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RESEARCH ARTICLE OPEN ACCESS

Offshore Wind Market in India and Global: A Systematic Review of the Current State, Risks, Mitigation Strategies, and Potential Opportunities

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ABSTRACT
Offshore wind energy projects are significant due to their ability to develop at sea, are far from terrestrial interference, and have the potential to meet the renewable energy needs of a country. These projects are increasingly considered in India, albeit with varying rates of deployment and operational approaches. However, they face numerous challenges and require adoption strategies that range from technological innovations to financial constraints. These issues require comprehensive risk management and assessment, which this study addresses. The objective of this study is to conduct a critical evaluation of the offshore wind energy market in India in the context of the global ecosystem, focusing on the current status, associated risks, and mitigation strategies that facilitate the achievement of the renewable energy utilization targets. A systematic literature review (SLR) was conducted, resulting in 63 selected references. This study highlights the increasing adoption of offshore wind energy in India and worldwide, identifying three primary challenges: operational, financial, and technological. Various strategies, ranging from optimization to strategic capital allocation, are discussed, along with their potential implications for offshore wind energy projects and facilities in India.

Keywords: Offshore Wind Market, Indian Offshore Wind Energy, Offshore Wind Projects, Wind Project Risks, Wind Project Risk Management Strategy

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I. INTRODUCTION

Offshore wind energy projects are installations within a country's sea boundaries that harness the higher wind speeds over the ocean to generate electricity. India, with its extensive coastlines and strong sea winds, has significant potential for such developments, as noted in a study by Bhattacharjee et al [1]. Tamil Nadu and Gujarat are two major states where there have been notable advances in the installation and development of offshore wind projects, aimed at utilizing the strongest oceanic winds. These initiatives are believed to be crucial to achieving the renewable energy goals of the nation. However, they are associated with various risks, as identified in a study by Katsanos et al [2]. Risks arise from geographical factors (such as the distance from the port, the nature of the seabed, and the conditions of the sea wind) and technical factors (including the quality of the turbines and blades, challenges in grid integration, and the autonomy of the system). Financial challenges, such as unprofitability during the initial phase, capital scarcity, and high operational costs, are also significant hurdles. To address these challenges, Xu et al [3] have suggested several strategies, ranging from enhancing research and development, fostering international collaboration, to providing financial assistance with more favorable terms to developers. It is imperative to tailor these strategies to the specific needs of each company, taking into account factors such as market demand, wind speed data, geographical characteristics, and energy pricing.

1.1 Comparison of Indian offshore wind energy projects with other countries around the world

According to the 2024 GWEC Global Wind Report [4], the offshore wind industry experienced substantial expansion in 2023, as evidenced by the installation of 10.8 GW of new systems, bringing the total global capacity to 75.2 GW. This marked a 24% increase over the previous year, placing 2023 as the second most prolific year for offshore wind installations. Leading the charge, China maintained its position as the leading offshore wind developer for the sixth consecutive year, adding 6.3 GW, 58% of the total global for the year. This increased China's cumulative offshore wind capacity to 38 GW, surpassing Europe's by 3.7 GW. In the Asia-Pacific region outside of China, Taiwan added 692 MW, while Japan and South Korea introduced 62 MW and 4 MW, respectively. Europe also witnessed a substantial increase, commissioning 3.8 GW across six countries, thereby raising its total to 34 GW by year's end. Within Europe, the UK represented 43% of the capacity, followed by Germany with 24%. Although the US did not commission any new offshore capacity in 2023, it continued construction on two major projects, Vineyard Wind 1 and South Fork Wind, maintaining its status as the only North American market with operational offshore wind facilities. In terms of the aggregate number of offshore installations, China surpassed the United Kingdom in 2021 and has maintained its lead in the years that followed. Meanwhile, Germany, the Netherlands, and Denmark rounded out the top five offshore wind markets. Although ceding its position as the largest offshore wind market globally in 2022, Europe maintains its dominant position in the floating wind industry, accumulating an additional 37 MW in 2023. This represented 79% of floating wind installations worldwide during the year, bringing the total floating capacity of Europe to 208 MW, or 88% of the global total. The offshore market on a global scale is expected to increase from 10.8 GW in 2023 to 37.1 GW in 2028, accounting for a greater percentage of new installations than its current 9% to 20% in 2028. In Europe, it is forecasted that more than 42 GW of offshore wind capacity will be developed between 2024 and 2028, with 44% of this expected in the UK, largely due to the scheduled activation of projects from CfD Allocation Rounds 3, 4, and 6. Furthermore, Germany is expected to install 15%, Poland 11%, the Netherlands 8%, France 6%, and Denmark 5%. In Asia, China's offshore wind development is poised for rapid progress once deep-sea project development regulations are established. China is projected to maintain its dominance in the region, adding 72 GW in the next five years, with Taiwan (China) adding 6.9 GW, South Korea 3.1 GW, and Japan 1.7 GW.

India's offshore wind energy sector is poised for significant expansion, presenting substantial opportunities for the country's renewable energy framework. India has established an ambitious objective of installing 30 GW of offshore wind capacity by 2030, using designated zones off the coast of Gujarat and Tamil Nadu, despite the lack of operational installations. These regions alone have an estimated potential of approximately 70 GW, sufficient to power more than 50 million households. The government's proactive efforts to harness this potential and attract investment make India an attractive market for technology companies and developers in the renewable energy sector. Significant strides have been made toward completing the inaugural offshore wind seabed tender. This includes the issuance of the updated ‘Strategy Paper for the Establishment of Offshore Wind Energy Projects’, which introduces three different models to allocate 37 GW of capacity by 2030. In addition, regulations have been published for offshore wind leases. Having started the leasing procedure for 4 GW of seabed capacity in Tamil Nadu for offshore wind projects in early February 2024, the Solar Energy Corporation of India (SECI) launched the endeavor. Furthermore, an exemption from interstate transmission system (ISTS) tariffs has been granted until 2032 in conjunction with the provision of viability gap funding (VGF) for the initial 1 GW of offshore wind capacity. Offshore wind is critical for decarbonizing India's power sector despite its higher initial costs compared to offshore wind and solar power. This is because offshore wind uses larger turbines, ranging from 5 to 15 MW, which contribute to its higher capacity utilization factors. This context underscores the importance of assessing specific risks and strategic approaches for India, as the nation strives to increase its renewable energy capacity and move toward a net zero economy. The present investigation, constructed as a systematic review of the literature (SLR), aims to examine and amalgamate previous scholarly work on offshore wind energy markets, encompassing those of India and the rest of the world. This methodology will produce an exhaustive examination and present discernments that may stimulate additional expansion in the offshore wind industry of India.

On the basis of the different aspects discussed here, the study will address the following objectives.

1. Undertake an exhaustive and comparative examination of the offshore wind energy industry in India, assessing its current condition, discerning intrinsic hazards, and revealing prospective prospects, with a specific focus on the worldwide offshore wind energy market.
2. Critically assess India's offshore wind energy infrastructure, policy framework, and technological advances, and compare these with international standards and practices to pinpoint gaps and suggest areas for improvement.
3. Explore the opportunities that the global offshore wind market offers India, including potential collaborations, technology transfers, and investment prospects.

II. RESEARCH METHODOLOGY

2.1 Search strategy

To facilitate the identification of recent and relevant studies in accordance with the study objectives, the current investigation has been structured as a systematic review of the literature (SLR). These studies were selected using predetermined criteria. The choice to employ an SLR is grounded in its ability to mitigate researcher bias, which can occur if researchers selectively favour studies that align with their own opinions, potentially leading to inadequate analysis and a skewed understanding of the topic. The current condition of offshore wind projects, the inherent dangers associated with these endeavours, and the diverse approaches to risk mitigation are the three primary aspects that this study intends to investigate. To ensure a thorough and precise examination of these components, an SLR is considered suitable. Furthermore, to improve the quality of this review, the PRISMA methodology (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), as described in studies by Page et al. [5], has been implemented. A well-defined database of studies that directly address the research objectives is the result of the PRISMA systematised framework, which details each stage of the study selection and filtering procedure.

Specific inclusion and exclusion criteria were implemented to ensure the currentness and relevance of the incorporated research. Only studies published in English or readily translatable into English were incorporated into the analysis, which spans the years 2016 to 2024. Furthermore, it is imperative that all research studies be designed so that they can be readily available to anyone with a valid reference. By sticking to this methodology, the chosen research articles are guaranteed to be current, pertinent, and easily accessible. In order to ensure precision and pertinence, the selection procedure has omitted all conference papers and books.

2.2 Methods for Study Selection and Evaluation

Figure 1 shows the PRISMA model adopted for the current study and utilized two primary databases for the literature search: ScienceDirect and PubMed. Initial searches were conducted using two key phrases: offshore wind energy and India and offshore wind energy and technology. This initial query yielded a total of 43,306 references. To refine these results, duplicates and titles not relevant to the study were removed, resulting in a reduced pool of 33,299 articles. Further refinement involved applying a timeline criterion, selecting only articles published between 2016 and 2024. This step excluded an additional 773 articles, leaving 25,926 for further consideration. The next filter applied was accessibility; All articles not openly accessible were removed, significantly narrowing the field to 5,937 articles.

