IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 9 April 2024, accepted 30 April 2024, date of publication 6 May 2024, date of current version 16 May 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3397243

TOPICAL REVIEW

Winds of Progress: An In-Depth Exploration of Offshore, Floating, and Onshore Wind Turbines as Cornerstones for Sustainable Energy Generation and Environmental Stewardship

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This work was supported in part by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education under Grant 2020R1A2C1004743; and in part by the Deanship of Scientific Research, Northern Border University, Arar, Saudi Arabia, under Project NBU-FFR-2024-1475-07.

ABSTRACT This research paper conducts an extensive exploration of onshore, offshore, and floating offshore wind turbines, pivotal components in the landscape of sustainable energy generation. The study thoroughly investigates various wind energy systems, shedding light on their distinct attributes, advantages, and limitations. The examination of onshore wind turbines encompasses aspects such as installation procedures, size considerations, wind dynamics, accessibility challenges, and visual impact assessments. Similarly, the analysis of offshore wind turbines covers considerations such as location selection, installation complexities, size variations, wind conditions, environmental impacts, and visual aesthetics. The paper also delves into the emerging technology of floating offshore wind turbines, highlighting their unique features, advantages, and technological advancements. A thorough comparative examination is conducted to assess the economic, environmental, and social aspects of onshore, offshore, and floating offshore wind turbines. The research paper concludes by offering insights into policy considerations, addressing research gaps, and outlining prospects for the seamless integration and advancement of these diverse wind energy systems. This comprehensive review aspires to contribute to the existing knowledge base in sustainable energy generation, fostering informed decision-making for a greener and more sustainable future.

INDEX TERMS Renewable energy technologies, sustainable energy generation, comparative analysis, onshore wind turbines, floating offshore wind turbines, offshore wind turbines.

The associate editor coordinating the review of this manuscript and approving it for publication was R. K. Saket.

I. INTRODUCTION

Recently, there has been remarkable growth in the onshore wind energy industry, with many countries planning for further expansion [1]. Wind energy has appeared as a viable unconventional to fossil fuel combustion, offering the potential to significantly reduce greenhouse gas production and establish itself as a dominant renewable energy source [2]. Nevertheless, onshore wind turbines, while contributing significantly to renewable energy generation, are not without their drawbacks. These limitations include visual effects on the landscape, as the towering structures modify the natural scenery, potentially impacting the aesthetic attractiveness of the surroundings. Onshore wind turbines can generate noise disturbances, which may pose challenges for nearby residents. Concerns arise regarding the ecological effects on birdlife and the environment, as the rotating blades can pose risks to local wildlife [3].

Balancing the benefits of onshore wind energy with these drawbacks remains a key consideration in the broader context of sustainable energy solutions [5]. The multitude of considerations, encompassing visual impact, noise disturbances, and ecological implications, renders the task of identifying suitable sites for future onshore wind development increasingly challenging. Striking a balance between harnessing the benefits of renewable energy and mitigating the adverse effects on landscapes, local communities, and wildlife becomes a complex endeavor. Conducting comprehensive assessments and engaging the community in the site selection process is essential for effectively addressing these challenges. With the increasing demand for sustainable energy solutions, addressing these factors becomes essential to ensure the responsible and efficient growth of onshore wind projects [6].

Energy planners have shifted their attention to the expansive offshore wind resources as a solution to meet growing energy demands. While offshore wind turbines address noise concerns associated with onshore counterparts, visual disamenity persists as a worry. The decision between onshore and offshore wind power generation is influenced, to some extent, by public acceptance. Surprisingly, despite ongoing discussions about the impacts of wind power, there has been a notable absence of a comprehensive analysis that considers attitudes towards both onshore and offshore wind development together. This gap in understanding poses a challenge for energy planners seeking to efficiently strike a balance between onshore and offshore wind development [7], [8]. Figure 1 categorizes wind farms into onshore, offshore, floating, hybrid, community, and small-scale types, highlighting their distinct features and locations. Renewable energy sources play a crucial role in the global pursuit of sustainable energy generation [4]. While discussions continue to delve into the diverse impacts of wind power, there remains a significant gap in the comprehensive and systematic analysis of attitudes toward both onshore and offshore wind development collectively. This absence of a unified assessment hinders a holistic understanding of the preferences and concerns of the public, impeding the development of effective strategies and policies that strike a balance between onshore and offshore wind projects. Addressing this analytical gap is essential for fostering informed decision-making in the renewable energy sector and promoting sustainable energy solutions [9].

