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Wind Turbine Research Map: An Overview of Renewable Energy Technology Innovation Trends

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Abstract: The purpose of this study is to identify current research trends in wind turbine technology and explore emerging innovations in the field of renewable energy based on the wind turbine research map. The research method of this study is the Bibliometric-Systematic Literature Review (B-SLR) which includes a 10-step process. The B-SLR framework emphasizes critical analysis, timeliness, comprehensive coverage, methodological rigor, coherence, and originality of contributions, with a focus on creating new and relevant theoretical insights. Bibliometric analysis is obtained using Vosviewer software to determine the mapping of trends, patterns, and gaps for further research related to wind turbines. Based on the Google Scholar database through data collection using POP (Publish or Perish). This study systematically reviews 730 scientific articles related to wind turbine innovation from 2015–2025, producing a wind turbine research map obtained by five main research clusters, namely energy production, industrial policy, turbine component design, control innovation, and future trends. The dominant topics are wind turbine blades, China, and power generation. The research progresses from a policy focus (2016–2018) to technical innovation and sustainability (2020–2022). The analysis reveals wind turbine research areas are blade design, offshore operations, and new materials, while themes such as alternative energy and emerging markets remain under-explored. These results reveal significant opportunities for technological innovation and cross-disciplinary exploration in renewable energy.

Keywords: Wind Turbine, Trends, Bibliometric.

INTRODUCTION

Population growth and use of fossil fuels threaten energy availability and increase greenhouse gas emissions (Wardana, 2023). The energy crisis and oil price fluctuations are complex global problems. Understanding these dynamics is important for responding to future energy challenges (Waruwu, 2023). The energy crisis not only has a negative impact, but also triggers positive opportunities such as increased investment in renewable energy, energy saving attitudes, infrastructure development, technological innovation, and increased international cooperation (Logayah et al., 2023)). Fossil energy significantly increases greenhouse gas emissions and global temperatures. On the other hand, renewable energy such as solar, wind and bioenergy can reduce carbon emissions and support environmental sustainability (Tjiwidjaja et al., 2023).

Wind energy is a renewable energy source that promises to support environmental sustainability and reduce dependence on fossil energy (Akbar MF, 2024). Wind energy is seen as having a strategic role in creating a clean and sustainable global energy mix (Wahyuningsih et al., 2016). Wind turbines support decarbonization and energy transition in urban areas by integrating wind turbines in buildings and urban areas (Ismail et al., 2025). Small wind turbines can be a sustainable solution to meet local energy needs and reduce carbon emissions (Elnaggar et al., 2022). So that Wind turbines are one of the main solutions in efforts to decarbonize and world energy security.

As technology advances, wind turbine research has undergone a significant transformation in the last decade. Evolution of wind turbine technology from the late 1990s to the present, with a focus on increasing turbine capacity from 5 MW to over 15 MW, especially in offshore applications (Lucena, 2021). Technological innovations such as longer blades, taller towers and advanced control systems could increase the potential for economically viable wind energy by 80% by 2025 (NREL, 2025) The large number of scientific publications gives rise to the need to thoroughly understand research trends, patterns and gaps.

Bibliometric analysis and systematic reviews are becoming important approaches to present comprehensive insights. Research by analyzing publication trends using data from Scopus, Microsoft Excel, and VOSviewer, found the highest number of publications and the highest number of citations (Sunadi et al., 2023). Studies that examine a topic through systematic literature reviews and bibliometric analysis can acknowledge the limitations of research in that field (Sari & Yuliarti, 2023). A more in-depth study using bibliometric analysis found increasing research trends as well as research gaps (Hasbiyati et al., 2023). So by finding a wind turbine research map you can identify the latest research trends in wind turbine technology and explore developing innovations in the field of renewable energy.