To ensure relevance to the study's focus, all books, book chapters, and conference papers were then excluded, further reducing the pool to 1,203 articles. Each of these articles was then individually reviewed to confirm a primary focus on offshore wind energy, which led to the selection of 283 articles. The final refinement involved a thorough analysis of the abstract of each article to ensure alignment with the objectives of the study, which ultimately resulted in 63 final references that were included in the study analysis.

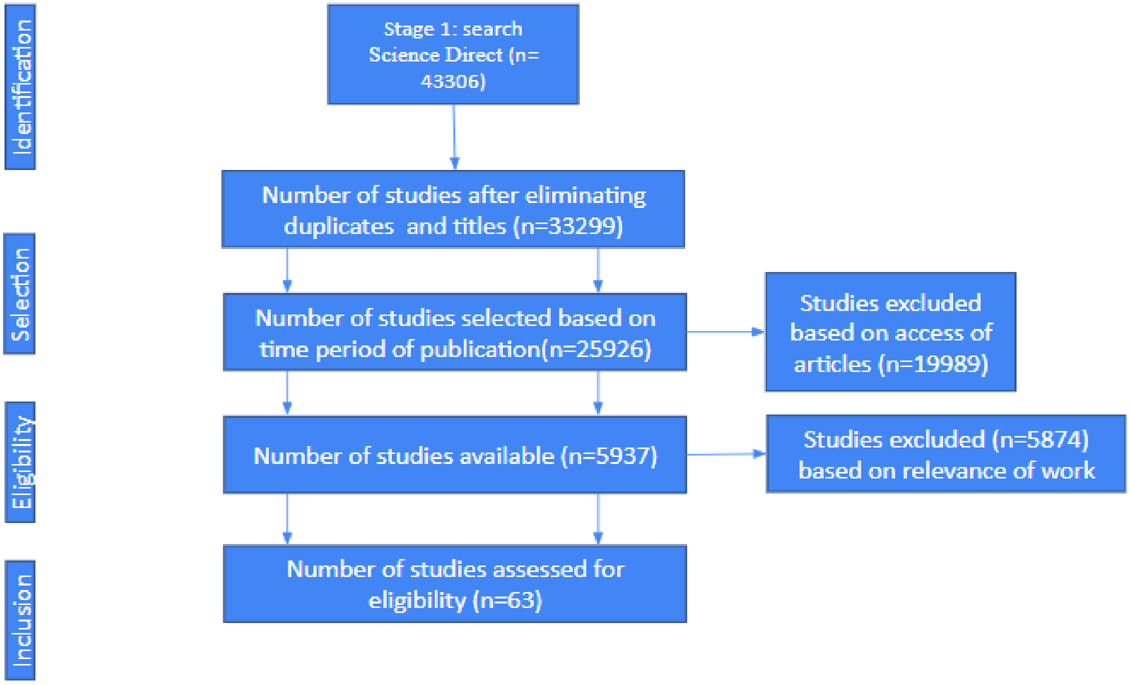

Fig. 1 PRISMA model

III. REVIEW OF THE LITERATURE

This section presents a detailed information from various studies focusing on offshore wind energy, highlighting significant findings that contribute to understanding the complexities of wind resource assessment, supply chain readiness, and the economic viability of offshore wind projects under different technological and geographical scenarios. Each entry provides a concise overview of the study methodology and key outcomes, helping to elucidate the challenges and opportunities within the offshore wind energy sector.

a. Economic Feasibility and Wind Energy Potential

Alham, M. H., Gad, M. F., and Ibrahim, D. K. [6] employed a dual-phase methodology to assess the economic feasibility and wind energy potential of four Egyptian locations: Ras El-Hekma, Farafra, Nuweiba, and Aswan. Initially, the equilibrium optimizer algorithm was used to determine the optimal heights for turbine hubs to maximize energy production and minimize costs. The study compared the cost of energy (COE) at these sites with Egyptian and global benchmarks through economic analysis. The analysis revealed that Ras El-Hekma, equipped with the EWT-DW61/22 turbine, had the highest average wind speed, energy potential, and the lowest COE.

b. Wind Speed Distribution and Modeling

Aljeddani, S. M., and Mohammed, M. A. [7] investigated discrepancies between predicted and observed wind velocities using the Weibull distribution. They employed adjusted maximum likelihood (MML), energy pattern factor, and method of moments (MOM) to evaluate Weibull distribution variables. Their statistical comparison of simulated and actual wind velocities confirmed the Weibull distribution's feasibility, precision, and efficiency for wind speed modeling.

c. Offshore Wind Turbine Efficiency

Antoniou, M. et al. [8] explored the operational efficacy of offshore wind turbines (OWTs) designed to withstand wind and seismic loads using suction bucket jackets (SBJs) made from clay. They introduced an enhanced Winkler-based Caisson-on-Winkler-Soil (CWS) model and a three-dimensional finite element (FE) model for the soil-foundation-structure system. The study accurately predicted the H–M failure boundary under concurrent loading but faced challenges in representing caisson settlements during seismic events due to dual shearing at the caisson shaft. Regression equations were developed to correlate caisson settlement with specific parameters and Arias intensity of ground motion.

d. Renewable Energy Initiatives in Tunisia

Attig-Bahar, F. et al. [9] highlighted Tunisia's commitment to reducing greenhouse gas emissions by 41% by 2030 compared to 2010 levels. The study focused on the evolution of wind energy in Tunisia from 2000 to the present, providing an overview of global wind energy trends and emphasizing proactive measures in the energy sector to promote renewable resources and enhance energy efficiency.

e. Fault-Tolerant Control in Offshore Wind Farms

Badihi, H. et al. [10] introduced an advanced fault-tolerant cooperative control (AFTCC) strategy for offshore wind farms, integrating fault detection and diagnosis (FDD) with fault-tolerant control (FTC). They developed an automated signal correction algorithm to efficiently manage and mitigate defects within wind farms, based on precise and timely diagnostics provided by a sophisticated FDD system.

f. Wind Energy Potential in Turkey

Başaran, H. H., and Tarhan, İ. [11] analyzed wind energy potential in the Northwest (South Marmara) region of Turkey using WindPro software data from 1992 to 2022. They applied the MOORA method, a multi-criteria decision-making tool, to identify the most advantageous sites for offshore wind turbines, determining the most suitable regions in the Southern Marmara area based on received data and selected criteria.

g. Wind Energy in India

Bharani, R., and Sivaprakasam, A. [12] examined wind energy attributes by analyzing meteorological variables and frequency distribution data from various monitoring locations. They calculated wind power density at 100 meters above mean sea level using the Weibull distribution in 2016, identifying Sites 1, 2, and 3 as highly suitable for wind energy harvesting. Stations S1 and S3 were deemed highly favorable for wind turbine installation, while station S2 was marginally less so.

h. Maritime Power Generation Optimization

Bhattacharjee, P. et al. [1] aimed to enhance the financial viability of maritime power generation systems in the Bay of Khambhat, near the coast of Gujarat, India. They proposed an innovative modification of the genetic algorithm to increase the projected annual revenue of the wind farm. The optimization trial outcomes validated the proposed dynamic approach over conventional static methods for assigning crossover and mutation function proportions.

i. Global Offshore Wind Energy Capacity

Bosch, J. et al. [13] outlined a methodology using the Geospatial Information System (GIS) to calculate worldwide offshore wind energy capacity in terawatt hours per year (TWh/year). Their approach meticulously computed capacity factors of future offshore wind farms using high-resolution worldwide wind speed data, categorizing hourly wind speeds into 32 yearly segments. The analysis covered 157 countries, classifying their potential for generating offshore wind power based on proximity to grid connections, ocean depth, and average annual capacity factor.

j. Historical Wind Power Density Analysis

Carreno-Madinabeitia, S. et al. [14] computed wind power density (WPD) and capacity factor (CF) for wind turbines at a hub height of 90 meters using reanalysis data. They adjusted ERA20 data with ERA5 as a reference, revealing that the Atlantic zone and the Gulf of Lyon had the highest values of WPD, CF, and wind speed (WS) in the 20th century, while the Balearic Islands had the lowest. The Theil-Sen estimator showed notable upward trends in these measurements around the Iberian Peninsula between 1900 and 2010.

k. Anchor Performance in Offshore Wind Turbines

Cerfontaine, B. et al. [15] investigated potential improvements in the performance-cost relationship for various anchor types used in offshore wind turbines. Enhancements were classified into four categories: improving anchor performance through advanced design techniques and better understanding of ground response, increasing anchor size, streamlining production and installation processes, and developing new anchor technologies.

l. Reliability of Offshore Wind Farms

Cevasco, D., Koukoura, S., and Kolios, A. J. [16] estimated the operational availability of various offshore wind farm scenarios and compared these with recent performance statistics. The study highlighted that offshore environmental conditions negatively impact reliability, although similarities were noted between offshore and onshore systems in blade adjustment reliability and power generation and control system maintainability.

