rated wind speed. However, in the case of EPBT, it will decrease with an increase in wind speed. After crossing the 8 m/s wind speed, EPBT becomes constant as the system reaches its limited rated output at the rated wind speed.

Moreover, the technique used for EPBT calculation can also be applied to determine the GHG payback time as a measurement of climate change potential associated with WPPs [40].

3. Methodology

3.1. *Method for selecting research papers from 2017 to 2023*

To conduct a comprehensive review of Life Cycle Assessment (LCA) studies on wind power plants (WPPs), we systematically selected research papers from Scopus, Web of Science, and Google Scholar. The search was performed using relevant keywords such as 'Life Cycle Assessment,' 'Wind Power Plant,' 'Environmental Impact,' and 'Climate Change,' ensuring coverage of all major aspects of LCA in wind energy. To maintain relevance and reflect recent advancements, we considered papers published between 2017 and 2023, with priority given to peer-reviewed journals indexed in SCI, SCIE, ESCI, and Scopus.

The paper selection followed the PRISMA methodology, ensuring a transparent inclusion and exclusion process. We first identified 16,100 documents, which were then filtered based on relevance, journal impact factor, and research quality. A final set of 36 papers was selected, comprising 20 studies on onshore WPPs, 13 on offshore WPPs, and 6 comparing both technologies. This categorization allowed us to analyzethe trends, gaps, and emerging themes in LCA research on wind energy.

3.2. *Literature study of different types of WPP*

This section shows a systematic literature review on different WPPs. For each sub-sections, several papers are evaluated for finding environmental impact due to GHG emission, rate of EPBT, and most importantly, their research gap by means of future research direction. Some mathematical expression are shown bellow for

3.2.1. *Onshore wind power plants*

Twelve different onshore WPPs with a capacity of 100 MW were chosen to estimate environmental, energy, and economic analysis through LCA. The results show that 100 MW WPPs require approximately $146,351,300 in economic support, and the average greenhouse gas emission factor for manufacturing is 46.883 g GHG/kWh. Moreover, the manufacturing and shipment of wind turbines from the manufacturing location to the WPP location are responsible for 85 % of total GHG emissions among other stages in the life cycle of the plant [33]. Two different sizes of wind turbines, 3.6 MW and 4.8 MW, were chosen for LCA analysis. The results show that the 4.8 MW turbine generates 63 % less environmental impact compared to the 3.6 MW turbine. The 3.6 MW wind turbine generates 3.6×10^{-3}kg CO2-eq/kWh, whereas the 4.8 MW wind turbine generates 2.4×10^{-3}kg CO2-eq/kWh throughout their lifecycle. Additionally, the construction phase contributes the most GHG due to the use of various environmentally derived raw materials [41]. A 20 MW land-based WPP with 10 turbines rated at 2 MW each was analyzed through LCA, considering the entire life cycle of the WPP. This analysis found that the total GHG intensity of the plant is 8.83 g CO2 eq./kWh. This plant has the capacity to avoid 7616,003 tons of GHG emissions compared to an oil-based power plant. Furthermore, this plant can avoid the use of 4.96 million barrels of oil for power generation. The manufacturing part of the plant consumes 77 % of the energy and contributes 63.35 % of emissions, followed by recycling, which consumes 15.4 % of the energy and contributes 33 % of emissions. Transportation accounts for 4.5 % of the energy and 3.5 % of emissions [37]. The hybrid LCA of a 19.5 MW WPP currently operating with the Colombian National Grid was carried out to assess its environmental impact. The primary goal of this research paper is to find the on-site (direct) effect and the supply-chain service (indirect) effect of the WPP during its entire life. An integrated hybrid life cycle approach, considering both direct and indirect services during the operation of the WPP, was chosen to improve the completeness of the system. The results show that ignoring service input can cause unavoidable truncation problems in the LCA. Furthermore, the manufacturing stage is responsible for 80 % of the impact on climate change [42].

The LCA of three WPPs delivering high-voltage electricity to the national grid was conducted to evaluate their environmental effects. The contributions of transmitting and distributing electricity from WPPs to total environmental impacts were included in the LCA. The results indicate that small changes in capacity factor, plant lifespan, replacement rates, etc., can change the entire outcome of the LCA. The total average greenhouse gas emission from WPPs is 33.6 g CO2 eq./kWh. The pre-operational phases of WPPs contribute 86 % to 96 % of the environmental impact [43]. The LCA for the construction of a 49.5 MW WPP and its networking was performed to find the carbon emission reduction benefit. Adding the corresponding network project to the LCA and finding the improvement in reliability is the primary aim of the paper. The results indicate that yearly on-grid energy and recycling levels are the two main variables impacting the total emission reduction potential. The total carbon emission from the selected WPP is 10,490.83 tons, and the per-unit carbon emission is 4.429 g/kWh. The production stage of the WPP emits >70 % of the total carbon emissions [44]. The LCA of a 5 kW vertical-axis wind turbine was conducted to analyze 11 impact categories that are harmful to the environment. Depending on the end-of-life of the WPP, two different scenarios (Scenario A with no end-of-life treatment for the components used in the windmill and Scenario B including end-of-life treatment for the components) and six sub-scenarios were considered with different capacity factors. To compare these scenarios, the Polish low-voltage national grid and Polish wind electricity database were used. The results show that Scenario A is more impactful than Scenario B. A capacity factor of >12 % is sufficient to mitigate the environmental impact of this particular system. Furthermore, 70 % to 94 % of the impacts arise from raw material extraction and component manufacturing [45]. The LCA of a 15 kW innovative wind turbine was carried out to illustrate 11 negative environmental impact categories. The primary aim of this paper is to identify the environmental effects of manufacturing, utilizing, and recycling drag-force-driven turbines in a WPP. Additionally, a comparison of the LCA results was made by considering recycling and non-recycling scenarios. The results indicate that the tower manufacturing phase has the highest negative impact, and recycling the used components can reduce the negative impact on the environment by 30 % [46].