LITERATURE REVIEW

Wind turbines are one of the main pillars in the global renewable energy system. As the need for clean and low-carbon energy increases, wind turbine technology continues to experience rapid developments, both in aspects of mechanical design, materials, system efficiency, and control and energy management strategies (Nycander et al., 2020). The importance of designing and developing turbine prototypes that are efficient and appropriate to local conditions to support a sustainable energy transition in Indonesia (Hasbiyati et al., 2024). factors that influence wind turbine efficiency, including blade design, wind speed, and control system, as well as the importance of optimization to improve the performance of wind power plants (Elektro & Haryudo, 2020). One component is the wind turbine blade which has a major influence on aerodynamic performance and energy conversion efficiency. Optimal blade design is the main focus in increasing the efficiency and reliability of wind energy generation (Wang et al., 2019).

Geographically, the dominance of wind turbine technology research comes from countries with large production capacities such as China. The country leads in the number of publications and technological developments, and shows significant increases in innovation and large-scale implementation (Sufyanullah et al., 2022). By 2023, the country will account for approximately 60% of global wind turbine production capacity, far surpassing Europe (19%) and the United States (9%) (Wood Mackenzie, 2023). Research in the 2016–2018 period tended to focus on aspects of wind energy policy and infrastructure development, while from 2020 to 2022 there was a shift in focus towards technical innovation, sustainability, and the development of materials and control systems that are more adaptive to complex natural conditions (Ajayi-Banji & Rahman, 2022), (Sim & Young, 2024). Additionally, there is an increase in the use of advanced composite materials for turbine blades, which improve durability and energy efficiency (S. Chen et al., 2025).

In bibliometric studies, the Bibliometric-Systematic Literature Review (B-SLR) approach is an effective method for mapping the development of scientific knowledge in a broad and structured manner. This method combines the power of systematic reviews with quantitative analysis of publications, enabling the identification of trends, collaboration patterns, and open research gaps (Snyder, 2019). B-SLR combines the advantages of systematic literature review (SLR), which is qualitative and based on critical synthesis, with an approach bibliometric analysis which emphasizes the quantitative aspects of scientific publications (Donthu et al., 2021). With the help of VOSviewer software, researchers can visualize the network of co-authorship, co-citation and co-occurrence of keywords in scientific literature, thereby producing a comprehensive intellectual map (van Eck & Waltman, 2014). This approach allows comprehensive mapping of development trends, collaboration patterns between authors or institutions, as well as identifying research gaps that have not been widely explored.

RESEARCH METHOD

This type of research is a literature review. The methodology used is Bibliometric-Systematic Literature Review' (B-SLR). Workflow includes:

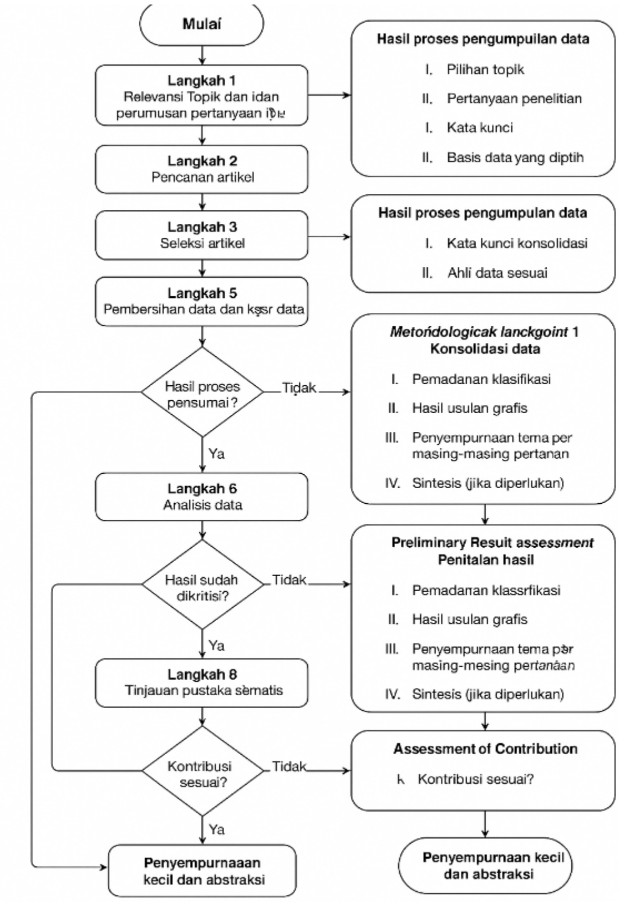

Figure 1. Research Procedures (Marzi et al., 2025).

