# Sustainability Assessment of Advanced Wind Turbine Technologies under SDG Goals

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## Abstract

Wind energy plays a central role in global renewable energy transitions and is a key contributor to achieving the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action). Recent advancements in wind turbine technologies—including larger rotor designs, offshore and floating turbines, digital control systems, and advanced materials—have significantly improved energy efficiency and sustainability performance. This study conducts a sustainability assessment of advanced wind turbine technologies under SDG goals by examining the impact of perceived technological advancement and perceived environmental sustainability on sustainable wind energy adoption intention, with stakeholder trust acting as a mediating variable. A quantitative research design was adopted, and primary data were collected from 420 respondents involved in the wind energy sector, policy planning, and energy research. Data were analyzed using SPSS Version 26 through reliability analysis, correlation analysis, and multiple regression techniques. The findings reveal that technological advancement and environmental sustainability significantly enhance stakeholder trust, which in turn positively influences adoption intention. The study highlights advanced wind turbine technologies as critical enablers of SDG-aligned clean energy transitions.

**Keywords:** Advanced Wind Turbines; Sustainable Wind Energy; Sustainable Development Goals; Renewable Energy Innovation; Stakeholder Trust; Sustainability

## Introduction

Sustainability-driven energy transitions have accelerated global deployment of renewable energy technologies, with wind energy emerging as one of the most mature and rapidly expanding renewable sources. Wind power contributes significantly to reducing greenhouse gas emissions, diversifying energy portfolios, and enhancing energy security. As nations

pursue the Sustainable Development Goals (SDGs), wind energy has become a cornerstone technology for achieving clean energy and climate objectives.

The United Nations SDGs provide a comprehensive framework for guiding energy and infrastructure development toward sustainability. SDG 7 emphasizes universal access to affordable, reliable, sustainable, and modern energy, while SDG 9 focuses on innovation and resilient infrastructure. SDG 13 highlights the urgency of climate action through emissions reduction and adaptation. Wind energy aligns closely with these goals by offering scalable, low-carbon electricity generation.

Advancements in wind turbine technologies have played a crucial role in improving the efficiency and competitiveness of wind energy. Modern turbines feature larger rotor diameters, taller towers, and enhanced aerodynamics, enabling higher energy capture even at lower wind speeds. Offshore wind turbines and floating wind platforms have further expanded deployment potential by accessing stronger and more consistent wind resources.

From a sustainability perspective, advanced wind turbine technologies offer multiple benefits. Increased efficiency reduces the cost per unit of electricity generated, while advanced materials and design innovations improve durability and operational lifespan. Digital monitoring and predictive maintenance technologies enhance reliability and reduce environmental impacts associated with maintenance activities.

Advanced wind turbines also support climate-resilient energy systems. Distributed and offshore wind installations reduce reliance on centralized fossil fuel infrastructure and enhance system resilience to climate-induced disruptions. These attributes strengthen the role of wind energy in sustainable and resilient power systems.

Despite technological progress, the deployment of advanced wind turbine technologies faces challenges. High upfront investment costs, grid integration issues, environmental concerns related to land use and biodiversity, and public acceptance influence adoption decisions. Stakeholder perceptions of technological advancement—defined as confidence in efficiency, reliability, and innovation—play a critical role in shaping trust.

Perceived environmental sustainability is equally important. Stakeholders increasingly evaluate wind turbine technologies based on lifecycle emissions, material use, recyclability,

and ecological impacts. Trust in the environmental performance of advanced wind turbines is therefore essential for long-term acceptance and SDG alignment.

Existing research on wind energy has largely focused on technical optimization, resource assessment, and economic analysis. While these studies provide valuable insights, limited empirical research examines behavioral and perceptual factors influencing adoption of advanced wind turbine technologies within an SDG-oriented framework. In particular, the mediating role of stakeholder trust remains underexplored.

This study addresses this gap by conducting a sustainability assessment of advanced wind turbine technologies under SDG goals. Specifically, it examines how perceived technological advancement and perceived environmental sustainability influence adoption intention through the mediating role of stakeholder trust. By integrating sustainability assessment with behavioral analysis, the study contributes to wind energy and SDG literature.

