International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18 (2026) pp. 1-9

https://doi.org/10.70917/ijcisim-2026-2308
Article

Wind Energy in Climate Change Mitigation: A Comprehensive Assessment of Emission Reduction Potential, Deployment Challenges, and Future Pathways

Zhelong Zhu [1,*]

[1] School of Science, University of Melbourne, Melbourne, Victoria, 3000, Australia
* Correspondence author: zlzhuedu@phc.ac.cn

Abstract: Climate change driven by greenhouse gas emissions necessitates deep decarbonization of the global energy system, with wind energy emerging as a central mitigation technology. This study systematically assesses the role of wind energy in climate change mitigation by analyzing its emission reduction potential, scientific evidence, implementation barriers, and actual deployment effects. Through a mixed methods approach combining life cycle assessment synthesis, global deployment trend analysis, and a case study of the London Array offshore wind farm, the research evaluates wind energy's quantifiable carbon abatement capacity and its contribution to global carbon budget targets. The findings demonstrate that wind power achieves life cycle emissions of 32 to 70 gCO_2 e/kWh, with carbon payback periods as short as 9.8 to 14 months, significantly outperforming fossil fuel based generation. Global cumulative installed capacity exceeded 906 GW by 2022, with an average annual growth rate of 14.2 percent from 2006 to 2020. The London Array case study confirms annual emission reductions of approximately 925,000 tonnes CO_2, with 298 tonnes CO_2 reduced per GWh generated. However, technical intermittency, high upfront investment costs, ecological disturbances, policy inconsistencies, and social acceptance barriers continue to constrain large scale deployment. Under high deployment scenarios, wind energy could contribute 10 to 15 $GtCO_2$ e per year in emission reductions by 2050, representing 20 to 30 percent of global energy related carbon emissions. This study concludes that wind energy represents a mature, quantifiable, and scalable climate mitigation pathway, yet realizing its full potential requires continued technological innovation, stable policy frameworks, and enhanced social coordination mechanisms.

Keywords: Wind Energy; Climate Change Mitigation; Life Cycle Assessment; Carbon Emission Reduction; Renewable Energy Deployment

1. Introduction

1.1. Background

Climate change has become one of the most pressing challenges facing human society in the 21st century. According to the latest assessment report of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2023), global warming is mainly driven by greenhouse gas emissions, and in particular the reliance on fossil fuels in the energy system remains the core source of carbon emissions [1]. Achieving net zero global emissions by mid century is necessary to keep global average temperature rise to within 1.5°C above pre industrial levels, which will require a deep structural transformation of all sectors, including energy.

Of all the mitigation pathways, decarbonisation of the energy system is considered to be the foundation and prerequisite for achieving climate goals. According to the International Energy Agency (IEA, 2023) in its 2050 Net Zero Roadmap, wind and solar energy will form the core pillars of the future power system, and it is expected that these two types of renewable energy will account for nearly 70 percent of the global power supply by 2050 [2]. Among them, wind energy is one of the most representative climate change mitigation technologies due to its abundant resources, mature technology, zero direct carbon emissions and good scalability.

In this paper, we will systematically assess the role of wind energy in climate change mitigation, analyse its emission reduction potential, scientific evidence, implementation barriers and actual deployment effects, and discuss its realistic contribution and future development prospects in the global transition to net zero in the context of typical cases.

1.2. Wind Energy Technology

The basic principle of wind power generation is to convert the kinetic energy of the wind into rotational mechanical energy through the blades of the wind turbine, and further converted into electrical energy by the generator. The wind pushes the blades to rotate around the rotor, driving the main shaft and gearbox, which in turn outputs electricity through the generator. This process is dependent on a number of variables such as wind speed, air density, blade length and system design [3]. Modern wind power systems typically contain components such as towers, nacelles, hubs, main shafts, gearboxes, generators, pitch systems, and wind measurement devices [4]. Wind speed enhances with increasing height, so the tower height is usually 80 to 150 metres to enhance the wind energy capture capacity per unit area (Table 1).