RESULT AND DISCUSSION

Stage 1: Data Gathering Process

In the initial stages of the research, topics focused on current research trends in wind turbine technology and the exploration of related renewable energy innovations. The research questions formulated are: (1) What are the main trends in wind turbine technology research in the last decade, (2) What innovations have been most developed in this field, (3) What is the scientific map of wind turbine technology innovation trends based on the results of bibliometric analysis. The specified inclusion criteria include scientific articles published in reputable journals on Google Scholar. Studies discussing technical innovation, design, materials, performance optimization and integration of wind turbines, Publication in the year 2015–2025. Meanwhile, exclusion criteria include: Non-peer reviewed articles (e.g. opinion pieces, editorials), studies that focus on social aspects or energy policy without discussing wind turbine technology, and publications before 2015.

The literature search strategy is structured using main keywords such as: "wind turbine technology", "wind energy innovation", "advanced wind turbine materials", And "renewable energy systems" through software Publish or Perish. In addition, Boolean combinations (AND, OR) are performed to expand the search without losing relevance. The search focused on metadata: article title, abstract, and keywords. A selection of primary databases were selected for data extraction, viz Google Scholar, considering that the database has broad multidisciplinary coverage and bibliometric features that support the analysis of scientific trends.

The data extraction process is carried out by downloading article metadata (title, author, year, keywords, abstract, journal source, and references). From the initial search results, 998 articles were obtained. Each article was examined based on inclusion and exclusion criteria. Several stages of examination were carried out, namely: Reading the title and abstract to assess relevance, eliminating articles published before 2015, and identifying potential articles that need to be analyzed more deeply through full-text review. After initial screening, the number of articles considered relevant was 742 articles. The curated dataset then went through a data cleaning process to remove: Articles that were found to be irrelevant after follow-up review, resulting in 730 final articles ready for analysis. The final dataset is then exported in a compatible format for bibliometric analysis using software VOSviewer. This stage aims to compile a scientific map of wind turbine technology innovation trends, identify main research clusters, relationships between topics, and collaboration patterns between researchers and institutions.

Stage 2: Bibliometric Approach

After obtaining the final dataset containing 730 articles from the database Google Scholar, an initial bibliometric analysis was carried out to obtain an overview of the literature that had been collected. This analysis includes: Distribution of publications by year., Frequency mapping of main keywords to discover the latest research trends in wind turbine technology and explore developing innovations in the field of renewable energy. The following are the results of the wind turbine research map from bibliometric analysis:

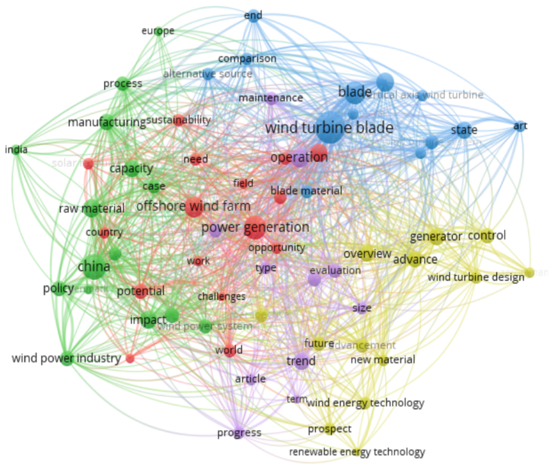

Figure 2. Mapping Results by Vosviewers (2025)

The results of this wind turbine research mapping show that research in the field of wind energy does not only focus on the technical aspects of turbine design, but also covers energy policy, resource management, and future trends in technological innovation. Thus, future wind turbine development needs to consider a cross-disciplinary approach that combines technical, policy and sustainability aspects.