m. Enhanced Inverter Control Systems

Chaithanya, S., Reddy, V. N. B., and Kiranmayi [17] presented an enhanced dynamic system for regulating a current source inverter (CSI) using a generic current controller (GCC) with voltage-dependent current limits (VDCL). This technology ensures consistent current flow in the DC connection regardless of load variations and grid voltage, allowing for the transfer of both real and reactive power. The proposed controller reduces complexity and operates autonomously without relying on external current limiters or additional monitoring devices.

n. Wind Energy in India

Chaurasiya, P. K., Warudkar, V., and Ahmed, S. [18] discussed India's significant renewable energy resources, particularly wind energy. By September 2018, India had installed approximately 34,605 megawatts of wind power plants, ranking fourth globally in wind energy conversion and utilization. The study emphasized the importance of assessing wind energy capacity for future installations.

o. Renewable Energy Resource Stability

Costoya, X., DeCastro, M., Carvalho, D., Arguilé-Pérez, B., and Gómez-Gesteira, M. [19] found that offshore wind energy resources were greater than solar photovoltaic resources on an annual basis across the western Iberian Peninsula. Both renewable resources exhibited substantial spatial and temporal fluctuations, and their combination significantly enhanced energy resource stability throughout the year.

p. India's Renewable Energy Strategy

Dawn, S., Tiwari, P. K., Goswami, A. K., Singh, A. K., and Panda, R. [20] analyzed key elements and promotion strategies that the Indian government is implementing to improve energy security through renewable sources. The study highlighted wind power as a significant and cost-effective energy source, noting the global installed capacity of wind power doubled approximately every three years over the past few decades of the 20th century.

q. Factors Influencing Wind Energy Adoption

Debnath, B., Shakur, M. S., Siraj, M. T., Bari, A. M., and Islam, A. R. M. T. [21] identified sixteen factors influencing the adoption of wind energy for national grid support using the IVT2IF DEMATEL approach. The most influential factors included "Disruption of fossil fuel supply," "Stable financial investment and resource mobilization," and "Geographical region."

r. Offshore Project Location Attributes

Dinh, Q. V., Mosadeghi, H., Pereira, P. H. T., and Leahy, P. G. [22] emphasized the importance of location attributes such as distance to port, ocean depth, and distance to the gas grid injection site in forecasting expenses associated with wind farm components and replacement of the electrolyte stack. A theoretical 510 MW wind farm was modeled using GIS to generate maps showing the levelized cost of hydrogen (LCOH) derived from offshore wind resources in Irish waters.

s. Maintenance Costs in Offshore Wind

Edesess, A. J., Kelliher, D., Borthwick, A. G., and Thomas, G. [23] addressed the high operational and maintenance (O&M) costs of offshore wind power, which can represent 25-50% of total energy production expenses. The current conservative method for accessing offshore turbines for maintenance based on significant wave height (HS) often leads to increased downtime and costs. The proposed method aims to reduce these costs by improving the analysis of crew transfer vessels' (CTVs) motion and stability, influenced by the turbine's presence.

t. Resonance-Induced Damage Prevention

Futai, M. M., Haigh, S. K., and Madabhushi, G. S. [24] used a piezoactuator to determine the natural frequencies of wind turbine monopiles and gravity-based foundations (GBFs) under harmonic loading conditions in centrifuge models. The findings confirmed the necessity of incorporating soil-structure interaction to derive the system's natural frequency, significantly decreasing from fixed base values and aiding in preventing resonance-induced damage to wind turbines.

u. Taiwan's Energy Transition

Gao, A. M. Z., et al. [25] discussed Taiwan's energy transition since 2016, aiming for nuclear-free status by 2025. The country's reliance on renewable energy sources increased from 5% in 2016 to 20% in 2025. Taiwan set ambitious offshore wind power capacity goals, growing from two 4-MW generators in mid-2016 to 5.7 GW by 2025, supported by substantial feed-in tariffs contingent on fulfilling domestic content prerequisites.

v. Wind Energy in Turkey

Gönül, Ö., et al. [26] emphasized Turkey's focus on energy diversification to reduce fossil fuel reliance, aiming to install 20 GW of wind capacity by 2023. However, the existing installed capacity of 8 GW falls short of this goal. The paper provides a comprehensive examination of Turkey's wind energy sector, focusing on policies and incentives designed to advance the sector.

w. Renewable Energy Challenges in India

Govindan, K. [27] examined technical and functional obstacles in developing countries like India, which face substantial energy requirements and depletion of non-renewable energy resources. The study identified a lack of awareness as a primary obstacle to the initial installation of critical renewable energy sources, suggesting that eliminating this barrier could significantly advance India's offshore wind energy systems.

x. Offshore Wind Investment in China

Guo, X., et al. [28] identified obstacles to grid integration at the provincial level in China, recommending a doubling of offshore wind investment levels by 2030. The potential offshore wind capacity in China could reach 1,500 GW by 2050, necessitating a paradigm shift in transmission infrastructure to favor long-term storage and enable green hydrogen production in coastal demand centers.

y. Wind Energy Potential Assessment

Hasan, M., et al. [29] evaluated six methods to determine the shape parameter (k), scale parameter (c), and k/c ratios for assessing wind energy potential. Sandwip was identified as the location with the most favorable annual mean wind speed of 4.89 meters per second. The yearly energy density and power density in Sandwip, determined using the Weibull distribution, were 104.92 kWh/m² and 88.59 W/m², respectively. The power density method exhibited the highest efficacy among the techniques employed, while the energy pattern factor method demonstrated the least favorable performance. Additionally, the study recommended the Enercon E-40 and E-48 models for Sandwip based on their capacity factors and annual energy production.

z. Future Cost Reductions in Wind Energy

Hughes, L., and Longden, T. [30] predicted that the average levelized cost of electricity (LCOE) for fixed-bottom wind technologies would decline to USD 72/MWh by 2040, while floating technologies would reach USD 81/MWh by 2050. The decline is attributed to advances in capacity factors and reductions in installation and capital expenditures. The study emphasized policy measures' importance in facilitating these cost reductions, highlighting competitive tender procedures as crucial for floating offshore wind technologies.

aa. Wind Industry Competitiveness

Irfan, M., et al. [31] identified several critical determinants impacting the wind industry's competitiveness, including demand conditions, factor conditions, fortuitous events, supporting and associated industries, firm strategy and structure, competition, and government intervention. The study recommended strengthening these elements to ensure the sustained growth of the wind industry.

bb. Offshore Wind Auction Mechanisms

Jansen, M., et al. [32] analyzed auction mechanisms in eight prominent offshore wind jurisdictions across Europe, Asia, and North America. The study evaluated each mechanism considering its regulatory and market environment, noting significant diversity influenced by jurisdictional factors. Despite market maturity, all offshore wind energy auctions incorporated some form of revenue stabilization mechanism.

cc. Decommissioning Strategies for Offshore Wind

Jensen, P. D., et al. [33] criticized current decommissioning strategies for offshore wind projects for being overly simplistic, highlighting the need for sustainable approaches to retrieve, manage, and reutilize valuable materials, including rare earth elements. The study emphasized the absence of viable strategies to support the transition to a circular economy, given the rapid expansion of low-carbon infrastructure.

dd. Institutional Frameworks in Sustainable Energy Transitions

Jolly, S., et al. [34] underscored the significance of institutional frameworks in transitions to sustainable energy, examining the dynamics in both established and developing environments. The study highlighted the substantial impact of various actors on forming these frameworks and contributed to the literature on institutional entrepreneurship by analyzing how actors modify their institutional contexts and the opportunities provided by emergent frameworks.

ee. Soil Properties in Wind Turbine Installations

Jose, N. M., and Mathai, A. [35] demonstrated that soil properties, as well as the embedded length and diameter of piles, significantly influence pile displacement and inclination angle in wind turbine installations.

ff. Wind Speed Distribution Methods

Kang, S., et al. [36] evaluated twelve methods for predicting wind speed distribution, identifying the Moment method, Empirical method of Justus, Empirical method of Lysen, and the standard deviation method as having the highest accuracies. In contrast, the graphical method, alternative maximum likelihood method, equivalent energy method, and energy pattern factor method were found to have the lowest accuracies.

gg. Computational Model for Offshore Wind Structures

Katsanos, E. I., et al. [2] constructed a comprehensive computational model of an offshore wind structure, including blades, nacelle, tower, and monopile, using an aeroelastic code. The model accounted for aerodynamic, hydrodynamic, elastic, and inertial forces. The analysis revealed significant detrimental effects of seismic excitations on the turbine tower's dynamic response, negatively affecting wind turbines' availability and reliability.

hh. Advancements in Offshore Wind Energy

Kou, L., et al. [37] noted that the implementation and upkeep of offshore wind energy are advancing towards intelligence and digitization. Research on monitoring, operation, and maintenance of offshore wind farms is crucial for reducing maintenance costs, improving power generation efficiency, ensuring system stability, and developing intelligent offshore wind farms.

ii. Potential of Low-Wind-Speed Turbines

Langer, J., et al. [38] indicated that low-wind-speed turbines could produce up to 6,816 TWh annually, significantly exceeding Indonesia's electricity generation in 2018 and expected generation in 2050. Globally, these turbines could generate up to 166 PWh annually. Despite not competing with established offshore turbines, low-wind-speed turbines could substantially contribute to climate mitigation, particularly in regions with abundant marine resources and high electricity costs. The study suggested prioritizing their advancement due to their current non-commercial availability.