Table 1. Key Technical Specifications of Modern Wind Turbine Systems

Component	Function	Typical Specifications
Tower	Supports nacelle and rotor, elevates turbine to higher wind speeds	Height: 80 150 m
Nacelle	Houses gearbox, generator, and control systems	Weight: 50 300 tonnes
Rotor Blades	Capture kinetic energy from wind	Length: 40 120 m per blade
Gearbox	Increases rotational speed from rotor to generator	Ratio: 50:1 to 100:1
Generator	Converts mechanical energy to electrical energy	Capacity: 2 15 MW
Yaw System	Aligns rotor with wind direction	Rotation: 360 degrees
Pitch Control	Adjusts blade angle for optimal power capture	Variable angle: 0 to 90 degrees

Based on the direction of the rotor axis, wind turbines are classified into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT).

As shown in Figure 1, the HAWT has a main axis parallel to the wind direction and relies on a yaw system to continuously align with the wind direction, which is a mature structure with high efficiency, and is the mainstream form of commercialisation; whereas the VAWT has a main axis perpendicular to the ground, does not require yawing, and is capable of accepting any wind direction, and has a compact structure with low noise level, which is suitable for urban areas and regions with complex wind conditions [5].

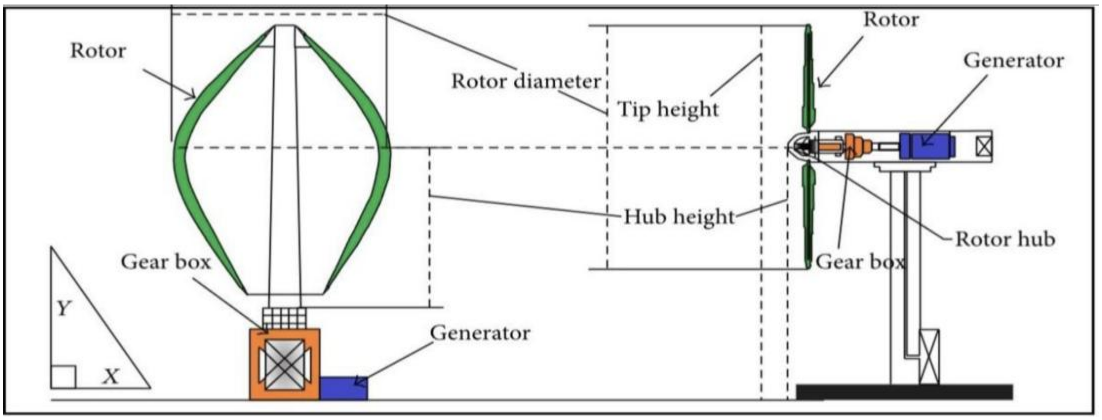

Figure 1. VAWT and HAWT

In recent years, as the demand for distributed wind energy in dense urban areas has grown, VAWTs have received renewed attention, showing particular advantages in low wind, small building top deployments. Meanwhile, in order to improve energy efficiency, modern wind turbines widely adopt three bladed structure with adjustable pitch control system, which can adjust the windward angle under different wind speed conditions to achieve stable output.

Among different turbine configurations, vertical axis wind turbines (VAWT) have demonstrated particular advantages in regions with complex wind conditions, and studies on their aerodynamic response to wind gusts have provided important insights for improving their operational stability and efficiency in urban environments [6].