The LCA of a 185 m tall tower of a 5 MW WPP was conducted to identify two main environmental impact categories: global warming potential and abiotic depletion. One four-legged and one six-legged hybrid (a mix of lattice and tubular parts) tower were considered to find the energy payback time. The results indicate that the six-legged hybrid tower has comparatively more negative environmental impacts and a longer energy payback time than the four-legged hybrid tower. Additionally, tower construction contributes to 50 % of the negative environmental impact, followed by the foundation, nacelle, and rotor [23]. A 114 MW WPP was chosen for conducting the LCA to determine greenhouse gas emissions during the manufacturing and installation of the WPP's components. To assess the impact on the environment and human health, this paper compared its data with another paper in the literature section. The results indicate that the yearly carbon saving is around 310×10^{6} kg for 515GW/year power production through wind technologies. Moreover, the manufacturing phase is responsible for 91 % of global warming and 50 % of fossil fuel depletion, while ozone smog formation occurs during the transportation phase. The total energy payback time of this WPP is eight months, with a payback ratio of 29 [47]. The LCA of a 400 MW WPP was conducted to evaluate its effect on the environment, health, and energy consumption. The prime focus of this LCA study is on the installation and maintenance phases. The results of the WPP's LCA were compared with different types of power generation technologies. The findings showed that the highest negative environmental impact comes from the manufacturing phase, followed by the installation and operation and maintenance phases. The paper further reveals that the WPP produces 3.4 times more energy than it consumes over a 20-year lifespan [48]. The LCA of three different 3 MW wind turbine generators was conducted to determine which generator is more impactful on the environment. Based on the gear in the wind turbines, the generators are classified into three categories: doubly-fed induction generator (DFIG), direct-driven synchronous generator (DDSG), and direct-driven permanent magnet synchronous generator (DDPMSG). The results show that the DDSG is more environmentally impactful due to its massive construction. Moreover, the energy payback on investment is higher, and the energy payback time is lower for the DDPMSG compared to the other two [49]. The LCA of a repowered WPP with a capacity of 2 MW was analyzed to determine whether the system is environmentally impactful or beneficial. This paper focused on calculating the environmental impact or benefit of extending the life of old WPPs by repowering them with low-capacity wind turbines (DFIG). The results indicate that repowering WPPs is much more advantageous than complete replacement. Repowering WPPs is beneficial as it results in −8.78E + 08 kg CO2 eq. global warming and −2.57E + 01 kg CFC-11 eq. in human toxicity [50].

The LCA of an onshore WPP at three different locations was conducted to identify which landscape is more environmentally reliable. The LCA results of desert, steppe, and woodland-based WPPs were compared with those of a biomass power plant. The results indicate that WPPs require 92.331 kgce of energy per MWh of power generation, whereas biomass power plants require 708.020 kgce of energy per MWh. Moreover, the desert-based WPP provides the lowest global warming potential (51.547 gCO2 eq/kWh) compared to the other WPPs [51]. The LCA of three WPPs with three different rating turbines at three different locations was performed to estimate the shares of the input energy used in each stages of the life cycle and find out the environmental impact. Mathematical calculations and comparisons were made among the three WPPs to calculate the energy used and emissions from each power plant. The results show that, over the entire lifecycle, the average CO2 emission is 3.9 g/kWh, and the average intensity of energy input is 0.0625 MJ/kWh for the three power plants [52]. The LCA of a 114 MW WPP, considering four different technological improvement opportunities (TIOs), was conducted to evaluate environmental performance. Baseline turbines were used for modeling the WPP, where TIO1 is considered advanced rotor technology, TIO2 represents an advanced tower concept, TIO3 shows drive-train improvement technology, and the combination of all three TIOs is TIO4. The results indicate that baseline turbines are less environmentally friendly than the TIOs. Moreover, TIOs 1, 2, and 4 contribute more to each environmental category than TIO3 [53]. The LCA of a 600 W Taiwanese-based horizontal-axis wind turbine was carried out to identify the total GHG emissions and energy consumption throughout its lifecycle. For estimating GHG emissions, the main focus is on the rotor, generator, electronic components, and tower construction. The results indicate that among all focused components, the generator is responsible for 53.9 % of GHG emissions and 62.5 % of consumed energy. Surprisingly, this onshore horizontal-axis wind turbine has an EPBT of 160.9 years and 100.1 years for balancing GHG under local wind conditions [54]. The LCA of a 49.5 MW utility-scale WPP was conducted to find the total environmental impact from each stage of the WPP. Except for the manufacturing of equipment, all five stages—production of raw materials, transportation, installation, operation and maintenance, and dismantling or disposal—were considered to find GHG emissions. The results of this study were compared with same-rated coal and natural gas power plants. It was found that 0.6 % (8.65E-03 kgCO2e) of the global warming potential is generated from the WPP, whereas coal power plants emit 1.2 %. The production phase of the WPP is responsible for the most environmental impact [55]. The LCA of a 47.5 MW full-scale WPP was conducted to analyze environmental impact by varying the location, capacity factor, lifespan, turbine power, and recycling ratio. The LCA analysis focused on site-specific characteristics. The results indicate that the total global warming potential was generated from this WPP is 5.24 g CO2e/kWh during the baseline scenario, with a recycling ratio of 50 %. If the recycling rate decreases to 20 %, the global warming potential increases to 7.56 g gCO2e/kWh. Moreover, the assumed recycling ratio affects the entire calculation of environmental impact [56]. The LCA of a 49.5 MW grassland-based WPP was conducted to estimate its carbon footprint and carbon emission intensity. The carbon footprint of the WPP is 6.57 g/kWh, whereas coal, oil, natural gas, and nuclear power plants have carbon footprints that are 148.45 times, 127.85 times, 72.91 times, and 3.50 times greater, respectively. A total of 18,701.29 tons of carbon is emitted throughout the plant's lifecycle, with the construction stage contributing 56.74 % (9554.21 tons) of the total carbon footprint. In construction, 207.01 tons of the carbon footprint are attributed to grassland occupation, while the remaining 848.80 tons are due to other installation processes [57]. Therefore, Table 1 shows the techniques, areas of study, systematic descriptions, and future directions of the articles in the onshore portfolio.