Based on the results of wind turbine research mapping, several clusters of wind turbine research topics were obtained. Visualization of results clustering made using VOSviewer, produce network map keyword-based, which shows the relationship between topics and the size of each cluster based on frequency of appearance. Dataset sorting Based on time and representative sample selection to understand the dynamics of research development over time, the dataset is sorted by year of publication.

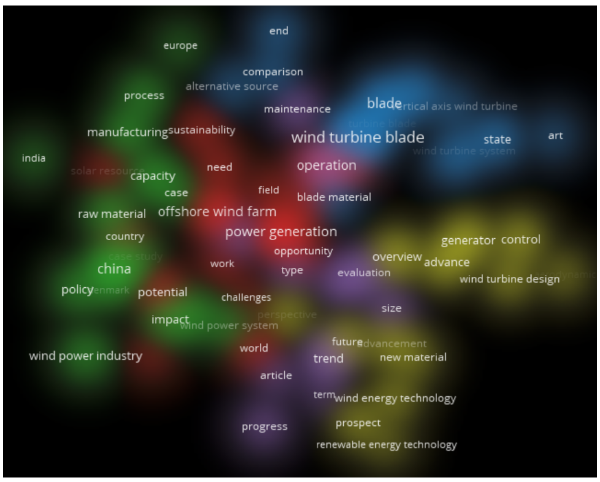

Figure 3. Cluster Density Visualization (2025)

From the wind turbine research pattern above, it was found that there are 5 clusters marked with 5 colors. The red cluster focuses on the theme "power generation", "wind farm", And "operation" which describes the operational and production aspects of energy. The green cluster includes terms such as "china", "policy", "manufacturing" And "impact" indicates a focus on policy aspects, production capacity and the wind energy industry. Meanwhile, the blue cluster focuses on developing specific components, such as "wind turbine blade" And "critical axis wind turbine"while the yellow cluster highlights innovation in the field of turbine design and generator control systems. The purple cluster, with keywords such as "trend" And "future" marks the future direction of technological development. The size of the nodes in this visualization is determined based on the weight of each topic. Node "power generation", "wind turbine blade" And "offshore wind farm" has the largest size, indicating that these topics dominate academic discourse and are the center of attention in this field. Analysis and discussion of the results cluster VOSviewer The resulting results show a pattern of interrelated concepts in the context of renewable energy, especially those related to wind energy and wind turbine technology. The following is an analysis of each cluster:

Table 1. Cluster Analysis of Wind Turbine Research Map

Cluster	Total Item	Keyword	Focus
1	16	*advanced material, challenges, country, field, need, offshore wind farm, opportunity, performance, potential, power generation, role, solar resource, sustainability, suistainable development, work, world.*	concepts related to the potential and role of renewable energy in a global context, especially those related to offshore wind *(offshore wind farm)*. Some keywords such as *advanced material, performance, sustainability*, And *power generation* demonstrate the relevance for material innovation and technological performance improvement in the offshore wind industry focused on sustainability and global market potential.
2	15	*capacity, case, case study, china, Denmark, Europe, impact, india, manufacturing, offshore wind power, policy, process, raw material, wind power industry, wind power system.*	capacity and case studies of specific countries or regions such as China, Denmark and India, which are leaders in the development and application of wind energy. Keywords *seperti offshore wind power, wind power industry*, And *policy* shows the importance of manufacturing policies and policies in influencing the development of the wind industry.
3	13	*alternative source, art, blade, blade material, comparison, composite material, comprehensive review, end, state, turbin blade, vertical axis wind turbin, wind turbine blade, wind turbine system*	aspects of wind turbine technology, particularly components such as blade materials and turbine design. Key words like *composite material, blade, dan vertical axis wind turbine* emphasizes the importance of new materials and designs to improve wind turbine efficiency.