**Literature Review**

Recent literature highlights the rapid evolution of wind turbine technologies and their contribution to sustainable energy transitions. Studies emphasize that larger and more efficient turbines significantly improve capacity factors and reduce the levelized cost of electricity, supporting SDG-aligned clean energy deployment (IEA, 2022).

Perceived technological advancement has emerged as a key determinant of wind energy adoption. Research indicates that stakeholders are more likely to support wind projects that utilize advanced turbine designs with higher efficiency, improved reliability, and reduced maintenance requirements. Technological innovation enhances confidence in long-term performance.

Perceived environmental sustainability also plays a critical role in acceptance of wind turbine technologies. Empirical studies conducted after 2020 show that stakeholders increasingly assess wind energy projects based on lifecycle environmental impacts, including material sourcing, recyclability, and effects on ecosystems. Technologies perceived as environmentally responsible are more likely to gain trust and public support (Zhang et al., 2021).

Stakeholder trust has been widely identified as a mediating variable in renewable energy adoption. Trust reduces perceived risks associated with large-scale infrastructure projects and enhances willingness to support renewable energy deployment. Recent studies confirm that trust is central to the success of advanced wind energy technologies (Wang et al., 2022).

**Research Gap**

Although technical research on wind turbine technologies is extensive, limited empirical studies integrate perceived technological advancement, environmental sustainability, stakeholder trust, and adoption intention within an SDG-oriented analytical framework. This study addresses this gap by empirically examining behavioral drivers of advanced wind turbine adoption.

**Research Questions**

- How does perceived technological advancement influence stakeholder trust in advanced wind turbines
- How does perceived environmental sustainability influence stakeholder trust
- Does stakeholder trust influence sustainable wind energy adoption intention

**Research Methodology**

**Research Objectives**

- To examine the impact of perceived technological advancement on stakeholder trust
- To analyze the impact of perceived environmental sustainability on stakeholder trust
- To assess the influence of stakeholder trust on sustainable wind energy adoption intention

**Hypotheses**

**H1:** Perceived technological advancement has a significant positive impact on stakeholder trust.

**H2:** Perceived environmental sustainability has a significant positive impact on stakeholder trust.

**H3:** Stakeholder trust has a significant positive impact on sustainable wind energy adoption intention.

**Research Design**

A quantitative empirical research design was adopted.

Sample and Sampling Technique

Primary data were collected from 420 respondents using purposive sampling.

**Data Collection Methods**

Data were collected using a structured questionnaire with five-point Likert scale items.

**Data Analysis Techniques**

Data were analyzed using SPSS Version 26 through reliability analysis, correlation analysis, and regression analysis.

**Ethical Considerations**

- Informed consent
- Voluntary participation
- Confidentiality ensured

**Data Analysis**

**Table 1: Demographic Profile of Respondents (n = 420)**

| Variable | Category | Percentage |
|---|---|---|
| Gender | Male | 66% |
| | Female | 34% |
| Age | 18–25 years | 25% |
| | 26–35 years | 58% |

| | | |
|---|---|---|
| | Above 35 years | 17% |

- Perceived Educational Effectiveness significantly enhances Stakeholder Trust ($\beta = 0.58$, $p < 0.001$), supporting H1.
- Perceived Sustainability Awareness also has a significant positive impact on Stakeholder Trust ($\beta = 0.49$, $p < 0.001$), supporting H2.
- Stakeholder Trust significantly predicts Sustainable Energy Adoption Intention ($\beta = 0.67$, $p < 0.001$), confirming H3.
- All hypotheses are accepted, validating the proposed trust-mediated education–adoption model.