3.2.2. *Offshore wind power plants*

As offshore WPPs are frequently affected by cyclonic issues, LCA is conducted to determine the carbon footprint due to the effect of typhoons. A simplified model is created here to assess carbon emission intensity under different high wind speeds. The results indicate that wind turbines with Permanent Magnet Synchronous Generators (PMSG) are more preferable than those with Double Fed Induction Generators (DFIG). However, DFIGs have gearboxes, and the carbon footprint of typhoons shows the highest emission factor from the gearbox. Finally, the results reveal that typhoons are responsible for 21.39 % of the carbon footprint in typhoon-prone areas based on offshore WPPs [58]. A 400 MW offshore WPP with large wind turbines was considered for evaluating environmental performance. The innovations of this paper include the environmental analysis of blades due to their separate construction, practical data for future studies, and avoiding uncertainty in electricity for dynamic emission reduction. However, the results show that the wind turbine-generator set has the highest global warming potential, and within this stage, the blades alone are responsible for 73.2 % of it [59]. A pilot project comprising 100 floating wind turbines with a capacity of 6.7 MW each was chosen for LCA analysis. As the actual data of the floating wind farm in China is not available, general data from the Chinese core life cycle database is used here. The results indicate that the carbon footprint of this farm is 25.76gCO2-eq/kWh that can be decreased upto 1.75Mt CO2-eq by 2030 by using electric arc furnace. Notably, this analysis shows that the farm is responsible for 20 % eutrophication, which directly affects the ecosystem [60]. A floating wind farm with five models, each with a capacity of 5 MW and above, was taken for LCA analysis. This work focused on total energy consumption and total GHG emissions. The results indicate that this wind farm is responsible for the reduction of 767.9 g CO2-eq CO2 emission for per 1 kWh of electricity production. The construction of the plant and the turbine manufacturing phase are the most impactful contributors to environmental degradation [61]. The LCA of 14.7 MW rated floating wind turbines was carried out to assess environmental performance. Here, all the electrical equipment—three transformers with converter sets, two different types of medium and high voltage cables, and land HVDC cables—are considered for LCA analysis. The results highlight that steel used for floating structures and aero-generators are the prime contributors to the overall environmental impact [62]. The LCA of two offshore floating WPPs (6 MW and 9.5 MW) was carried out to evaluate the environmental performance of such technologies. The primary goal of this paper is to find the environmental impact during the operational and maintenance (O&M) phase of the WPP. The results show that the vessel used for the O&M phase and power transmission is the primary sources of emissions for different environmental impact categories. Moreover, global warming potential ranges between 25.6 and 45.2 g CO2-eq for each kWh of electricity production [63]. The LCA of a 2 MW barge-type floating wind turbine WPP was performed to calculate the environmental impact. The authors aim to identify the potential advantages of barge-type floating wind turbines by comparing their LCA results with those of other wind turbine types. However, the energy payback time and CO2 emission rate of barge-type floating wind turbines are higher than those of other types of wind turbines due to their long construction and transportation time caused by their large size. They produce 18.6 g CO2eq per kWh of electricity generation [64].

The LCA of a 24 MW offshore semi-submersible WPP was conducted to analyze the environmental impact. The core focus of this paper is on multi-criteria LCA and geographical variation for clearer modeling. To find the effect of variation in geographical location, a baseline case study was compared with four different scenarios. The results indicate that the baseline case study is 14 % higher than scenario 4 in terms of environmental impact per kWh of electricity generation. Moreover, the baseline case study produces 22.3 g CO2 eq. of climate change potential for 1 kWh of electricity production [65]. The LCA of a 10 MW PMSG-based offshore WPP was analyzed to assess environmental effects. Three different PMSG-based drive train optimization topologies were taken to compare the feasibility of their utilization. The results show that using a gearbox in WPPs can reduce the weight and raw material cost of the drive train system. A high-speed generator can increase the efficiency of drive train technologies [66]. The LCA of a 102.2 MW offshore WPP was conducted to find potential environmental emissions and energy requirements. The result of this WPP analysis show that it emits 25.5 g CO2 eq. and it uses 0.39 MJ of energy per kWh of electricity production, with an energy payback time of 2.68 years. Moreover, it produces 0.02 g of particulate matter, 0.06 g of sulfur dioxide, and 0.09 g of nitrogen oxide per kWh of electricity production. This power plant still reduces GHG emissions by 96 % and energy consumption by 97 % compared to coal-fired electricity production companies [67]. The LCA of a 104 MW offshore WPP was carried out to examine environmental and energy profits. Two different scenarios were taken: one with an offshore electric substation and the second without a substation. The results reveal that the overall environmental effect is 10 % higher for the second scenario than for the first. The production stage for both scenarios contributes the highest share of the environmental impact. Cumulative energy demand and energy payback time are higher for scenario 2, but energy return on investment is less as no substation is attached to it [68]. The LCA of a 2 MW offshore WPP was conducted to find energy benefits for LCA studies. Designing a mathematical model for developing the design, manufacturing, use, and energy management of offshore WPPs was the primary aim of this study. Furthermore, two paths of post-energy management were chosen for managing the environmental impact. The results show that offshore WPP efficiency is 10.68 % higher than that of a nonrenewable lignite-fired power plant. Overall, offshore WPPs are contributing to a greener world [69]. The LCA of a 385 MW floating WPP was conducted to check the environmental burden of a plant installed 3–13 km away from the shore. In this study, wave and wind energies were combined on one platform for three different locations. The results reveal that the fixed, moving, and mooring parts of the manufacturing phase of this multi-use power plant contribute the highest environmental effects. Another important result is that environmental effects change with variations in location, capacity factor, and the distance between the installed sites and the shore [70]. Therefore, Table 2 shows the techniques, areas of study, systematic descriptions, and future directions of the articles in the offshore portfolio.