Cluster	Total Item	Keyword	Focus
4	13	*advance, advancement, aerodynamic, control, future, generator, new material, overview, perspective, prospect, renewable energy technology, wind energy technology, wind turbine design*	technological advances in wind energy more generally, with keywords such as *aerodynamic, control,* And *renewable energy technology*. This suggests that research is being focused on improving turbine aerodynamic performance and control to achieve this in the future.
5	11	*article, evaluation, maintenance, offshore wind turbine, operation, part, progress, size, term, trend, type*	evaluation and operation aspects in wind turbine construction, including maintenance, operations, and size evaluation. Keywords like *maintenance, operation,* And *part* shows the importance of maintenance and operational management in the life cycle of a wind turbine.

Overall, the results of this cluster show that research on offshore wind energy is highly diversified, with a focus on new materials, policy and industry, turbine design, and operational evaluation. This discussion illustrates the major efforts being made to increase the efficiency and sustainability of renewable energy, especially in the context of global wind energy development. To identify the research focus and direction of study development in the field of wind energy, bibliometric analysis was carried out using VOSviewer. The data analyzed comes from the table "Verify Selected Terms", which contains important terms based on their frequency of appearance and level of relevance in related literature. Through this approach, a visualization map is obtained that illustrates the relationship between concepts, dominant trends in research, as well as the potential for developing new themes in the future. Following are the results of the analysis:

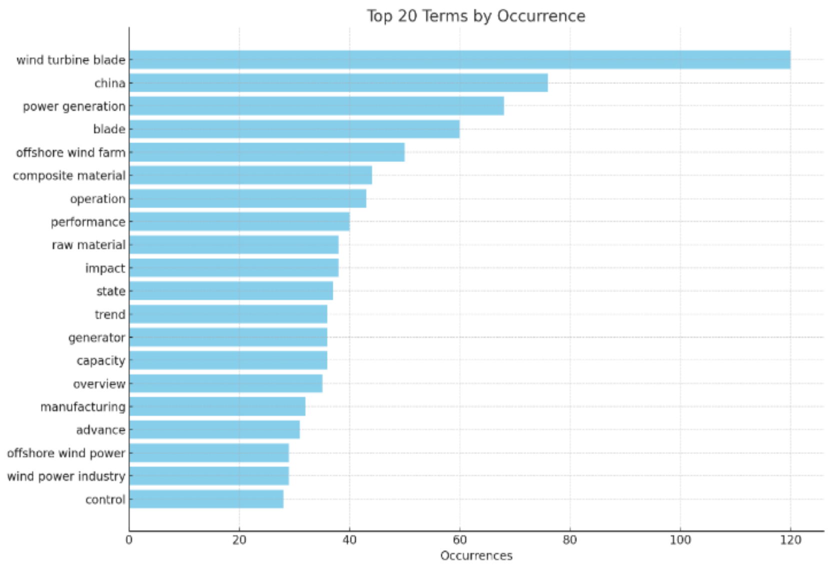

Figure 4. Graphics frequency of frequently occurring terms (2025)

Based on the bar graph, it depicts the frequency (number of occurrences) of terms that frequently appear in the analysis using VOSviewer. Based on data, terms "wind turbine blade" dominates with 120 occurrences, indicating that the research focus very strong in wind turbine blade components. Furthermore, "china" appeared 76 times, indicating that much research related to wind energy focuses on developments in China, perhaps related to China's role as a large player in renewable energy technology. Term "power generation" is in third position with 68 occurrences, indicating that energy production from wind sources is the main topic in this study. Then, "offshore wind farm" (50 times) also appears quite significant, indicating the existence of a major research trend related to the development of offshore wind farms. Furthermore, terms such as "composite material" (44 times) and "operation" (43 times) shows great attention to the material and operational aspects of wind turbines. This shows that not only location and production are the focus, but also material technology and turbine operational management. Other words like "manufacturing", "offshore wind turbine", And "maintenance" also addresses technical topics related to offshore turbine assembly, maintenance, and specifications. In general, these bar graphs make it clear that the study of key components (such as blades), key development countries (such as China), aspects of energy production, and the use of new material technologies are the dominant trends in current wind energy research.