2. Scientific Evidence

2.1. The Potential in Reducing Emission of Wind Energy

In recent years, life cycle assessment (LCA) studies on the effectiveness of wind energy in reducing emissions have been accumulating, and a reliable scientific evidence base has been formed. Nassar et al. (2024) carried out a systematic LCA study of 12 proposed wind farms in Libya, and constructed a model covering the triple system boundaries of the manufacturing country, the transport pathway, and the local deployment based on the ISO 14040/14044 standard, comprehensively tracing the energy consumption and carbon emission pathways of wind power systems [7]. The study finds that the whole life cycle GHG emission factor of wind power is 32 to 70 gCO_2 e/kWh, with an average of only 46.88 gCO_2 e/kWh, which is significantly lower than the global average of thermal power (greater than 800 gCO_2 e/kWh), and the carbon payback period (CPT) and energy payback period (EPT) are 9.76 and 14.01 months, respectively, demonstrating the rapid emission reduction capability of wind energy in climate change mitigation.

Earlier studies have provided fundamental support for the above results. Guezuraga et al. (2012) pointed out that the manufacturing phase of wind power generation accounts for 84 percent of the total life cycle energy consumption, with towers accounting for about 55 percent of the material sources, but its CO_2 emission per unit of electricity is only 9 g/kWh, which is the lowest among all types of power technologies [8]. The paper further points out that the larger the capacity of a WTG, the lower its emissions per unit of electricity generated, suggesting that the trend towards larger sizes contributes to systematic carbon emission reduction. Vargas et al. (2015), on the other hand, find in the Mexican case that different material compositions can lead to more than 30 percent of the difference in life cycle emissions even for WTGs of the same power, highlighting the criticality of wind turbine design choices in the LCA [9]. Nassar et al. (2024) also refer to the payback period of wind power projects in India, showing that the carbon payback period is as low as 50 days, and the energy payback period is about 1.12 years, which fully demonstrates that wind power is one of the most cost effective forms of energy to reduce emissions in a short period of time [7] (Table 2).

Table 2. Life Cycle Assessment Results of Wind Energy Compared to Conventional Power Generation

Parameter	Wind Power (Onshore)	Wind Power (Offshore)	Coal Power	Natural Gas Power
Life Cycle GHG Emissions (gCO_2 e/kWh)	10 15	12 20	800 1000	400 500
Carbon Payback Period (months)	9.8 14	12 18	N/A	N/A
Energy Payback Period (months)	12 18	15 24	N/A	N/A
Manufacturing Phase Energy Share (%)	84	80	N/A	N/A
Manufacturing Phase Material Share: Tower (%)	55	50	N/A	N/A

2.2. Current Status of Global Wind Energy Development

Wind energy, a key source of zero carbon electricity, has continued to grow rapidly worldwide in recent years. According to the Global Wind Energy Council (GWEC, 2023), by the end of 2022, the cumulative installed capacity of wind power worldwide had exceeded 906 GW, with onshore wind accounting for about 93 per cent of the total, and offshore wind continuing to expand its share [10]. Wind energy currently supplies around 7 percent of the world's electricity, accounting for the second largest share of the renewable energy mix after hydropower.

Wind energy has experienced sustained and steady growth over the past fifteen years. As shown in Figure 2, between 2006 and 2020, the cumulative installed capacity of wind power has shown a significant upward trend: from less than 100 GW to more than 700 GW, with an average annual growth rate of around 14.2 percent. The solid black line represents the actual growth trajectory of total installed capacity, while the dashed line is the theoretical 14.2 percent CAGR reference line, which coincides with the actual growth trajectory of total installed capacity, indicating a high degree of consistency and stability of wind energy deployment globally [11] (Table 3).