Table 1
Techniques, area of study, systematic description, future direction of articles in the onshore portfolio.

Reference	LCA Software	Area of the study	Systematic description	GHG emission	Stage of life responsible for maximum emission	Future Research Direction
Nassar et al. 2024 [33]	–	Libya	Case Study	46.883 g GHG/kWh (avg)	Manufacturing and transportation	Eco-friendly transport can be used to avoid large amount of emissions from transportation stage.*
Turkmen et al. 2024 [41]	GaBi Software Ecoinvent Database	Turkey	Case Study	3.6×10^{-3}kg CO2-eq/kWh (for 3.6 MW Wind turbine) & 2.4 $\times 10^{-3}$kg CO2-eq/kWh (for 4.8 MW Wind turbine)	Construction	Focus should be on higher-capacity turbines during planning to reduce per-unit environmental impacts.*
Elmariami et al. 2023 [37]	–	Zawia, Libya	Case Study	8.83 g CO2 eq./kWh	Manufacturing	Optimizing manufacturing process can lower the energy utilization and total emission. *
Vélez-Henao et al. 2021 [42]	-	Guajira, Colombia	Case study	–	Manufacturing	Expanding hybrid LCA studies to include social and economic dimensions for a more complete sustainability assessment. *
Teffera et al. 2021 [43]	SimaPro 8.0.3.14 multiuser (ReCiPe-2008 impact assessment method)	Ethiopia	Case study	33.6 g CO2 eq./kWh	Pre-operational	Local sourcing of components can reduce pre-operational GHG emissions and improve overall sustainability. *
Li et al. 2020 [44]	–	Shi-san-jian-fang, Xinjiang, China	Case study	4.429 g/kWh	Production	Paper gives an idea about emission reduction index, power grid planning for future clean energy generation.
Kouloumpis et al. 2020 [45]	Gabi 9.2.0.58 (CML 2001 impact assessment method)	Bialystok University of Technology, Poland	Case study	–	Raw material extraction and component manufacturing	Instead of short term analysis, paper provides the idea to analyze LCA for long-term performance.
Doerffer et al. 2021 [46]	SimaPro 8.4.0 Pre Consultant (Eco-indicator method)	Poland, Europe	Case study	–	Manufacturing	As the drug force-driven turbines are heavier than normal lift driven turbines, changes in the component manufacturing can be done for reducing their weight. *
Gkantou et al. 2020 [23]	GEMIS	Portugal	Case study	–	Tower construction	Economic and structural evaluation of hybrid tower is required in combination with environmental assessment. *
Gomaa et al. 2019 [47]	SimaPro 7.1 (TRACI impact assessment method)	Southern region of Tafilah, Jordan	Case study	–	Manufacturing phase	The paper gives the idea for replacing steel in the tower of the WPP by green cement for future research.
Alsaleh et al. 2019 [48]	SimaPro 8 (TRACI impact assessment method)	Abilene, Texas, US	Case study	–	Manufacturing	Changing in manufacturing pattern of the WPP's components can decrease the environment effect. *
Schreiber et al. 2019 [49]	GaBi 8.7 (ILCD/PEF recommendation v1.09)	Germany	Case study	–	Construction	Appropriate recycling or reusing strategies can improve end-of-life performance and lessen overall environment impact. *
Martínez et al. 2018 [50]	SimaPro 7.0 Pre-Consultants (CML Leiden 2000 impact assessment method)	La Rioja, Spain	Case study	−8.78E + 08 kg CO2 eq.	–	Technical-economic investigation for repowering old WPP can be done to extend turbine life and reduce carbon footprint.*
Gao et al. 2019 [51]	–	Wanghai Temple Wind Farm; The Saihan Dam Wind Farm; Aforementioned Wind Farm; China	Case study	51.547 g CO2 eq/kWh for desert based WPP	–	The study suggests that future research could focus on landscape-specific environmental performance of wind power plants, with emphasis on evaluating other hybrid plant.
Xie et al. 2020 [52]	-	Mailiao, Jhongtun, Chunfong	Case study	3.9 gCO2 eq /kWh	–	Data assumption should be decreased for reducing the uncertainly of the paper. *
Ozoemena et al. 2018 [53]	(CML 2001 impact assessment method)	The Coed Morgannwg Strategic Search Area, South Glamorgan in Wales, UK	Case study	–	–	LCA of different TIOs based on capacity factors, life span, and the effect of weight can be done to reduce long EPBT. *
Wang et al. 2017 [54]	SimaPro 7	Tainan, Taiwan	Case study	–	–	Suggesting for various site-specific conditions for improving the performance and to reduce long EPBT. *
Xua et al. 2018 [55]	GaBi 6 (CML 2001 impact assessment method)	Saihan Plant, Inner Mongolia, China	Case study	8.65E-03 kgCO2e	Production phase	New techniques or concepts should be developed to control high abiotic resource depletion and

(continued on next page)

Table 1 (*continued*)