jj. Cost Optimization for Renewable Energy

Lu, T., et al. [39] used a cost optimization model to illustrate that renewable energy sources can be more competitive than fossil-based alternatives. With ongoing price reductions in wind turbines and solar PV systems, allocating resources towards renewable energy to meet 80% of India's projected power requirements by 2040 could reduce carbon dioxide emissions by 85%, compared to continued reliance on coal.

kk. Risk-Based Paradigm in Offshore Wind

Macrander, A. M., et al. [40] analyzed recent technological and operational developments to establish a risk-based paradigm that facilitates the timely development of offshore wind energy, utilizing various regional data inputs.

ll. Future Wind Resource Reduction

Martinez, A., and Iglesias, G. [41] predicted a substantial reduction in global wind resources by 2100, with the most significant declines occurring in densely populated mid-latitudes of the Northern Hemisphere. While some regions in polar and tropical zones may see exceptions, these areas are less populated. By 2100, wind power density deficits could exceed 30% of current levels, impacting wind energy generation and grid integration.

mm. Complementarity of Renewable Energy Sources

Mejia, A. H., et al. [42] found that onshore wind and solar energy are highly complementary, while no discernible correlation exists between offshore wind sites and solar power, energy demand, or other offshore wind sites. A demand-based value metric indicated that six prospective offshore wind sites in California provide superior value compared to alternative renewable resources during prime summer hours. Fourier analysis showed that offshore wind energy might be exceptionally volatile.

Future Requirements of Robotic and Autonomous Intelligence

Mitchell, D., et al. [43] provided a comprehensive analysis of the current state and future requirements of robotic and autonomous intelligence (RAI) in offshore energy. The study assessed necessary investments, regulations, and skill development for implementing RAI, highlighting challenges such as certification of autonomous platforms, development of digital architectures, adaptive mission planning, and optimization of human-machine interactions. The study suggested incorporating technological advancements into a "symbiotic digital architecture" to improve offshore wind farm lifecycle management.

Wind Power Potential in India

Nagababu, G., et al. [44] determined upper limits for annual mean wind speed (MWN) and wind power density (WPD) for a 2.1 MW rated capacity wind turbine at 9.7-13.4 m/s and 1048.7-1632.5 W/m², respectively. The classification of the region into zones according to wind classes and foundation technology revealed that approximately 74% of the area belongs to class 1. Offshore wind has the potential to supply India with at least 1.6 times its electricity demand for the 2015-16 fiscal year.

Data Sharing in Wind Assessments

Pelser, T., et al. [45] highlighted significant obstacles to data sharing and scientific reproducibility in wind assessments, with only 10% of studies making their data publicly accessible. The study criticized overreliance on single-source wind data and inadequate characterization of temporal wind variability, pointing out optimistic capacity density assumptions and simplistic turbine location and wake loss characterization approaches that could lead to overestimated wind potentials.

Accuracy of Wind Speed Models

Potisomporn, P., et al. [46] compared hourly 10 m ERA5 reanalysis wind speed data with in situ measurements from 205 onshore and offshore observation stations throughout the UK. The ERA5 model exhibited biases of 0.166 m/s and 0.136 m/s in mean wind speed for onshore and offshore domains, respectively, with increased errors during fall and winter seasons. These inaccuracies resulted in inadequate estimates of low-velocity wind events' frequency. The most substantial errors were in mountainous and coastal areas, where ERA5 may not account for short-range topographical variability and local wind impacts.

Offshore Wind Supply Chain

Poulsen, T., and Lema, R. [47] analyzed the supply chain capability in the offshore wind energy sector, focusing on Europe and China. The research indicated that offshore wind logistics significantly impede the rapid implementation of wind energy systems. Extending offshore wind legislation beyond 2020 is essential to ensure investments in logistics assets, transport equipment, and personnel. The study highlighted obstacles in the Chinese wind energy supply chain, primarily in logistics, and suggested international cooperation and knowledge exchange to accelerate progress.

Reanalysis Data for Offshore Wind

Prasad, K. M., et al. [48] verified four reanalysis datasets, including EMD-ERA, ERA5, CFSR2, and MERRA2, using short-term wind data from LIDAR at an offshore site in Gujarat, India. The reanalysis data sets generally underestimated wind speed measurements, with ERA5 exhibiting the highest reliability, evidenced by a correlation coefficient of 0.9329 with LIDAR data. Based on ERA5 data, a theoretical wind farm with one hundred 6-MW wind turbines, achieving an overall capacity factor of 39.27%, could produce a maximum power output of 2.064 TWh.

Floating Offshore Wind Technology

Putuhena, H., et al. [49] quantified the necessity for floating offshore wind (OW) technology to overcome water depth barriers, access uncharted sea regions, and develop accompanying port and grid infrastructure in the UK, which has the most installed offshore wind capacity worldwide. The study evaluated the potential consequences of increased ocean space utilization for OW.

Offshore Wind Power Station Location Evaluation

Rani, P., et al. [50] developed a decision-making framework to evaluate offshore wind power station (OWPS) locations based on various criteria and uncertainty levels. The framework integrated normalization tools and utility measures to validate the impact of advantageous and disadvantageous criteria.

Offshore Wind Power Feasibility in Thailand

Ranthodsang, M., et al. [51] evaluated the feasibility of constructing offshore wind power facilities with turbine capacities of 9.5 MW, 3.3 MW, and 8.0 MW in line with Thai energy policies. Annual energy production, capacity factors, levelized cost of electricity (LCOE), CO2 equivalent emission avoidance, and mandatory feed-in tariffs (FiT) were analyzed. Results indicated that a 3.3 MW turbine could generate over 13 GWh annually under the Very Small Power Producer (VSPP) scenario, while 50 MW and 90 MW plants could generate 68 GWh/year and 123 GWh/year, respectively.

Rare Earth Elements in Wind Energy

Rybak, A., et al. [52] examined the influence of rare earth elements (REE) availability on wind energy production capacity in Poland using the WE ARE Energy 1.0 software. The program optimized forecast model parameters and generated wind energy production capacity forecasts incorporating two developmental scenarios. To address potential depletion of REE resources such as neodymium, dysprosium, praseodymium, and terbium, the research suggested using fly ash from coal combustion in Poland as a substitute, which could meet or exceed demand in most cases.

Levelized Cost of Energy for Offshore Wind

Santhakumar, S., et al. [53] evaluated the levelized cost of energy (LCoE) for fixed-bottom offshore wind, finding it to be 40€/MWh at 31 GW cumulative capacity (2023–2024), excluding grid connection costs. This value decreased to 28±3€/MWh as capacity increased by 100 GW. Floating wind had an LCoE of 123€/MWh at 1 GW cumulative capacity (2027-2030), dropping to 33±6€/MWh with 100 GW capacity. Cost parity (40 €/MWh excluding grid connection cost) could be achieved by deploying 21 GW of floating wind, requiring a 44 billion euro learning investment in subsidies.

Cost Trends in Offshore Wind Development

Santhakumar, S., et al. [54] discussed the cost trends in offshore wind farms during the development phase (2000-2010), where specific capital expenditures increased from 2 million €/MW to 5 million €/MW, raising the LCoE from around 110 €/MWh to over 150 €/MWh and producing negative learning rates (LR). However, during the upscaling and growth phase (2011-2020), specific capital expenditures decreased from 5.4 million euros per megawatt to 3.3 million euros per megawatt, representing an 8-11% LR. Concurrently, LCoE decreased more rapidly than capital expenditure, falling by 54% from approximately 150 €/MWh to 69 €/MWh. Recent auction results suggest LCoE will decrease to 55 €/MWh in 2021-2023 and 48 €/MWh in 2024-2026.

Wind Energy Potential in India

Sharma, S., and Sinha, S. [55] highlighted the practical uses of wind energy, such as grinding grains, pumping water, and sailing vessels, and its current primary use for electricity production. They noted that India has substantial wind resources, with capacities of 302 GW at 100 m height and 102 GW at 80 m height. The article provided a detailed analysis of fiscal incentives and development initiatives by the Indian government to promote wind energy industry growth.

Offshore Wind Investments in China

Sherman, P., Chen, X., and McElroy, M. [56] attributed a significant portion of China's reduced growth in greenhouse gas emissions to substantial offshore wind investments. Using assimilated meteorological data, the study evaluated China's prospective offshore wind capacity, finding it exceeded current coastal power demand by a factor of 5.4. The study suggested that China's offshore resources could be exploited cost-competitively, supplying 6383.4 TWh in a low-cost scenario and 1148.3 TWh in a high-cost scenario.

Renewable Energy Transition in India

Siram, O., Sahoo, N., and Saha, U. K. [57] discussed India's transition to renewable energy sources (RE) in response to increasing concerns about climate change and its commitment to reducing carbon emissions. Currently, approximately 20% of India's electricity is generated from RE, but numerous obstacles remain, particularly due to the country's significant reliance on conventional energy sources for economic activities.