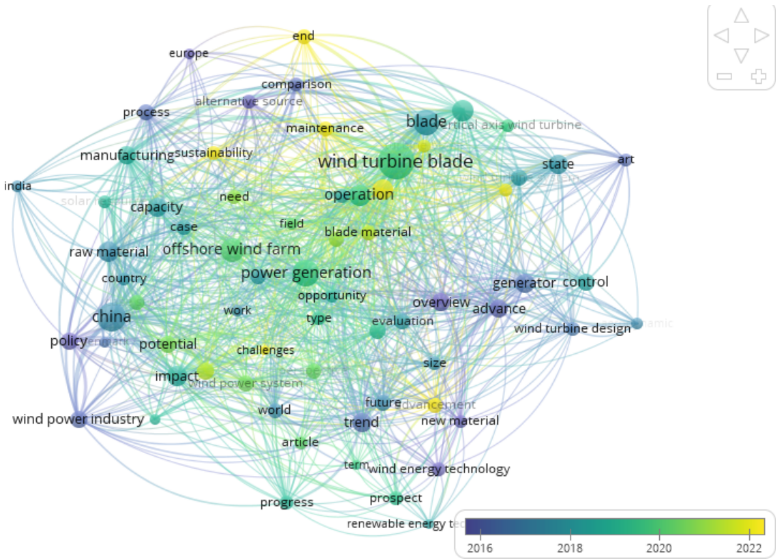

Figure 5. Overlay Visualization (2025)

Network visualization mapping results using VOSviewer shows that research topics related to wind turbine prototype design form complex and closely interconnected structures. From this visualization, it can be observed that the topic "wind turbine blade," "operation," And "power generation" occupies a central position in the network with a relatively large node size. This shows that aspects of turbine blade design, turbine operation, and energy generation are the main focus in the development of literature in this field. Next, yellow color on several nodes such as "operation" And "advancement" suggests that these topics are a relatively new research trend, growing rapidly between 2020 and 2022. These studies tend to highlight innovations in turbine operating technology and performance improvement efforts, including the use of new materials and more efficient maintenance techniques. Meanwhile, topics such as "policy," "china," And "wind power industry" purplish blue, indicating that attention to energy policy, the development of the wind power industry, and national strategy were the dominant focus in the early period (2016–2018).

This shift in focus shows the dynamics of changing priorities in research, from policy aspects to technical and innovative aspects. The relationship between topics is very close, such as between "wind turbine design," "generator control," And "blade material," shows that research in the field of turbine prototype design is multidisciplinary. These studies combine aspects of mechanical design, system control, material selection, as well as operational efficiency of wind turbines. Apart from that, the analysis also shows the emergence of new themes related to sustainability, such as "future advancement," "renewable energy technology," And "prospect," which reflects increasing attention to the development of more sustainable and environmentally friendly renewable energy technologies.

Figure 6. Density Visualization (2025)

Based on visualization analysis using VOSviewer, identified several main keywords that frequently appear in studies related to wind energy, especially in the context of technological and industrial development. The most dominant keywords are "wind turbine blade", "power generation", And "offshore wind farm", which indicates that much of the research focus is directed at wind turbine blade technology and energy generation, both onshore and offshore. Additionally, topics such as "operation", "generator control", And "wind turbine design" also emerged as an important theme, showing attention to operational and design aspects in improving wind turbine efficiency. Some other keywords such as "china", "impact", And "policy" indicates a geographic focus and attention to policy aspects, especially considering China's significant role in renewable energy development.

Additional frequently correlated topics include "manufacturing", "raw material", "maintenance", as well as "renewable energy technology", indicates that research does not only focus on the use of technology, but also on aspects of production, availability of raw materials, and sustainability of wind energy technology. The emergence of terms such as "trend", "advancement", And "future" also shows attention to the prospects for future technological developments. Lighter colors in the visualization indicate keywords that have a high frequency of occurrence and strong connections between concepts. Conversely, areas with darker or less bright colors indicate themes that have been researched less frequently or have not been the main focus. For example, terms like "alternative source", "comparison", "solar resource", and “india” appear in the dark colored areas, indicating that although related to energy and renewable resources, these themes still have a relatively low frequency of occurrence.