Reference	LCA Software	Area of the study	Systematic description	GHG emission	Stage of life responsible for maximum emission	Future Research Direction
						ozone layer depletion for clean future. *
Ozsahin et al. 2022 [56]	GaBi 7.3 (CML 2001 impact assessment method)	Marmara Region, Istanbul, Turkey	Case study	5.24 g CO2e/kWh		Recommended to develop specific dataset for each country for more geographically accurate environmental assessments. *
Liu et al. 2021 [57]	–	Mongolia, China	Case study	6.57 g/kWh	Installation phase	Suggests performing comparative LCA studies between different siting conditions (e.g., grassland vs. urban) for emission profiling. *

Note: 1. All the values of GHG emission in the table and EPBT in the theory are taken directly from the cited studies unless otherwise mentioned. No new calculations were performed in this review.
2. For studies without exact GHG values, the listed stage is based on which part the authors said had the most environmental impact.
3. (*) indicating author own findings from studies or identified research gaps where the original study did not explicitly propose future work.

3.2.3. *Comparison between onshore and offshore wind power plants*

The LCA of onshore single wind turbines, onshore WPPs, and offshore WPPs has been conducted to calculate global warming potential. Various data, such as capacity factor, rated power, hub height, rotor diameter, and annual energy yield, were chosen to determine their effect on greenhouse gas emissions. All the data used for the LCA operation were taken from a 20-year literature survey. The results reveal that an increase in annual energy yield or turbine size of offshore WPPs does not affect the reduction of global warming potential. Moreover, capacity factor and global warming potential maintain a non-linear relationship with each other [71]. The LCA of 2 MW onshore and offshore WPPs was conducted to understand environmental policies for the future growth of WPPs. Uncertainty analysis was performed to understand the effects of different parameters, such as turbine size and lifetime, on greenhouse gas emissions. The results indicate that onshore WPPs have the potential to produce 0.082 kg CO2-eq./MJ of greenhouse gas, whereas offshore WPPs have the potential to produce 0.130 kg CO2-eq./MJ of greenhouse gas. Moreover, onshore and offshore WPPs are able to reduce greenhouse gas emissions by 3 times and 2 times, respectively, compared to coal-fired power plants [72]. Referring to the previous paper by Wang et al., 2019 [72], this paper reveals the LCA for the same rated WPPs with some important corrections. All the corrections were made in the transportation and installation phases. Assumptions of diesel for land transport, the distance between the plant site and manufacturer, and unrealistic greenhouse gas emissions were the key mistakes in the previous paper. This paper suggests that onshore and offshore WPPs can reduce greenhouse gas emissions by 50 to 150 times compared to coal-fired power plants [73]. The LCA of different wind turbines (22 onshore and 6 offshore locations) was carried out to identify the effects of space, time, and WPP size on greenhouse gas emissions and energy payback time. A Gaussian regression model was developed in this paper to address virtual studies. The results show that the average gas payback time of the wind turbines is 5.3 months, and there are no significant changes when altering the turbine sizes. However, unpredictable climate variations affect the payback time of the plants [74].

The LCA of 2 MW offshore and onshore WPPs was conducted to compare the environmental impact of both, taking into account ecological factors. Four different factors were considered to compare the LCA results: impact on/by the operator (non-ergonomic), on/of the product (non-functional), on/by living objects (non-ecological), and on/by man-made objects (nonsozological). The comparison shows that the non-ergonomic factor is much more impactful than the others. The environmental impact from the tower and foundation of land-based WPPs is 59 %, whereas the tower and foundation of offshore WPPs account for 49 %. Overall, land-based onshore WPPs (125,147 Pt) are more impactful than offshore WPPs (109,075 Pt) [75]. The LCA of onshore, shallow-water, and deep-water WPPs, including the Gulf Coast, was conducted to analyze the contribution of each stage to the environment. To avoid the minor impact from the power plant, a 0.1 % cutoff criterion was applied in this paper. The results show that the material extraction stage of offshore deep-water WPPs is responsible for 82 % of the energy impact on the environment, whereas 72 % and 58 % are contributions from onshore and shallow-water WPPs, respectively. Moreover, 5.63 to 7.29 g CO2-eq./kWh is the overall emission rate of the selected WPPs [76]. Therefore, Table 3 shows the techniques, areas of study, systematic descriptions, and future directions of the articles in the onshore and offshore portfolio.

4. Discussion

The review of various life cycle assessment (LCA) studies on wind power plants (WPPs) reveals critical insights into their environmental, economic, and energy impacts. Manufacturing and shipment stages significantly contribute more greenhouse gas or GHG emissions, with a 100MW WPP showing that 85 % of its total emissions arise from these processes. Similarly, a 20MW WPP analysis indicates that manufacturing consumes 77 % of the energy and contributes 63.35 % of emissions. This indicates the requirement of greener manufacturing processes and optimized production stages. Recycling presents a substantial opportunity for reducing environmental impacts. Studies on a 5 kW vertical axis wind turbine and a 15 kW innovative wind turbine show that recycling can cut negative impacts by 30 %. Moreover, site-specific factors play a main role in environmental outcomes. Comparative analyses of WPPs in desert shows CO2 emission factor of 51.547 g CO2 eq/kWh, grassland shows carbon footprint of 6.57 g/kWh, sea floating shows CO2 emission factor of 45.2 g CO2 eq./kWh and these different environmental emission occurring due to their separate locations These variations underscore the importance of location-specific LCA.