Precision of Climate Models for Offshore Wind

Srinivas, B. A., Nagababu, G., and Kachhwaha, S. S. [58] assessed the precision of six CORDEX-SA climate models and their ensembles in the Indian offshore region by comparing them with in situ buoy readings and ERA5 reanalysis data. The ensemble model exhibited 77% correspondence with offshore wind velocities of ERA5. Future forecasts under two emission scenarios (RCP 4.5 and RCP 8.5) indicated a substantial increase in wind speeds in the Northeast region and a cumulative decline in the Northwest region.

Wind Resource Accuracy in the Cambodian Sea

Tuy, S., Lee, H. S., and Chreng, K. [59] revealed satisfactory accuracy of the WRF model compared to L2 OCN data, with a mean bias and root mean square error of 0.70 m/s and 0.79 m/s, respectively. Annual mean wind velocities at 80 m, 100 m, and 140 m above sea level were documented as 5.15 m/s, 5.20 m/s, and 5.27 m/s over the Cambodian Sea. The analytical hierarchy process (AHP) determined the most suitable locations along the Kampot and Kep coastlines for offshore wind energy.

Global Market Access for Wind Energy

van der Loos, H. A., Negro, S. O., and Hekkert, M. P. [60] noted that established corporations have advantageous access to global markets, significantly contributing to nascent industries. In contrast, younger firms enter international markets through robust innovation systems, capitalizing on local market leaders' efforts, gaining direct market entrance, or operating within protected niche markets.

Determinants of Offshore Wind Power Sector

Xu, Y., Yang, K., and Zhao, G. [3] delineated fourteen determinants impacting the offshore wind power sector, organized into five hierarchical tiers. Surface factors included economic incentives, operational mechanisms, the industrial chain, energy market mechanisms, and investment and financing mechanisms. Intermediate factors comprised generation costs, operational administration, and offshore wind energy technology. The deepest levels involved development planning, grid pricing, site selection, R&D investment, environmental policies, and electricity supply, which influence intermediate factors and ultimately shape industry progress.

Recommendations for Wind Industry Improvement

Zhang, H., Yang, J., Ren, X., Wu, Q., Zhou, D., and Elahi, E. [61] recommended enhancing technical innovation in grid-connected systems, penalizing entities impeding wind-generated power integration into the grid, perfecting market-oriented transaction mechanisms and spot trading, incorporating an energy storage strategy, and bolstering wind industry oversight.

Impact of National Policies on Wind Energy Growth

Zhang, J., Lu, J., Pan, J., Tan, Y., Cheng, X., and Li, Y. [62] examined the impact of national policies on wind energy sector growth in China, Denmark, Germany, and the United States. Germany's offshore wind power development was driven by favorable public policies, while Denmark's leadership resulted from comprehensive energy plans. The expansion of the wind energy industry in the United States was facilitated by promotional policies and tax incentives. Despite China's substantial wind power sector growth from 2000 to 2021 and its entry into the "parity era," the study highlighted a notable lack of wind energy utilization, with significant wind curtailment challenges in the northwestern regions.

Viability of Small-Scale Residential Wind Turbines

Zhang, Z., Liu, X., Zhao, D., Post, S., and Chen, J. [63] investigated the viability of small-scale residential wind turbines (0.004 to 16 kW) in New Zealand cities through three case studies. They analyzed the construction, operation, life cycle, and capacity coefficients of these turbines, contrasting them with larger commercial turbines (1 to 3 MW). The results suggested that small-scale residential wind turbines could generate substantial electricity and provide enduring economic benefits.

Wind-Hydrogen-Natural Gas Nexus System

Zou, X., Qiu, R., Yuan, M., Liao, Q., Yan, Y., Liang, Y., and Zhang, H. [64] presented a wind-hydrogen-natural gas nexus (WHNGN) system designed for the sustainable development of offshore oil and gas fields. Using a case study from Bohai Bay, China, the system was compared to traditional energy supply (TES) and wind-natural gas nexus (WNGN) systems. Both WHNGN and WNGN systems reduced overall investment costs and generated additional profits while mitigating carbon emissions. WHNGN was particularly advantageous in regions with high hydrogen and natural gas sales prices, such as China, Kazakhstan, Turkey, India, Malaysia, and Indonesia.

Risks and Returns in Offshore Wind Auctions

Đukan, M., and Kitzing, L. [65] noted that increased competition from offshore wind project auctions forced the sector to accept greater risks and lower returns. Banks reduced debt margins, and major investors decreased hurdle rates and equity returns despite uncertainties. Smaller applicants faced deterrents from potential sunk costs without obtaining support. Sliding premiums in competitive tendering reduced secured revenues and increased offtaker risks. However, the competitiveness of project sponsors led to reduced financing costs and hurdle rates, resulting in a lower cost of capital for these endeavors.

3.1 Current Situation of the Offshore Wind Industry in India and Worldwide

Hasan et al. [29] identified six distinct commercial wind energy models, each tailored to meet specific project requirements and site characteristics in both the global and Indian offshore wind energy markets. Dawn et al. [20] highlighted the critical need for cost-effectiveness in project development, noting the importance of profitability given the rapid doubling of global wind energy capacity every three years. Santhakumar et al. [53] emphasized the importance of including grid and fixed plant costs in the initial planning stages of offshore wind projects to ensure their viability.

Bharani & Sivaprakasam [12] noted that meteorological parameters, such as rainfall and wind speed, play an important role in influencing project attributes and profitability, particularly in the Indian context. Govindan [27] examined the issue of India's increasing energy requirements and proposed a meticulous evaluation as a means to mitigate the strain on the progress of offshore wind initiatives. Zhang et al. [61] proposed spot trading and multiple grid systems as potential approaches to surmount obstacles in the offshore wind energy sector. This highlights the intricate nature of obtaining government support and collaboration from the industry. Additionally, Jose & Mathai [35] stressed the ongoing need to consider soil properties and pile-related factors, such as length and displacement, which are crucial for the sustainable operation of offshore wind plants in both global and Indian scenarios.

In their scholarly article, Potisomporn et al. [46] emphasise the critical importance of hourly wind speed assessments in the operation and development of wind projects that seek to satisfy energy requirements in offshore wind energy markets in India and around the world. Despite the generally lower electricity prices observed from offshore wind energy projects in both markets, Guo et al. [28] identified the difficulties that may arise during the integration of such projects into the main grid. These inefficiencies may result from the integration process. Debnath et al. [21] pinpoint two major challenges shared by the Indian and global markets: selecting appropriate geographical regions for project development and ensuring the availability of financial resources for operational and repair needs. Sherman et al. [56] highlight the higher costs associated with offshore compared to onshore wind projects, emphasizing the need for a comprehensive analysis to assess project feasibility in both markets. As a strategy applicable to both markets, Ranthodsang et al. [51] suggest performing a comparative cost analysis of wind energy and electricity prices in each region before making a decision. The evolution of wind energy projects since 2000, driven by emissions reduction and the promotion of renewable energy, as noted by Attig-Bahar et al. [9], is reflected in the Indian market. Finally, Poulsen & Lema [47] emphasize the importance of developing supply infrastructure to facilitate the distribution of wind energy at affordable prices in both global and Indian contexts. Dinh et al. [22] highlight two critical geographical factors that significantly impact project cost and profitability in both the global and Indian offshore wind energy markets: depth of water at the project site and distance from the port. Dukan & Kitzing [65] proposed an international auction system that could ensure equitable energy utilization and long-term profitability in both markets. Katsanos et al. [2] emphasize the complex nature of wind turbines, including blades, monopiles, and towers, and underscore the need for a comprehensive review in both markets. Badihi et al. [10] advocate for an error detection and control system to improve operational efficiency and profitability, a strategy relevant both to the Indian and global markets. Pelser et al. [45] identified the lack of publicly available wind speed data as a major challenge, affecting the development of prediction and decision-making models in both markets. The concerns mirrored in the Indian and global offshore wind energy markets are examined by Van der Loos et al. [60] with regard to obstacles to international collaboration and innovation, with a specific focus on government policies and additional risks. The importance of conducting cost evaluations and construction in a timely manner for offshore wind energy projects is underscored by Jansen et al. [32]. The authors highlight the necessity of conducting region-specific assessments in both Indian and global contexts.

3.2 Risks to the offshore wind market: India and the world

Major capital expenditure is often associated with ongoing offshore wind energy project development. Offering creative and low-interest finance products is one-way Santhakumar et al. [54] proposes to address this problem and promote the expansion of offshore facilities. Jolly [34] highlights the role of various institutions in promoting entrepreneurialism, technological innovation, and raising stakeholder awareness, which are essential for the holistic development of such systems throughout the country. The importance of the material composition of the project site, particularly soil and clay, is emphasized by Antoniou et al. [8], who suggest tailoring the material selection to each specific case. Technological reliability is another critical aspect, with Cevasco et al. [16] advising on the evaluation of failure propensity across different systems to improve maintenance and repair strategies. Hughes & Longden [30] identified turbine installation costs as a major financial burden, advocating for more accessible financing terms and long-term loans for developers. Zou et al. [64] suggested the incorporation of diverse energy sources, solar, wind, and oil, into a single system in order to meet public demand and guarantee the operational sufficiency of wind farms.