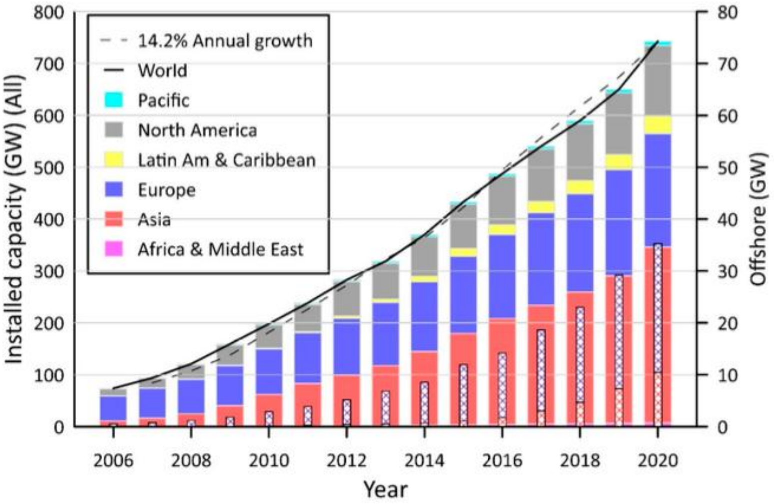

Figure 2. Global cumulative installed wind power capacity by region (2006–2020). Offshore wind capacity is shown with patterned segments. The dashed line indicates a 14.2% annual growth rate. (Source: Barthelmie & Pryor, 2021.) [11]

Table 3. Global Wind Energy Deployment Statistics (2010 2022)

Year	Cumulative Onshore Wind Capacity (GW)	Cumulative Offshore Wind Capacity (GW)	Total Cumulative Capacity (GW)	Annual Addition (GW)	Percentage of Global Electricity Supply (%)
2010	178	3	181	35	2.0
2012	268	5	273	45	2.5
2014	358	8	366	52	3.0
2016	459	14	473	64	4.0
2018	568	23	591	51	5.0
2020	707	36	743	93	6.0
2022	842	64	906	78	7.0

Source: Adapted from GWEC (2023) [10] and Barthelmie & Pryor (2021) [11]

The bar chart shown in the figure visualises the scale up of wind power through the stacking of annual capacity additions. There has been an accelerating growth in wind energy installations after 2006, with annual additions continuing to zoom in especially after 2010. In addition, the diagonally filled part of the graph illustrates the growth of offshore wind. Although its overall share is still small, it is growing at a remarkable rate, from less than 10 GW in 2006 to nearly 75 GW by 2020, a more than sevenfold increase. This reflects the trend of expanding wind technology from traditional onshore wind farms to more promising offshore resources.

Overall, global wind energy development has entered a stage of large scale and systematic deployment. Total installed capacity continues to rise at a steady rate, and technology types are diversifying. Figure 2 not only provides visual data to support the development history of wind power, but also reflects the important position of wind power technology in the global energy structure is rapidly increasing. In the future, wind power is expected to play an even more critical role in the global energy transition and climate change mitigation, with the promotion of policies, technological advances and improved system integration capabilities.

2.3. The Emission Reduction Role of Wind Energy

The highly linear relationship between the magnitude of global warming and cumulative anthropogenic greenhouse gas emissions has led to the "carbon budget" control framework widely used in current climate policy.

As shown in Figure 3, the cumulative carbon emissions corresponding to different Representative

Concentration Pathways (RCPs) are highly correlated with global warming (ΔT): a cumulative emission of more than 7000 GtCO$_2$e would lead to a global warming of more than 3.5°C, and to limit warming to the 1.5°C to 2°C range proposed by the Paris Agreement, cumulative emissions in the 21st century would have to be controlled to 2800 to 3500 GtCO$_2$e.