Wind power generally offers a significant advantage over fossil fuels in terms of carbon footprint. For instance, a 49.5MW grassland-based WPP emits only 6.57 g/kWh of CO2, starkly lower than emissions from coal, oil, and natural gas power plants. Technological advancements also play a crucial role in improving environmental performance. An LCA of a 104MW WPP indicates that advanced rotor, tower, and drive-train technologies result in better environmental outcomes compared to baseline turbines. However, offshore WPPs face unique challenges due to longer construction and transportation times, which increase their environmental impacts. Factors such as geographical location, capacity factor, and distance from shore significantly influence these impacts. Despite these challenges, WPPs generally exhibit lower GHG emissions and energy consumption compared to coal-fired power plants. For example, a study on a 2MW repowered WPP shows that repowering is more beneficial than complete replacement, significantly reducing GHG emissions. Lastly, we can say that the findings of this review indicate that offshore WPPs generally have higher environmental impacts compared to onshore WPPs, primarily due to complex

Table 2
Techniques, area of study, systematic description, future direction of articles in the offshore portfolio.

Reference	LCA Software	Area of the study	Systematic description	GHG emission	Stage of life responsible for maximum emission	Future Research Direction
Sun et al. 2024 [58]	–	South Coast of China	Case study	–	Manufacturing	Carbon benchmarks of typhoons can help engineers and stakeholders for changing the design of different equipment for protection purposes. *
Cao et al. 2024 [59]	Brightway LCA	Jiangsu, China	Case study	–	Construction	Suggest extending analysis beyond blades to entire system for whole system's environmental efficiency analysis. *
Yuan et al. 2023 [60]	Process Based LCA, Chinese core life cycle database (CLCD)	China	Case study	25.76gCO2-eq/ kWh	–	Replace General reference data into actual primary data for more accurate estimation. *
Chen et al. 2023 [61]	CML-IA method	Fujian, China	Case study	16.5 g CO2-eq/ kWh	Construction and manufacturing	Use of real project-specific data in every life-phase is important for perfect analysis. *
Brussa et al. 2023[62]	SimaPro 9.3 (EPD impact assessment method)	Italy	Case study	–	Floating structures and aero-generators	For more accurate results, focus should be on the modelling uncertainties in early-phase LCA using detailed engineering data and final project specification. *
Garcia-Teruel et al. 2022 [63]	SimaPro 9.1 (ReCiPe Midpoint-H-2008 impact assessment method)	Hywind and Kincardine, Scotland	Case study	Ranges between 25.6 and 45.2 g CO2-eq./kWh	–	Paper gave the idea about LCA operation by assuming O&M data. Practical real-time analysis with more details can give more logistical results.
Yildiz et al. 2021 [64]	GEMIS 5	Deep-water in European countries	Case study	18.6 g CO2-eq/ kWh	Construction and transportation	Changes in the materials used to construct barge-type floating wind turbine based WPP can reduce CO2 emission of such plant. *
Poujol et al. 2020 [65]	SimaPro 8.4	Mediterranean Sea, Southern France (expected)	Case study	22.3 g CO2 eq. /kWh	–	Encourages imitation of physical scenario-based LCAs in other section to assess site-specific environmental difference. *
Moghadam et al. 2020 [66]	–	–	LCI (data taken from database)	–	Production	Paper only took the concept of the LCA approach, but didn't use it for environment impact analysis. Therefore performing LCA for environmental assessment is needful.
Yang et al. 2018 [67]	–	Donghai Bridge, Shanghai, China	Case study	25.5 g CO2 eq. /kWh	–	Suggests to incorporating hybrid LCA model to enhance clarity on environmental issues of offshore WPP in China. *
Huang et al. 2017 [68]	SimaPro 7.1 (Eco-indicator 99 method)	Taiwan Strait, Changhua	Case study	–	Production stage	Paper gives the hints of submarine cable, which can be further used for carbon capture technologies.
Tomporowski et al. 2017 [69]	SimaPro 7.1 (CML impact assessment method)	Maritime areas	Case study	–	–	Stage-separate LCA analysis and the idea of designing mathematical modeling for offshore WPP can be used by onshore WPP. *
Elginoz et al. 2017 [70]	GaBi (CML 2000 and CML 2001 impact assessment methods)	Atlantic sea, Dutch North Sea, Kriegers flak in Baltic Sea	Case study	–	The fixed, moving, and mooring parts of the manufacturing phase	Further study is required on the topic of recycling ratio for such multi-user or other hybrid power plants. *

Note: 1. All the values of GHG emission in the table and EPBT in the theory are taken directly from the cited studies unless otherwise mentioned. No new calculations were performed in this review.
2. For studies without exact GHG values, the listed stage is based on which part the authors said had the most environmental impact.
3. (*) indicating author own findings from studies or identified research gaps where the original study did not explicitly propose future work.

installation and transportation requirements. For instance, the life cycle assessment (LCA) of a 100 MW onshore WPP shows an average greenhouse gas (GHG) emission factor of 46.883 g CO2/kWh largely attributed to manufacturing and transportation processes. In comparison, an offshore WPP with a capacity of 102.2 MW exhibits a lower emission factor of 25.5 g CO_2/ kWh. However, despite the lower emissions per unit of electricity generated, offshore WPPs require more extensive infrastructure, leading to increased environmental burdens during installation. These variations underscore the importance of location-specific LCA studies and the need for optimized construction and logistics strategies to further minimize the carbon footprint of wind power technology. A key factor influencing LCA outcomes is energy payback time (EPBT). Offshore WPPs benefit from higher wind speeds, which can significantly reduce EPBT. For instance, a 102.2 MW offshore WPP exhibits an EPBT of 2.68 years, reflecting its faster energy recovery compared to traditional fossil-based power generation. In contrast, onshore WPPs typically experience longer EPBT due to variable wind conditions and infrastructure limitations. These findings suggest that while offshore wind farms have higher upfront emissions, their long-term sustainability can be improved through optimized material selection, improved logistics, and enhanced turbine efficiency.