Furthermore, the accuracy of existing wind speed datasets, which are crucial for project planning, is questioned by Prasad et al. [48]. They call for the creation of more reliable data sets to support better decision making in the sector. A significant challenge identified by Siram et al. [57] is that major economic activities in India rely heavily on electricity generated from conventional sources, complicating the transition to wind energy. Kang et al. [36] evaluated 12 wind prediction methods and found that each method has limitations in various scenarios, emphasizing the need for separate consideration, testing, and simulation of each method. Zhang et al. [63] propose to focus on two critical factors for analyzing long-term feasibility: the life cycle of the project and its maximum energy output, both essential for assessing long-term profitability. Gonül et al. [26] propose the implementation of an energy diversification approach that incorporates solar energy as a supplementary source to wind energy. This would result in cost reductions and improved profitability for offshore wind projects that are spread throughout the nation. In their study, Cerfontaine et al. [15] propose the use of a performance-cost model in early simulation and pilot initiatives as a means of mitigating potential risks that could manifest in large-scale projects. Srinivas et al. [58] conducted an analysis indicating that the north-northwest zone of India has more advantages for offshore wind energy projects compared to the northwest zone, suggesting targeted development in the more favourable region. Additionally, Costoya et al. [19] highlight the significant variability in energy throughout India, noting that this variability must be carefully managed to effectively address seasonal challenges.

Jensen et al. [33] suggest implementing low-carbon-consuming infrastructure and systems, which can enhance profitability and promote environmental conservation over the long term. Mitchell et al. [43] recommends the development of an autonomous management system, along with compliance and safety certification by relevant authorities, to ensure systematic and proper management of each project plant. Tuy et al. [59] highlight the variability of wind speeds across different seas and water bodies, which is crucial for a country like India with its diverse aquatic environments; this variability requires thorough analysis.

In their study, Carreno-Madinabeitia et al. [14] evaluated the correlation between turbine capacity and wind power density, concluding that the integration of these variables has the potential to improve project profitability and operational efficiency. Chaurasiya et al. [18] state that numerous wind energy plants in India need regular audits to improve performance, capacity utilization and cost-efficiency. Sharma & Sinha [55] emphasize the need for clear and comprehensive legal regulations to ensure better compliance and address the challenges faced by various stakeholders in the industry. Macrander et al. [40] state that technological innovations and improvements in operational efficiency should be implemented promptly, given the significant impact of timing on project success.

3.3 Mitigation Strategies for Risks in Offshore Wind Market: India and Global

The absence of a correlation between the implementation of solar energy and offshore wind energy initiatives, as determined by Mejia et al. [42], suggests that a more comprehensive examination and case-specific evaluation of solar integration are required. Nagababu et al. [44] recommend performing average annual power simulations to determine the advisability of government investment in such plants. Langer et al. [38] discuss the presence of low- and high-speed wind turbines, each with its own set of benefits and challenges, suggesting that their adoption should be tailored to specific situational attributes across India. Bosch et al. [13] advocate for the use of Geographic Information Systems (GIS) to analyse potential project areas and assess the feasibility of energy projects, ensuring that site selection meets essential criteria. Martinez & Iglesias [41] conducted a geographical analysis indicating that wind energy availability may decrease at mid-latitudes, a factor that should be considered when evaluating the long-term sustainability and profitability of projects in India. Başaran & Tarhan [11] emphasize the importance of conducting wind level analyzes over 2-3 decades to make informed decisions about regional project development in India. According to Lu et al.[39], cost reduction is an essential factor in ensuring the long-term viability of wind energy projects. Successful cost reduction would enable the expansion of such projects to more regions and result in increased profitability.

Rani et al. [50] emphasizes the importance of aligning system performance capacity with safety requirements, ensuring that safety systems are adequate to fully meet energy demands. Aljeddani & Mohammed [7] applied the Weibull distribution method to wind speed analysis, discovering significant deviations from average speeds that must be considered in offshore project development and management. Edesess et al. [23] highlight that higher operational and maintenance costs are major challenges that adversely affect profitability and must be addressed in project planning. Xu et al. [3] categorize the challenges identified in their study into three types, operational, technological, and financial, each of which must be addressed at every stage to improve the efficiency of the project. Chaithanya et al. [17] propose a control system based on load and energy requirements, which enables automatic management of disruptions, thus enhancing plant stability. Bhattacharjee et al. [1] underscores the role of technological innovation in improving the long-term profitability of projects, based on an analysis of an Indian project, suggesting that such innovations could be replicated in other projects in India for better performance. Gao et al. [25] observed that island countries have significant locational advantages for offshore wind energy, a perspective that should also be applied to Indian islands to leverage their unique geographical benefits.

Rybak et al. [52] point out that the production and operation of offshore wind energy plants require significant electricity, an aspect that must be considered in terms of both availability and cost. Kou et al. [37] emphasize the extensive operation and maintenance needs of these projects, recommending that these factors be considered during the simulation stages and factored into the planning for several years prior to actual deployment in any region. For the implementation and operation of offshore wind projects, Alham et al. [6] state that the average wind speed and the cost of energy production are both critical factors. In instances where wind power fails to secure a market customer, Zhang et al. [62] examine the critical role that government support plays in fostering private participation, including the use of energy buyback agreements. The main strategies for promoting offshore wind energy, according to Irfan et al. [31], are total energy demand and government incentives. Putuhena et al. [49] suggested a significant potential application for floating wind projects in India in their analysis of the challenge of water depth. Furthermore, to ensure optimal operation and maintenance, Futai et al. [24] emphasize the importance of measuring and analysing the natural frequency of the turbines and the geographical conditions of the project site on a regular basis.

IV. DISCUSSION AND FINDINGS

Efficient approaches to tackling the technical obstacles encountered by offshore wind power facilities have been defined in several studies [66]. Initially, innovation and the implementation of cutting-edge technology are vital. Floating turbines, which can function in deeper waters characterised by stronger and more consistent wind velocities, could be an example of how this approach could be implemented in the form of larger and more efficient wind installations. In addition, to improve overall dependability, turbine performance can be optimised by implementing advanced monitoring and control systems. Furthermore, to ensure the longevity and effectiveness of offshore wind turbines, it is critical to implement rigorous inspection and maintenance procedures. Preventing expensive failures through timely maintenance and restorations, routine inspections utilising underwater robots, remote sensors, and drones can detect potential issues in their nascent stages. Additionally, proactive maintenance scheduling is made possible through the use of predictive maintenance techniques, such as condition monitoring and data analytics, which forecast equipment failures. Ultimately, to maximize the contribution of offshore wind power to energy balance, it is vital that the grid and infrastructure be better integrated. This involves improving the efficiency of transmission and distribution systems to establish connections between offshore wind farms and power infrastructures. Ensuring a consistent and reliable power supply can be accomplished by allocating resources toward energy storage solutions, such as hydrogen production or battery technology. Offshore wind farms can make substantial contributions to the transition towards sustainable energy futures by directing their attention toward technological advances, maintenance, and utility integration.

The offshore wind power sector faces significant financial challenges, as discussed in this study and corroborated by research by Shields et al. [67] and Wei et al. [68]. To mitigate these challenges, several strategies can be employed. First, capitalizing on economies-of-scale and cost-saving measures can substantially reduce the capital costs associated with offshore wind projects. This can be achieved by installing larger turbines, which offer efficiency gains and lower the cost per megawatt of installation. In addition, standardizing designs and harmonizing construction processes between projects can further reduce development costs. Second, securing favorable financing arrangements and incentives is crucial to mitigate financial risks. Offshore wind project developers may be encouraged to commit to such ventures through the use of government incentives such as feed-in tariffs and tax credits. Furthermore, to mitigate perceived project risks and reduce financing expenses, the establishment of stable and transparent regulatory frameworks can enhance investor confidence. Lastly, promoting collaboration and partnerships within the industry can improve efficiency and cost effectiveness. By sharing knowledge, transferring technology, and combining resources, stakeholders can take advantage of their collective expertise to mitigate similar risks and reduce overall costs in offshore wind power generation.

In conclusion, by focusing on reducing expenses, securing beneficial financial arrangements, and fostering cooperative initiatives, offshore wind farms can address their economic challenges and emerge as a viable and environmentally friendly renewable energy source. This study offers valuable information for policymakers and government agencies, guiding them to identify and address technical and financial challenges, thus improving efficiency and profitability in the sector.

V. CONCLUSIONS AND FUTURE RESEARCH AGENDA

There is a significant potential for offshore wind energy to satisfy industrial and residential energy requirements. It is generated through wind farms situated in the depths of the oceans and seas. This study assesses the viability of such plants and identifies various risks and challenges they face within the Indian context and the global ecosystem. The main identified challenges can be broadly categorized into three main areas: operational, technical, and financial. Each category represents significant risks that could impact the profitability and operational efficiency of the plants. These challenges require thorough consideration at every stage of operation, given their potential to adversely affect profitability and, consequently, the overall functioning of the plants. The study also explores several mitigation strategies; however, it is important to note that the suitability of these strategies will vary depending on the specific attributes of each plant, including geographical location, technology used, and financial factors.