Step 3: Systematic Literature Review and Theory Development

After the articles have been filtered and clustered, a systematic literature review (SLR) is carried out to examine in depth research and innovation trends in wind turbine technology. Literature reviewThis ew provides a comprehensive overview of research trends and developments in the field of wind energy, with an emphasis on several main themes that emerge from the visualization results VOSviewer. This analysis identifies several important directions in wind energy research, particularly those related to turbine technology, energy policy, and sustainability. The following is a summary of the results of the literature analysis based on the results VOSviewer:

1. **Cross-Disciplinary Approach**: Overall, research in the field of wind energy covers more than just the technical aspects of turbine design. There is an increasingly strong focus on energy policy, resource management and sustainability. This research shows that wind turbine development should not only focus on technical efficiency, but also on the integration of supportive energy policies and the long-term sustainability of the technology. Therefore, the development of future wind turbines requires a cross-disciplinary approach that combines technology, policy and sustainability.
2. **Diversifying Research in Offshore Wind Energy**: In the context of offshore wind energy, research shows a significant diversity of topics. The main focus of this research includes the use of new materials, policy development, turbine design, and operational evaluation. This reflects major efforts to increase efficiency and sustainability in renewable energy, especially in order to support the development of wind energy at the global level. This research also reflects the larger challenges associated with the operation and utilization of wind energy in offshore areas, which require a more complex and multidisciplinary approach.
3. **Innovations in Turbine Prototype Design**: The mapping results show that current wind turbine designs focus not only on increasing energy efficiency, but also on material innovation and operational optimization. Research on wind turbines is increasingly considering aspects of sustainability in the product life cycle, including in terms of material selection and reducing environmental impacts. This trend reflects increasing global demand for cleaner and more efficient technologies, along with the need to increase the contribution of renewable energy in electricity supply.
4. **Technology Trends and Strengthening Wind Turbine Efficiency**: The distribution of identified keywords indicates that research in the field of wind turbines is currently focused on strengthening the core technology of turbines, in particular through the development of new materials and more advanced control systems. This focus also includes increasing efficiency in electricity generation, especially for offshore locations that demand optimal performance in more extreme environmental conditions. It is hoped that this technological improvement can support the transition towards a cleaner and more sustainable energy system.

In the last decade, wind turbine technology innovation has experienced very significant developments, following various global energy needs, sustainability pressures, and technological advances across fields. This evolution can be mapped through several main stages based on high-citation scientific studies. DSelect a representative sample by considering: Articles with a high number of citations in each annual period. Review articles and state-of-the-art as a reference for major developments. This approach ensures that the data used reflects the evolution of wind turbine technology innovation from the beginning of the 2015 decade to 2025.

Table 2. Highest Quotes in each annual period

Authors and year	Title
2025	*Vibration response on the rod of vortex bladeless wind power generator for a sandwich beam with various face sheets and cores based on different boundary*
2024	*The integration of wind and solar power to water electrolyzer for green hydrogen production*
2023	*Contribution of renewable energy sources to the environmental impacts and economic benefits for sustainable development*
2022	*Techno-economic analysis and Monte Carlo simulation for green hydrogen production using offshore wind power plant*
2021	*Power electronics: The enabling technology for renewable energy integration*
2020	*Power electronics: The enabling technology for renewable energy integration*
2019	*Grand challenges in the science of wind energy*
2018	*Scavenging wind energy by triboelectric nanogenerators*
2017	*Is the supply chain ready for the green transformation? The case of offshore wind logistics*
2016	*Life cycle assessment of onshore and offshore wind energy-from theory to application*
2015	*A survey on wind turbine condition monitoring and fault diagnosis—Part I: Components and subsystems*