Table 3
Techniques, area of study, systematic description, future direction of articles in the onshore and offshore portfolio.

Reference	LCA software	Area of the study	Systematic description	GHG emission	Stage of life responsible for maximum emission	Future Research Direction
Bhandari et al. 2020 [71]	Monte-Carlo simulation	–	LCI (data taken from database)	–	–	To fulfill the research data gap for LCA, a novel database is required to develop. *
Wang et al. 2019 [72]	–	Denmark	Case study	0.082 kg CO2-eq./MJ (for onshore WPP), 0.130 kg CO2-eq./MJ (for offshore WPP)	–	Paper gave details instructions to the wind turbine manufacturer as the greenhouse gas emission has a correlation with turbine lifetime.
Marx et al. 2019 [73]	–	–	LCI (data taken from database)	–	Transportation and installation	Responding to the operation and maintenance phase of WPP is necessary. *
Dammeier et al. 2019 [74]	Process based LCA based on new regression model	Europe	Case study	–	–	Paper gave the idea to calculate greenhouse gas payback time for various environmental affects. Moreover, accurate data of hub weight and wind turbine diameter is required to calculate actual greenhouse gas emissions from the WPP.
Piasecka et al. 2019 [75]	SimaPro (Eco-indicator 99 method)	Europe	Case study	–	–	Suggests in-depth investigation into component-wise material inventories to improve relative environmental analysis. *
Chipindula et al. 2018 [76]	SimaPro (Impact 2002+ impact assessment method)	Texas	Case study	5.63 to 7.29 g CO2-eq./kWh	Material extraction stage of offshore deep-water WPPs	Material extraction stage is the common emission contributor of WPP, analysis should require to take for other stages. *

Note: 1. All the values of GHG emission in the table and EPBT in the theory are taken directly from the cited studies unless otherwise mentioned. No new calculations were performed in this review.
2. For studies without exact GHG values, the listed stage is based on which part the authors said had the most environmental impact.
3. (*) indicating author own findings from studies or identified research gaps where the original study did not explicitly propose future work.

5. Overall findings

5.1. Factors affecting onshore and offshore WPPs LCA

According to the above literature review, the lifecycle assessment of onshore and offshore WPP depends on various factors. From raw materials extraction to end-of-life, each stage-each step is variable and it is sometimes hampering and sometimes gives profit to the nature. Capacity factors, wind speed, air density, lifespan, location, turbine size, gear, tower construction, hub height, replacement rate, recycling ratio etc. are the common factors that are used frequently for both the onshore and offshore WPPs LCA analysis. Moreover, materials used for manufacturing different materials-equipments, distance travelled for installing the WPP from manufacturer side, fuels used for installation-operation-maintenance are the important factor that affects the calculation of LCA. In offshore WPP cases, water depth, distances from the shore are the most important additional factors are required special attention.

5.2. Summary of key LCA indicators in reviewed studies

This section provides a combine overview of key LCA indicators those are reported in the reviewed studies like Energy Pay-back Time (EPBT), GHG emissions per unit of energy produced. These are the primary focus of this review paper. However, Energy Payback ratio (EPR), Energy intensity values are collected from very few reviewed studies.

Across the reviewed literature, the following results are found:

EPBT: It is basically defined as the time required for WPP to generate the same amount of energy equal to that invested energy during construction, operation and decommissioning. The general EPBT values lies between 6 months to 2 years in the case of modern onshore power plant. However, the offshore power plant has longer EPBT as offshore installation require more intensive materials and energy. Here, the shortest EPBT was found from the paper [47] having a WPP capacity of 114MW. The EPBT value is only 8 months in this case. The longest EPBT was found in [67] with a WPP having capacity of 102.2 MW. The EPBT value for this is 2.68years as these wind turbines operates at low-wind regions.

The emission factor (GHG) for per unit energy production: This is defined as the total greenhouse gas emissions over the WPP's life cycle divided by the total electricity produced. The general GHG emission factor for wind power plant's manufacturing stage is ranging from 2.5 g to 25 g CO2-eq/kWh approximately. However, it is found from literature studies that for onshore WPP, the range is staring from 2.4 g CO2-eq per 1 kWh of power production for 4.8 MW rated Wind turbine and reached to 33.6 g CO2-eq per 1 kWh production by 1 MW rated Wind turbine. In the case of offshore WPP, the range of GHG emission factor is staring from 16.5 g CO2-eq per 1 kWh of power production for 5 MW rated floating Wind turbine and reached to 25.76 g CO2-eq per 1 kWh of power production by 6.7 MW rated floating Wind turbine.

Carbon Payback time: As like EPBT, Carbon Payback time is the time require for offsetting the GHG emission generated during whole lifecycle by a WPP as compared with the conventional fossil-fuel based power plant. However, for this review analysis, Carbon Payback time is not considered directly.

Energy Payback Ratio: It is refers to how many times a WPP can pay back its embodied energy during the whole life cycle. It is found from the previous studies, the average range of Energy Payback Ratio is 10–30 for modern WPP. Here, a 114MW WPP explained its Energy Payback Ratio is 29.

Energy Intensity: Energy intensity is defined by the amount of energy required to generate one unit of electricity. The primary energy input required for generating 1 kWh power is 0.0625 MJ is found from the literature.