Ultimately, this study provides a comprehensive review and underscores the need to develop customized solutions that align with the unique aspects of each project and the long-term objectives of the plant. This study faces several limitations that could impact the reliability and precision of its findings. First, the analysis is based primarily on secondary data, observations, and simulations previously conducted by scholars. Such methods might not capture the dynamic characteristics of offshore wind energy in their entirety, thereby limiting the accuracy. Moreover, historical wind patterns are taken into account, which might not precisely mirror present or forthcoming meteorological and geographical circumstances; thus, the dependability of the results could be compromised. Another limitation arises from the selection criteria for the literature review. The study only includes articles published between 2016 and 2024, written in English and openly accessible. Consequently, significant insights from studies that do not meet these criteria, including potentially valuable non-English research or more recent findings post-2024, are omitted. The aforementioned omission may impede the development of a holistic understanding of the hazards and countermeasures relevant to offshore wind energy projects in India. Furthermore, due to its emphasis on preexisting literature, the study fails to integrate primary data from every prospective offshore wind energy site in India. This omission is a critical limitation, as it could lead to a lack of site-specific information, which is crucial to understanding the feasibility and challenges of developing offshore wind plants in these areas. Future research could potentially improve the reliability and completeness of the study by incorporating primary data analyzes and broadening the scope to encompass a more diverse array of studies, including those published beyond the specified time period and in languages other than the one utilized.

To enhance the validity and applicability of their own work, future researchers should take into account the limitations identified in the present study. By gathering data from various offshore wind centres and formulating strategic frameworks to assess the viability and advancement of novel plants, they are motivated to expand on the models that have been established in this research. Furthermore, it would be beneficial for future scholars to adopt a qualitative methodology that not only includes data simulation and observations but also incorporates interviews. Such interviews should aim to capture diverse perspectives from key stakeholders, such as plant managers, government officials, and financiers. This approach will provide a deeper understanding of how stakeholders perceive risks and prepare for risk management and mitigation. Furthermore, comparative analyses of offshore wind power facilities in various countries should be an integral part of future research. This would facilitate the recognition of distinctive technological and geographical attributes and allow the extraction of insights that can be implemented in the Indian context to further its objectives related to renewable energy. Such research has the potential to shed light on the pivotal elements that impact the achievements and obstacles encountered in offshore wind energy endeavours globally, as well as propose practical approaches that can be implemented in India. In summary, as part of the larger transition towards renewable energy sources, policymakers and business executives should familiarize themselves with and consider the substantial potential of offshore wind energy in India. Further investigation and improvement of the risks and mitigation approaches deliberated in this study should be the focus of future research efforts within the renewable energy industry, with the ultimate objective of optimizing performance and achieving desired results.

References

[1] Bhattacharjee, P., Jana, R. K., & Bhattacharya, S. (2022). Boosting the annual profit of an offshore wind farm in India with a bio-inspired meta-heuristic scheme. Environmental Challenges, 9, 100642.

[2] Katsanos, E. I., Sanz, A. A., Georgakis, C. T., & Thöns, S. (2017). Multi-hazard response analysis of a 5MW offshore wind turbine. Procedia engineering, 199, 3206-3211.

[3] Xu, Y., Yang, K., & Zhao, G. (2021). The influencing factors and hierarchical relationships of offshore wind power industry in China. Environmental Science and Pollution Research, 28(37), 52329-52344.

[4]Global Wind Energy Council. (2024). Global Wind Report 2024. https://gwec.net/wp-content/uploads/2024/04/GWR-2024_digital-version_final-1.pdf

[5] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., ... & Moher, D. (2021). Updating guidance for reporting systematic reviews: development of the PRISMA 2020 statement. Journal of clinical epidemiology, 134, 103-112.

[6] Alham, M. H., Gad, M. F., & Ibrahim, D. K. (2023). Potential of wind energy and economic assessment in Egypt considering optimal hub height by equilibrium optimizer. Ain Shams Engineering Journal, 14(1), 101816.

[7] Aljeddani, S. M., & Mohammed, M. A. (2023). A novel approach to Weibull distribution for the assessment of wind energy speed. Alexandria Engineering Journal, 78, 56-64.

[8] Antoniou, M., Kourkoulis, R., Gelagoti, F., & Anastasopoulos, I. (2022). Simplified method for performance-based seismic design of suction caissons supporting jacket offshore wind turbines. Soil Dynamics and Earthquake Engineering, 155, 107169.

[9] Attig-Bahar, F., Ritschel, U., Akari, P., Abdeljelil, I., & Amairi, M. (2021). Wind energy deployment in Tunisia: Status, drivers, barriers and research gaps—A comprehensive review. Energy Reports, 7, 7374-7389.

[10] Badihi, H., Zhang, Y., & Hong, H. (2016). Model-based active fault-tolerant cooperative control in an offshore wind farm. Energy Procedia, 103, 46-51.

[11] Başaran, H. H., & Tarhan, İ. (2022). Investigation of offshore wind characteristics for the northwest of Türkiye region by using multi-criteria decision-making method (MOORA). Results in Engineering, 16, 100757.

[12] Bharani, R., & Sivaprakasam, A. (2022). A meteorological data set and wind power density from selective locations of Tamil Nadu, India: Implication for installation of wind turbines. Total Environment Research Themes, 3, 100017.

[13] Bosch, J., Staffell, I., & Hawkes, A. D. (2018). Temporally explicit and spatially resolved global offshore wind energy potentials. Energy, 163, 766-781.

[14] Carreno-Madinabeitia, S., Ibarra-Berastegi, G., Sáenz, J., & Ulazia, A. (2021). Long-term changes in offshore wind power density and wind turbine capacity factor in the Iberian Peninsula (1900–2010). Energy, 226, 120364.

[15] Cerfontaine, B., White, D., Kwa, K., Gourvenec, S., Knappett, J., & Brown, M. (2023). Anchor geotechnics for floating offshore wind: Current technologies and future innovations. Ocean Engineering, 279, 114327.

[16] Cevasco, D., Koukoura, S., & Kolios, A. J. (2021). Reliability, availability, maintainability data review for the identification of trends in offshore wind energy applications. Renewable and Sustainable Energy Reviews, 136, 110414.

[17] Chaithanya, S., Reddy, V. N. B., & Kiranmayi, R. (2019). Modeling & analysis of grid-tied PMA based offshore wind energy system using PSCAD/EMTDC. Ain Shams Engineering Journal, 10(2), 411-417.

[18] Chaurasiya, P. K., Warudkar, V., & Ahmed, S. (2019). Wind energy development and policy in India: A review. Energy Strategy Reviews, 24, 342-357.

[19] Costoya, X., DeCastro, M., Carvalho, D., Arguilé-Pérez, B., & Gómez-Gesteira, M. (2022). Combining offshore wind and solar photovoltaic energy to stabilize energy supply under climate change scenarios: A case study on the western Iberian Peninsula. Renewable and Sustainable Energy Reviews, 157, 112037.

[20] Dawn, S., Tiwari, P. K., Goswami, A. K., Singh, A. K., & Panda, R. (2019). Wind power: Existing status, achievements and government's initiative towards renewable power dominating India. Energy Strategy Reviews, 23, 178-199.

[21] Debnath, B., Shakur, M. S., Siraj, M. T., Bari, A. M., & Islam, A. R. M. T. (2023). Analyzing the factors influencing the wind energy adoption in Bangladesh: A pathway to sustainability for emerging economies. Energy Strategy Reviews, 50, 101265.

[22] Dinh, Q. V., Mosadeghi, H., Pereira, P. H. T., & Leahy, P. G. (2023). A geospatial method for estimating the levelised cost of hydrogen production from offshore wind. International Journal of Hydrogen Energy, 48(40), 15000-15013.

[23] Edesess, A. J., Kelliher, D., Borthwick, A. G., & Thomas, G. (2017). Improving global accessibility to offshore wind power through decreased operations and maintenance costs: a hydrodynamic analysis. Energy Procedia, 138, 1055-1060.

[24] Futai, M. M., Haigh, S. K., & Madabhushi, G. S. (2021). Comparison of the dynamic responses of monopiles and gravity base foundations for offshore wind turbines in sand using centrifuge modelling. Soils and Foundations, 61(1), 50-63.

[25] Gao, A. M. Z., Huang, C. H., Lin, J. C., & Su, W. N. (2021). Review of recent offshore wind power

strategy in Taiwan: Onshore wind power comparison. Energy Strategy Reviews, 38, 100747.

[26] Gönül, Ö., Duman, A. C., Deveci, K., & Güler, Ö. (2021). An assessment of wind energy status, incentive mechanisms and market in Turkey. Engineering Science and Technology, an International Journal, 24(6), 1383-1395.

[27] Govindan, K. (2023). Pathways to low carbon energy transition through multi criteria assessment of offshore wind energy barriers. Technological Forecasting and Social Change, 187, 122131.

[28] Guo, X., Chen, X., Chen, X., Sherman, P., Wen, J., & McElroy, M. (2023). Grid integration feasibility and investment planning of offshore wind power under carbon-neutral transition in China. Nature Communications, 14(1), 2447.