In the early stages, the focus of innovation lies in developing new structural designs that are more efficient and adaptive. One important breakthrough is the concept of bladeless turbines (bladeless wind turbine) as studied in research on the vibration response of turbine shafts based on sandwich structures with material variations (Pahlavanzadeh et al., 2024). This approach offers a solution to reduce environmental impact and minimize noise, as well as increasing resilience to extreme weather conditions. Along with that, innovation is moving towards the integration of renewable energy sources. Research on the integration of wind power and solar power for green hydrogen production (Ikuerowo et al., 2024) marks the transformation of the function of wind turbines not only as electricity generators, but also as part of a hydrogen-based clean energy production system. This indicates the evolution of wind turbines into an important component in the multi-source energy ecosystem of the future.

Attention to the contribution of wind turbines to sustainable development is also growing. Study of the contribution of renewable energy sources to environmental impacts and economic benefits (Algarni et al., 2023) shows that wind turbine innovation is now being evaluated not only from technical aspects, but also from its added social and economic value. In the context of offshore energy, the development of offshore turbines is very important. Research on techno-economic analysis and Monte Carlo simulation on green hydrogen production using turbines offshore (Jang et al., 2022) illustrates that the complexity of this technology is not only in the engineering aspect, but also in the financial risks and long-term project feasibility.

In line with these developments, power electronics technology has emerged as an enabling technology in the integration of renewable energy (Tang et al., 2022). Development in inverter, converter, and digital control systems enable modern wind turbines to connect more stably and efficiently to the power grid. Major challenges in wind energy science have also been systematically identified (Veers et al., 2019), including the need for new aerodynamic models, the development of lightweight, durable materials, and the design of giant-scale turbines to increase energy production. On the new technology side, triboelectric nanogenerators (B. Chen et al., 2018) is starting to be explored to capture micro-scale wind energy, opening up opportunities for application in small devices and Internet of Things (IoT) systems, expanding the spectrum of wind energy applications.

In operational and infrastructure aspects, supply chain readiness is a major issue, especially for offshore turbine projects (Poulsen & Lema, 2017). This shows that innovation is not only occurring in turbine design, but also in logistics efficiency and large component distribution management. Further, approach Life Cycle Assessment (LCA) on wind energy (Bonou et al., 2016) makes clear the importance of assessing the environmental impact of the entire turbine life cycle, from production to recycling. Finally, developments in condition monitoring and turbine damage diagnosis (Qiao & Lu, 2015) shows a shift towards digitalization of maintenance systems through the use of smart sensors and artificial intelligence to predict and prevent early system failures. Based on this study, the evolution of wind turbine technology innovation in the last 10 years has moved from developing structural design, integrating renewable energy, optimizing operations and logistics, to digitalization and full sustainability. This marks a comprehensive transformation of wind turbines as a pure energy technology into a strategic component in a sustainable global energy system.

CONCLUSIONS AND RECOMMENDATIONS

The initial stage of this research succeeded in systematically collecting and curating scientific data related to wind turbine technological innovation from the 2015–2025 period. Through the application of strict inclusion and exclusion criteria, as well as a focused keyword-based literature search strategy in the database Google Scholar, 730 relevant and high quality articles were obtained. At this stage, bibliometric analysis of 730 articles resulted in a mapping of wind turbine research uses VOSviewer. A visualization of the wind turbine research map shows five main clusters: energy production, industrial policy, turbine component design, control innovation, and future trends. The dominant topic is wind turbine blade, China, And power generation. Research progressed from a policy focus (2016–2018) to technical innovation and sustainability (2020–2022). The most studied research is blade design, operation offshore, and new materials, while themes such as alternative energy and emerging markets are still less explored. These results reveal great opportunities for technological innovation and cross-disciplinary exploration in renewable energy. Stage 3 involves a systematic literature review to examine trends, innovations, and directions of development of wind turbine technology over the last decade, including new structural designs, integration of renewable energy, operational optimization, digitalization, and contribution to global energy sustainability.

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