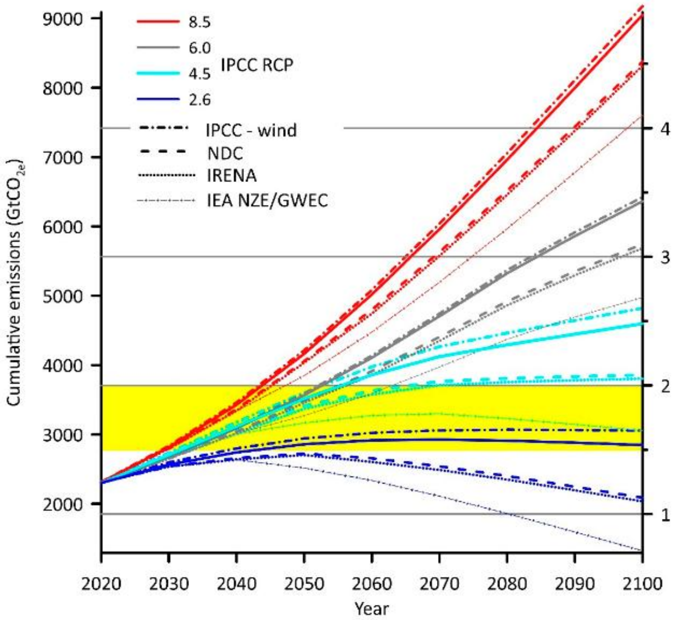

Figure 3. Cumulative CO$_2$ emissions and associated temperature increases under different emission pathways (2020–2100). Wind energy deployment scenarios (NDC, IRENA, IEA NZE/GWEC) reduce emissions relative to IPCC RCP baselines.(Source: Barthelmie & Pryor, 2021.) [11]

The emission reduction pathways achievable under different wind deployment scenarios (NDC, IRENA, IEA NZE/GWEC) are further modelled in the figure. The results show that cumulative global carbon emissions can only be expected to fall within the "climate safe zone" under a high intensity wind deployment scenario. In particular, in the IEA NZE/GWEC pathway, wind power can effectively limit total emissions to around 2800 GtCO$_2$e in this century by replacing fossil fuels in power generation, which corresponds to a warming of around 1.5 to 1.6°C and meets the stringent requirements for temperature control. In contrast, the current policy pathway (NDC) has some mitigation effect, but not enough to avoid the risk of exceeding 2°C (Table 4).

Table 4. Projected Emission Reduction Potential of Wind Energy Under Different Scenarios (2030 2050)

Scenario	**Global Wind Capacity by 2030 (GW)**	**Global Wind Capacity by 2050 (GW)**	**Annual Emission Reduction by 2030 (GtCO$_2$ e)**	**Annual Emission Reduction by 2050 (GtCO$_2$ e)**	**Share of Global Energy Related CO$_2$ (%)**
Current Policy (NDC)	1,200	2,000	3.5	6.0	12 15
IRENA Moderate Scenario	1,800	4,000	5.5	10.0	20 25
IEA NZE/GWEC High Scenario	2,500	6,500	8.0	15.0	25 30
Paris Compatible (1.5°C)	3,000	8,000	10.0	18.0	30 35

Source: Adapted from Barthelmie & Pryor (2021) [11] and IEA (2023) [2]

The results emphasise that wind is not only a "zero carbon electricity source" in the current renewable energy mix, but also a key pillar in the global carbon budgeting mechanism. The speed and scale of deployment will have a direct impact on the timing and accessibility of temperature control targets, especially in developing countries where the carbon intensity of the power generation sector is still high, and where the marginal mitigation effect of fossil fuelled electricity generation will be particularly significant.

3. Case Study of London Array

3.1. Project Description

The London Array is an early flagship offshore wind project in the UK and one of the most iconic commercial wind farms in the world. Located in the Thames Estuary in south east England, the project has a total installed capacity of 630 MW with 175 offshore wind turbines. The project, which started in 2011 and became fully operational in 2013, was developed by a consortium of companies including E.ON and Ørsted [12].

3.2. Project Emission Reduction Capacity

According to official operational data, the London Array generates an average of about 3,100 GWh per year, enough to meet the annual electricity demand of about 500,000 households. Compared to coal based fossil fuels, the project will reduce carbon dioxide (CO_2) emissions by about 925,000 tonnes per year, making it one of the key projects in the UK's energy mix transition from coal to wind [13]. On a per unit basis, the project will reduce CO_2 emissions by approximately 298 tonnes for every GWh of electricity generated, demonstrating its significant marginal abatement value under the "cleaner alternatives" pathway.