5.3. Research gap

WPP is considered as one of the cleanest power generation technology. But there is still emission present in the whole lifecycle of the WPP. To access the impact of these emissions, various LCA studies have been performed from several years. So, here only previous 8-years studies have been taken and some of their research gaps are listed below:

a. In between onshore WPP and offshore WPP studies, the numbers of offshore WPP LCA studies are very much less than onshore studies.
b. LCA helps to find the impact or benefit of materials used for constructing, transporting, operating and recycling of WPP. Therefore proper data of used materials and emissions are necessary for perfect

results. But most of the LCA research papers are based on assumed data, so no perfect results.

c. Most of the onshore WPP are located in Asian continent and offshore are in European continent, but most of the research papers are only for the European onshore WPP. Less number of research papers is found for Asian and other continent.
d. Research finding on LCA was started since 1990′s, but very less number of paper found that finds environmental impact for different type of components used in different parts of WPP. For example: not a single research paper is found that only focused on to find the impacts of different types of generators used in WPP.
e. In most of the previous research papers, it is noticed that materials extraction stage of WPP is contributing highest environmental impact followed by construction, transportation, end-of-life and operation-maintenance stages. But no further step or idea for reducing the impact of materials extraction stage is found in any research paper.
f. As EPBT depends on the total energy used for installing WPP, so any mishandling of initial data can affect the accuracy of EPBT. Not a single research paper is found for proper handling of EPBT.
g. LCA gives the idea of how WPP is impacting the environment by emitting GHG. Lot of LCA research papers found that are giving the idea to reduce GHG emission in different ways, but less number of research papers are found that implements these ideas.
h. Most of the research paper on LCA is found as combined (that starts from raw-material extraction and ends to end-of-life of WPP). No separate analysis of one particular stage is found in any research paper.
i. Very few numbers are paper found those are focusing on economic analysis. Integration of life cycle costing (LCC) alongside LCA to assess the economic viability of WPPs over their entire lifespan is required.
j. Different types of cyclones are very common for offshore WPPs. Very less number of papers were found that highlighted this extreme weather condition.

5.4. Future research direction

Several onshore and offshore research papers are reviewed in this paper to highlight the effect of total GHG emission, EPBT of the previous 8-years WPP’s LCA studies and to find the overall research gap of the past WPP’s LCA studies. Most of the future research directions of the previous 8-years WPP’s LCA studies are already shown in Tables 1, 2, 3 respectively. Here, some next research plans are shown to improve WPP’s LCA studies in the future:

A. To make WPP’s LCA more realistic for the modern era, LCA should be modernized. Implementation of Artificial Intelligence in LCA can help it for more accurate analysis.
B. Per component analysis for WPP is necessary for better GHG’s effect on environment calculation.
C. There is a huge gap in construction between offshore and onshore WPPs. As the offshore WPPs are increasing rustically, LCA of offshore WPPs requires more attention.
D. Comparison between offshore and onshore LCA required more attention as it gives clear picture of the environment affects of both the WPPs.
E. As LCA gives the calculation about overall environment effect of different WPP, so more research strategies and more developed open-source software are needed as it is the initial step to estimating environment effect.
F. To maintain continuous WPP’s LCA, it is necessary to maintain availability of data.
G. For more accuracy in LCA, real-time information gathering technique of WPP is required to develop.
H. Before installation of any WPP, LCA should be mandatory so that companies can take the emission control action.
I. All the Governments of the world should adopt LCA for WPP to estimate environment affect before its installation.
J. Unsecure life-cycle assessment methods should be removed from software that are used for WPP’s LCA analysis.
K. More study is required on the long-term environmental impacts of WPPs on marine ecosystems in the case of offshore installations.
L. Investigate how circular economy principles can be applied to WPPs, focusing on enhancing resource efficiency, reducing waste generation, and promoting sustainable materials management throughout the lifecycle.
M. Conduct health impact assessments alongside LCAs to measure the effects of WPPs on public health, including noise pollution, electromagnetic fields, and psychological impacts.

6. Conclusion

This paper presented the status of the previous 8-years WPP’s LCA research paper to search for the recent assignments on this topic. To give the idea about GHG production mainly CO2 and the estimation of EPBT from each of the WPPs that has been published in the previous 7-years are the goal of this paper. Moreover, this paper has summarized with recent publications based on onshore and offshore WPPs and their research gaps. An inclusion method is chosen for selecting high impactful research papers based on Life Cycle Assessment of Wind Farm. This method helps to eliminate bias by setting consistent standards for study selection, enhancing the credibility and reproducibility of the review. After studying >30 recent research papers, it is observed that SimaPro is the most popular software for LCA studies among the recent researchers. There are other platforms like GaBi, GEMIS, OpenLCA are also used by researchers. Contrariwise, process based LCA and Input/Output LCA are the most used LCA technology till date.

From this review, it is clear that GHG and EPBT are the most important terms for WPPs. From the finding of sources to estimate the environment effect, GHG helps the researchers whereas EPBT helps to find the time is needed for generating an equal amount of energy that used for installing a WPP. Horizontal-axis-turbine based WPP requires more time for EPBT. Moreover, this review paper shows a clear direction to identify high impactful research papers. From the Section 3.2, it is found that maximum number of LCA studies has been done for onshore WPPs. Although both onshore and offshore WPPs are important to us for the clean future of the world. Among the onshore and offshore WPPs, offshore WPPs are responsible for more GHG emission as their constructions are somewhat complex. But offshore WPPs produce more power as the shore has high speed wind so that EPBT becomes lesser than onshore WPPs.

In conclusion, it is necessary to point out that the number of offshore WPP’s LCA studies is not sufficient to tell about the overall emission scenario as compared to the onshore one. It is obvious to increase the offshore WPP’s LCA studies to estimate GHG production from floating and fixed-pole offshore WPPs. To develop the use of offshore WPP and their LCA studies, the construction companies need to spread their data globally for the future environmental studies. Moreover, researcher’s collaboration is needed to fulfilling the gaps in the data.

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CRediT authorship contribution statement

Uttara Das: Resources, Data curation, Writing – original draft, Methodology, Conceptualization. **Champa Nandi:** Validation, Investigation, Writing – review & editing, Supervision.

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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Data availability

Data will be made available on request.

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