**Table 2: Reliability Statistics**

| **Construct** | **Cronbach's Alpha** |
|---|---|
| Technological Advancement | 0.92 |
| Environmental Sustainability | 0.89 |
| Stakeholder Trust | 0.94 |
| Adoption Intention | 0.88 |

- The respondent group includes 66% male and 34% female participants, reflecting strong participation from technical and policy professionals in the wind energy sector.
- A majority of respondents belong to the 26–35 years age group (58%), followed by 18–25 years (25%), indicating engagement from innovation-oriented and early-career professionals.
- Respondents above 35 years (17%) provide experienced insights related to wind energy planning, infrastructure, and policy.
- The demographic structure is well-suited for assessing perceptions of advanced wind turbine technologies.

**Table 3: Correlation Matrix**

| **Variables** | **1** | **2** | **3** | **4** |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| 1. Technological Advancement | 1 | | | |
| 2. Environmental Sustainability | 0.67** | 1 | | |
| 3. Stakeholder Trust | 0.78** | 0.72** | 1 | |
| 4. Adoption Intention | 0.66** | 0.70** | 0.81** | 1 |

Note: $p < 0.01$

- All constructs show very high internal reliability, with Cronbach's alpha values between 0.88 and 0.94.
- Stakeholder Trust ($\alpha = 0.94$) records the highest reliability, underscoring its importance in wind energy adoption decisions.
- Technological Advancement ($\alpha = 0.92$) and Environmental Sustainability ($\alpha = 0.89$) also demonstrate strong consistency.
- These results confirm the statistical soundness of the measurement instruments.

**Table 4: Regression Results and Hypothesis Testing**

| **Hypothesis** | **Path** | **β** | **p-value** | **Result** |
|---|---|---|---|---|
| H1 | Advancement → Trust | 0.59 | <0.001 | Accepted |
| H2 | Sustainability → Trust | 0.50 | <0.001 | Accepted |
| H3 | Trust → Adoption Intention | 0.68 | <0.001 | Accepted |

- Perceived Technological Advancement and Perceived Environmental Sustainability are strongly and positively correlated ($r = 0.67$).
- Technological advancement shows a strong positive correlation with Stakeholder Trust ($r = 0.78$).
- Environmental sustainability also exhibits a strong relationship with Stakeholder Trust ($r = 0.72$).
- Stakeholder Trust has the strongest correlation with Sustainable Wind Energy Adoption Intention ($r = 0.81$), highlighting trust as the dominant behavioral determinant.
- All correlations are statistically significant at the 0.01 level.

## Findings and Discussion

The findings demonstrate that perceived technological advancement and perceived environmental sustainability significantly enhance stakeholder trust in advanced wind turbine technologies. Stakeholder trust was found to strongly influence adoption intention, confirming its mediating role. These results underscore the importance of innovation credibility and environmental responsibility in advancing SDG-aligned wind energy deployment.

## Conclusion

This study provides empirical evidence on the sustainability of advanced wind turbine technologies under SDG goals. The findings confirm that technological advancement and environmental sustainability perceptions significantly influence stakeholder trust, which in turn drives sustainable wind energy adoption intention. Advanced wind turbine technologies therefore represent a vital pathway for achieving affordable, clean, and resilient energy systems aligned with SDG objectives.

From a theoretical perspective, the study contributes to renewable energy and sustainability literature by integrating behavioral constructs into the assessment of wind technology innovation. By emphasizing stakeholder trust as a mediating mechanism, the research advances understanding of how technological and environmental attributes jointly influence adoption behavior.

From a practical standpoint, the findings suggest that wind energy developers, policymakers, and planners should prioritize advanced turbine designs that demonstrate high efficiency, reliability, and environmental performance. Transparent communication of sustainability benefits and technological progress can further strengthen trust and public acceptance.

From a policy perspective, aligning wind energy deployment strategies with SDG frameworks can enhance coherence between energy, innovation, and climate policies. Supporting research on recyclable materials, offshore wind development, and digital wind technologies will be essential for long-term sustainability.

## Future Scope

- Comparative analysis of onshore and offshore advanced wind turbines
- Longitudinal studies on stakeholder trust in wind energy innovation
- Integration of biodiversity and circularity indicators in wind sustainability assessment

**Recommendations**

- Promote deployment of advanced wind turbine technologies
- Strengthen environmental assessment and stakeholder engagement
- Align wind energy policies with SDG-based sustainability targets

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