See Figure 4, the successful operation of the project has not only driven the rapid development of the UK wind industry, but has also become a model for the design and deployment of wind energy policies around the world. For example, the European Union, through the "Green Deal", explicitly takes offshore wind power as a core component of the future net zero energy system, and plans to deploy 300 GW of offshore wind power by 2050; China's "14th Five Year Plan" also explicitly proposes the construction of an "offshore wind corridor" along the eastern coast, and by the end of 2022, the installed offshore wind power capacity had exceeded 30 GW. The experience of these countries suggests that wind energy technology has already crossed the "demonstration stage" and entered into the deployment of energy at the system level.

In terms of climate mitigation, several international modelling studies (e.g., Barthelmie & Pryor, 2021) have shown that wind power has a significant capacity to reduce emissions in the medium and long term [11]. In the IEA and IRENA high deployment scenarios, global wind energy could contribute 10 to 15 GtCO$_2$e per year of emission reductions by 2050, accounting for 20 to 30 percent of global energy related carbon emissions. The London Array's emission reduction capacity as a single project is limited, but its model has been replicated and amplified, creating a cumulative wind cluster effect of hundreds of GW in the UK, Germany, Denmark, China and elsewhere, constituting a systemic force for coal power substitution.

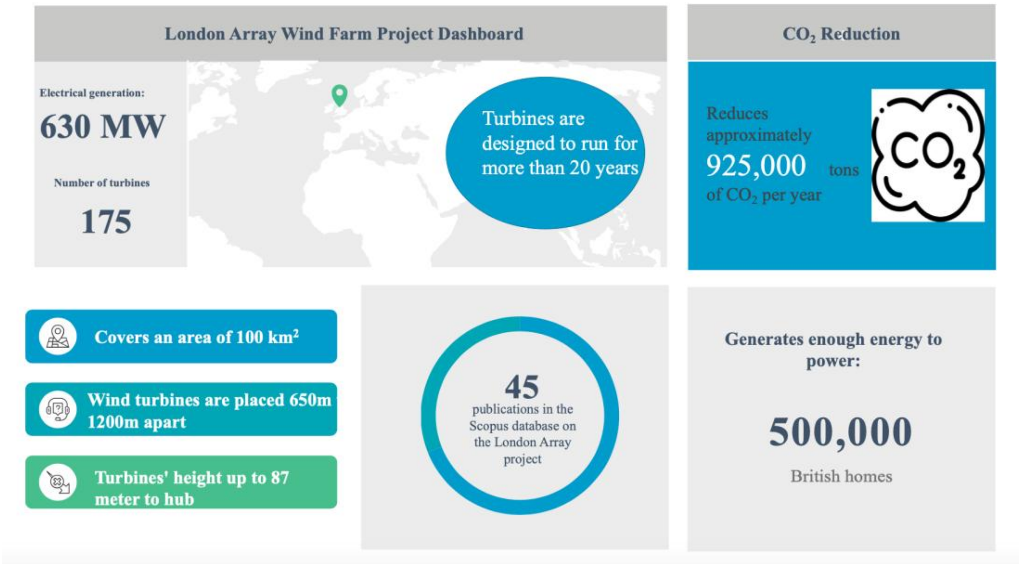

Figure 4. Overview of the London Array Wind Farm Project, highlighting key technical specifications, CO_2 reduction, and energy generation capacity. (Source: Olabi et al., 2023.)

3.3. Conclusion of Case Study

Therefore, from a comprehensive analysis of technology practices, operational data and global deployment trends, wind energy as a mitigation option has not only been widely implemented in many countries, but its emission reduction effect is also quantifiable and sustainable, making it a mature technology pathway with real "climate mitigation capability". Wind energy will continue to play a key role in the global net zero transition in the mid century by increasing the scale of deployment and improving the efficiency of system integration.