[29] Hasan, M., Dey, P., Janefar, S., Salsabil, N. A., Khan, I. J., Arefin, A., & Farrok, O. (2024). A critical analysis of wind energy generation potential in different regions of Bangladesh. Energy Reports, 11, 2152-2173.

[30] Hughes, L., & Longden, T. (2024). Offshore wind power in the Asia-Pacific: Expert elicitation on costs and policies. Energy Policy, 184, 113842.

[31] Irfan, M., Zhao, Z. Y., Ahmad, M., & Mukeshimana, M. C. (2019). Critical factors influencing wind power industry: A diamond model based study of India. Energy Reports, 5, 1222-1235.

[32] Jansen, M., Beiter, P., Riepin, I., Müsgens, F., Guajardo-Fajardo, V. J., Staffell, I., ... & Kitzing, L. (2022). Policy choices and outcomes for offshore wind auctions globally. Energy Policy, 167, 113000.

[33] Jensen, P. D., Purnell, P., & Velenturf, A. P. (2020). Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind. Sustainable Production and Consumption, 24, 266-280.

[34] Jolly, S., Spodniak, P., & Raven, R. P. J. M. (2016). Institutional entrepreneurship in transforming energy systems towards sustainability: Wind energy in Finland and India. Energy Research & Social Science, 17, 102-118.

[35] Jose, N. M., & Mathai, A. (2016). A study on lateral deformation of monopile of offshore wind turbine due to environmental loads. Procedia technology, 24, 287-294.

[36] Kang, S., Khanjari, A., You, S., & Lee, J. H. (2021). Comparison of different statistical methods used to estimate Weibull parameters for wind speed contribution in nearby an offshore site, Republic of Korea. Energy Reports, 7, 7358-7373.

[37] Kou, L., Li, Y., Zhang, F., Gong, X., Hu, Y., Yuan, Q., & Ke, W. (2022). Review on monitoring, operation and maintenance of smart offshore wind farms. Sensors, 22(8), 2822.

[38] Langer, J., Simanjuntak, S., Pfenninger, S., Laguna, A. J., Lavidas, G., Polinder, H., ... & Blok, K. (2022). How offshore wind could become economically attractive in low-resource regions like Indonesia. Iscience, 25(9).

[39] Lu, T., Sherman, P., Chen, X., Chen, S., Lu, X., & McElroy, M. (2020). India’s potential for integrating solar and on-and offshore wind power into its energy system. Nature communications, 11(1), 4750.

[40] Macrander, A. M., Brzuzy, L., Raghukumar, K., Preziosi, D., & Jones, C. (2022). Convergence of emerging technologies: Development of a risk-based paradigm for marine mammal monitoring for offshore wind energy operations. Integrated Environmental Assessment and Management, 18(4), 939-949.

[41] Martinez, A., & Iglesias, G. (2024). Global wind energy resources decline under climate change. Energy, 288, 129765.

[42] Mejia, A. H., Brouwer, J., & Copp, D. A. (2023). Performance and dynamics of California offshore wind alongside Western US onshore wind and solar power. Renewable Energy Focus, 47, 100490.

[43] Mitchell, D., Blanche, J., Harper, S., Lim, T., Gupta, R., Zaki, O., ... & Flynn, D. (2022). A review: Challenges and opportunities for artificial intelligence and robotics in the offshore wind sector. Energy and AI, 8, 100146.

[44] Nagababu, G., Simha, R. R., Naidu, N. K., Kachhwaha, S. S., & Savsani, V. (2016). Application of OSCAT satellite data for offshore wind power potential assessment of India. Energy Procedia, 90, 89-98.

[45] Pelser, T., Weinand, J. M., Kuckertz, P., McKenna, R., Linssen, J., & Stolten, D. (2023). Reviewing accuracy & reproducibility of large-scale wind resource assessments. Advances in Applied Energy, 100158.

[46] Potisomporn, P., Adcock, T. A., & Vogel, C. R. (2023). Evaluating ERA5 reanalysis predictions of low wind speed events around the UK. Energy Reports, 10, 4781-4790.

[47] Poulsen, T., & Lema, R. (2017). Is the supply chain ready for the green transformation? The case of offshore wind logistics. Renewable and sustainable energy reviews, 73, 758-771.

[48] Prasad, K. M., Nagababu, G., & Jani, H. K. (2023). Enhancing offshore wind resource assessment with LIDAR-validated reanalysis datasets: A case study in Gujarat, India. International Journal of Thermofluids, 18, 100320.

[49] Putuhena, H., White, D., Gourvenec, S., & Sturt, F. (2023). Finding space for offshore wind to support net zero: A methodology to assess spatial constraints and future scenarios, illustrated by a UK case study.

Renewable and Sustainable Energy Reviews, 182, 113358.

[50] Rani, P., Mishra, A. R., Cavallaro, F., & Alrasheedi, A. F. (2024). Location selection for offshore wind power station using interval-valued intuitionistic fuzzy distance measure-RANCOM-WISP method. Scientific Reports, 14(1), 4706.

[51] Ranthodsang, M., Waewsak, J., Kongruang, C., & Gagnon, Y. (2020). Offshore wind power assessment on the western coast of Thailand. Energy Reports, 6, 1135-1146.

Rueda-Bayona, J. G., Guzmán, A., & Eras, J. J. C. (2019). Wind and power density data of strategic offshore locations in the Colombian Caribbean coast. Data in brief, 27.

[52] Rybak, A., Rybak, A., & Kolev, S. D. (2024). Development of wind energy and access to REE. The case of Poland. Resources Policy, 90, 104723.

[53] Santhakumar, S., Heuberger-Austin, C., Meerman, H., & Faaij, A. (2023). Technological learning potential of offshore wind technology and underlying cost drivers. Sustainable Energy Technologies and Assessments, 60, 103545.

[54] Santhakumar, S., Smart, G., Noonan, M., Meerman, H., & Faaij, A. (2022). Technological progress observed for fixed-bottom offshore wind in the EU and UK. Technological Forecasting and Social Change, 182, 121856.

[55] Sharma, S., & Sinha, S. (2019). Indian wind energy & its development-policies-barriers: An overview. Environmental and Sustainability Indicators, 1, 100003.

[56] Sherman, P., Chen, X., & McElroy, M. (2020). Offshore wind: An opportunity for cost-competitive decarbonization of China’s energy economy. Science advances, 6(8), eaax9571.

[57] Siram, O., Sahoo, N., & Saha, U. K. (2022). Changing landscape of india's renewable energy and the contribution of wind energy. Cleaner Engineering and Technology, 8, 100506.

[58] Srinivas, B. A., Nagababu, G., & Kachhwaha, S. S. (2022). Future wind speed trends in the Indian offshore region. Energy Reports, 8, 513-519.

[59] Tuy, S., Lee, H. S., & Chreng, K. (2022). Integrated assessment of offshore wind power potential using Weather Research and Forecast (WRF) downscaling with Sentinel-1 satellite imagery, optimal sites, annual energy production and equivalent CO2 reduction. Renewable and Sustainable Energy Reviews, 163, 112501.

[60] van der Loos, H. A., Negro, S. O., & Hekkert, M. P. (2020). International markets and technological innovation systems: The case of offshore wind. Environmental Innovation and Societal Transitions, 34, 121-138.

[61] Zhang, H., Yang, J., Ren, X., Wu, Q., Zhou, D., & Elahi, E. (2020). How to accommodate curtailed wind power: A comparative analysis between the US, Germany, India and China. Energy Strategy Reviews, 32, 100538.

[62] Zhang, J., Lu, J., Pan, J., Tan, Y., Cheng, X., & Li, Y. (2022). Implications of the development and evolution of global wind power industry for China—An empirical analysis is based on public policy. Energy Reports, 8, 205-219.

[63] Zhang, Z., Liu, X., Zhao, D., Post, S., & Chen, J. (2023). Overview of the development and application of wind energy in New Zealand. Energy and Built Environment, 4(6), 725-742.

[64] Zou, X., Qiu, R., Yuan, M., Liao, Q., Yan, Y., Liang, Y., & Zhang, H. (2021). Sustainable offshore oil and gas fields development: Techno-economic feasibility analysis of wind–hydrogen–natural gas nexus. Energy Reports, 7, 4470-4482.

[65] Đukan, M., & Kitzing, L. (2021). The impact of auctions on financing conditions and cost of capital for wind energy projects. Energy Policy, 152, 112197.

[66] Micallef, D., & Rezaeiha, A. (2021). Floating offshore wind turbine aerodynamics: Trends and future challenges. Renewable and Sustainable Energy Reviews, 152, 111696.

[67] Shields, M., Beiter, P., Nunemaker, J., Cooperman, A., & Duffy, P. (2021). Impacts of turbine and plant upsizing on the levelized cost of energy for offshore wind. Applied Energy, 298, 117189.

[68] Wei, Y., Zou, Q. P., & Lin, X. (2021). Evolution of price policy for offshore wind energy in China: Trilemma of capacity, price and subsidy. Renewable and Sustainable Energy Reviews, 136, 110366.