4. Challenges

4.1. Technical Aspects

From a technical point of view, wind power has the characteristics of intermittency and variability that cannot be ignored, and is greatly affected by natural factors such as wind speed, climate, and topography, resulting in unstable output power. This puts forward higher requirements for grid scheduling and frequency control, especially in systems with a high proportion of access to renewable energy sources, and the lack of effective energy storage support and intelligent scheduling mechanisms will seriously constrain the controllability and security of wind power [14]. In addition, although offshore wind power has high potential, it also faces engineering challenges such as complex platform structure, difficult operation and maintenance, marine corrosion and extreme climate.

4.2. Economic Aspects

On the economic side, wind projects, especially offshore wind projects, are often accompanied by high upfront investment costs and long capital recovery cycles. While the levelised cost of electricity (LCOE) has declined significantly, system costs (e.g., access, grid upgrades, energy storage) still constitute a real burden. In the absence of stable policy subsidies and carbon pricing mechanisms, projects face significant financing risks and market uncertainty [15].

4.3. Environmental Aspects

At the environmental level, wind power projects may cause some disturbance to ecosystems. For example, turbine operation may affect the migration paths of birds and bats, and offshore wind may interfere with fisheries, underwater noise and marine ecological stability. In addition, onshore wind power may bring landscape impacts and land conflicts, affecting the original land structure for agriculture and pasture.

4.4. Social and Political Aspects

Institutional and policy barriers cannot be ignored. In many countries and regions, wind power projects face cumbersome approval processes, long licensing cycles, and inconsistent policy implementation, which affect the predictability and attractiveness of projects. Particularly in developing countries, weak institutional enforcement capacity and low levels of electricity marketisation often constrain the scale of wind energy deployment.

Finally, social acceptance remains an important non technical factor limiting wind power deployment. Although the majority of the public supports renewable energy development, there is still a tendency for the project to have a "neighbourhood avoidance effect" (NIMBY) when it involves its own community. Residents may be resistant to noise, visual disturbances, or ecological risks, and the lack of good community communication mechanisms and benefit sharing strategies will further exacerbate local resistance.

5. Conclusion and Future Pathways

By systematically analysing the emission reduction potential, technology maturity, deployment status and challenges of wind energy in global climate change mitigation, it is clear that wind energy, as a mature renewable energy technology, has significant and quantifiable carbon emission reduction benefits. The successful practice of the London Array wind farm and the trend of expanding the cumulative installed capacity of wind power around the world fully demonstrate that wind power has passed the initial demonstration stage and entered the scale and systematic deployment stage in the global energy transition process. Specifically, wind power's life cycle carbon emissions are as low as 32 to 70 gCO_2 e/kWh, much lower than traditional fossil fuel based power generation, and its carbon payback and energy payback periods are quite short, with net reductions in carbon emissions typically achieved in less than a year.

Nonetheless, the technical, economic, policy, environmental and social acceptance challenges for the large scale deployment of wind energy cannot be ignored. The intermittent nature of wind energy, high upfront investment costs, policy and institutional discontinuities, potential environmental and ecological disturbances, and the public's neighbourhood avoidance of wind power projects all require future wind energy development to be supported not only by continued investment in technological innovation, but also by policy stability and social coordination mechanisms.

Looking ahead, with the rapid progress of energy storage technology, the promotion of smart grid construction and global climate policy is increasingly clear, wind energy is expected to achieve a higher proportion of global energy supply in the middle of this century. High deployment scenario projections from the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) show that by 2050, the global annual emission reduction potential of wind power could be as high as 10 to 15 $GtCO_2e$, accounting for 20 to 30 percent of global energy related carbon emissions. This means that wind energy will not only be an effective tool for the energy mix transition, but will also be a key and indispensable component for the global realisation of the Paris Agreement's climate goals.

Therefore, in the future deployment of wind energy, countries should accelerate the synergistic innovation of energy storage and grid technologies, strengthen policy support, and improve social communication and public participation mechanisms. Only in this way can wind energy give fuller play to its emission reduction potential and help the world realise the net zero carbon emission target and the long term vision of climate change mitigation.

References

1. Intergovernmental Panel on Climate Change. (2023). Climate change 2023: Synthesis report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Core Writing Team, H. Lee & J. Romero, Eds.). IPCC. https://www.ipcc.ch/report/ar6/syr/
2. International Energy Agency. (2023). Net zero by 2050: A roadmap for the global energy sector (2023 update). IEA. https://www.iea.org/reports/net-zero-by-2050-2023-update
3. Schubel, P. J., & Crossley, R. J. (2012). Wind turbine blade design review. Wind Engineering, 36(4), 365–388. https://doi.org/10.1260/0309-524X.36.4.365
4. Hart, E., Clarke, B., Nicholas, G., Kazemi-Amiri, A., Stirling, J., & Carroll, J. (2020). A review of wind turbine main bearings: Design, operation, modelling, damage mechanisms and fault detection. Wind Energy Science, 5, 105–124. https://doi.org/10.5194/wes-2019-25
5. Roga, S., Bardhan, S., Kumar, Y., & Dubey, S. K. (2022). Recent technology and challenges of wind energy generation: A review. Sustainable Energy Technologies and Assessments, 52, 102239. https://doi.org/10.1016/j.seta.2022.102239
6. Onol, A. O., & Yesilyurt, S. (2017). Effects of wind gusts on a vertical axis wind turbine with high solidity. Journal of Wind Engineering and Industrial Aerodynamics, 162, 1–11. https://doi.org/10.1016/j.jweia.2017.01.003
7. Nassar, Y. F., El-Khozondar, H. J., El-Osta, W., Mohammed, S., Elnaggar, M., Khaleel, M., Ahmed, A., & Alsharif, A. (2024). Carbon footprint and energy life cycle assessment of wind energy industry in Libya. Energy Conversion and Management, 300, 117846. https://doi.org/10.1016/j.enconman.2023.117846
8. Guezuraga, B., Zauner, R., & Pölz, W. (2012). Life cycle assessment of two different 2 MW class wind turbines. Renewable Energy, 37(1), 37–44. https://doi.org/10.1016/j.renene.2011.03.035
9. Vargas, A., Zenón, E., Oswald, U., Islas, J., Güereca, L., & Manzini, F. (2015). Life cycle assessment: A case study of two wind turbines used in Mexico. Applied Thermal Engineering, 75, 1210–1216. https://doi.org/10.1016/j.applthermaleng.2014.10.056
10. Global Wind Energy Council. (2023). *Global wind report 2023*. GWEC. https://gwec.net/global-wind-report-2023/
11. Barthelmie, R. J., & Pryor, S. C. (2021). Climate change mitigation potential of wind energy. *Climate, 9*(9), 136. https://doi.org/10.3390/cli9090136

---

12. Olabi, A. G., Obaideen, K., Abdelkareem, M. A., AlMallahi, M. N., Shehata, N., Alami, A. H., Mdallal, A., Hassan, A. A. M., & Sayed, E. T. (2023). Wind energy contribution to the sustainable development goals: Case study on London Array. Sustainability, 15(5), 4641. https://doi.org/10.3390/su15054641
13. London Array. (2023). Project facts and figures. https://www.londonarray.com/
14. Zappa, W., Junginger, M., & van den Broek, M. (2019). Is a 100% renewable European power system feasible by 2050? Applied Energy, 233–234, 1027–1050. https://doi.org/10.1016/j.apenergy.2018.08.109
15. Wiser, R., Rand, J., Seel, J., Beiter, P., Baker, E., Lantz, E., & Gilman, P. (2021). Expert elicitation survey on future wind energy costs. Nature Energy, 6(5), 555–565. https://doi.org/10.1038/s41560-021-00810-z