The significance of wind energy lies in its pivotal role in addressing pressing global issues, particularly climate change and the imperative for sustainable energy sources. Wind power emerges as a crucial component of the clean energy transition, offering a renewable alternative that significantly reduces greenhouse gas emissions compared to conventional fossil fuels. By harnessing the natural power of the wind, this form of energy contributes to mitigating climate change impacts and lessening dependence on finite resources. The scalability and environmental benefits of wind energy underscore its potential to reshape the energy landscape, making it an essential element in the quest for a more sustainable and resilient future [10]. The inherent eco-friendly nature of wind energy aligns with the urgent need to shift towards cleaner energy sources, providing a tangible solution to address environmental concerns and promote a more sustainable energy future [11]. The heightened focus on renewable energies has stemmed from a confluence of factors, among which a prominent catalyst is the recognition of global warming directly linked to carbon dioxide emissions resulting from the combustion of fossil fuels. Scientific consensus attributing climate change to human activities, particularly the burning of fossil fuels, has intensified the urgency to transition towards cleaner energy alternatives. The undeniable impact of carbon emissions on the Earth's climate has prompted a paradigm shift in energy policies globally. Governments, industries, and individuals alike are increasingly recognizing the imperative to reduce reliance on conventional fossil fuels and embrace sustainable alternatives like solar, wind, and hydropower. This acknowledgment of the environmental repercussions of fossil fuel consumption has become a driving force behind the worldwide push for a more sustainable and resilient energy landscape [12].

The momentum behind the advancement of renewable energy has been significantly bolstered by the introduction of greenhouse gas emissions limits, a key component of international agreements such as the Kyoto Protocol. As environmental consciousness has risen globally, the imperative to curb carbon emissions has driven nations to seek cleaner energy alternatives, catalyzing a shift towards renewable sources. Simultaneously, concerns surrounding the environmental and safety aspects of traditional nuclear power have added impetus to the development and adoption of renewable energy technologies. Furthermore, the escalating energy demand, coupled with the anticipation of its resurgence following the end of economic crises, has underscored the critical importance of transitioning to renewable energy solutions [13]. The landscape of onshore wind turbine suppliers is shaped by key players operating in strategic regions such

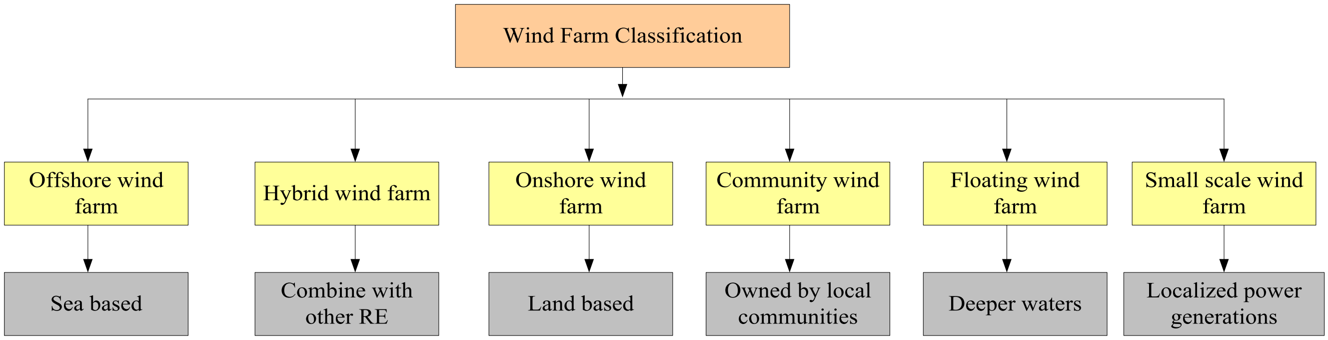


FIGURE 1. **Classification of distinct types of wind farms [4].**

as the European Union, China, India, and the United States. In the pivotal year of 2018, certain manufacturers stood out as industry leaders, contributing significantly to the global onshore wind energy market. Among these notable manufacturers was Vestas, based in Denmark, renowned for its technological innovation and market presence. China's Gold wind emerged as a major player, reflecting the country's growing influence in the renewable energy sector. Siemens Gamesa, German-Spanish collaboration, showcased its expertise in wind turbine manufacturing, while GE (General Electric) from the United States demonstrated its commitment to advancing onshore wind technology. These manufacturers collectively play a crucial role in shaping the onshore wind energy landscape, contributing to the global effort to transition towards sustainable and clean energy solutions [14].

Wind energy involves the conversion of the kinetic energy inherent in the wind into either mechanical or electrical energy [15]. This process is typically achieved through the use of wind turbines, which are designed to capture the force of the wind and convert it into a usable form of power [16]. In the case of mechanical energy, wind turbines propel the rotation of blades connected to a shaft, which, in turn, activates a generator to produce electricity [17]. Alternatively, in electrical energy conversion, the rotational movement of the turbine directly powers a generator, producing electrical energy. This dual capability underscores the versatility of wind energy, providing a renewable and sustainable source that plays a crucial role in the global pursuit of cleaner and more environmentally friendly power generation [18]. Wind turbines serve as the fundamental devices responsible for capturing and converting the kinetic energy present in the wind into electricity. Comprising blades attached to a central hub, these turbines are strategically positioned to intercept the flow of the wind [19]. As the wind drives the rotation of the blades, the kinetic energy is transformed into mechanical energy. This mechanical energy is then transferred to a generator, where it undergoes further conversion into electricity [20]. The fundamental principle behind wind turbines underscores their crucial role in harnessing a clean and sustainable energy source, contributing significantly to the global effort to reduce reliance on fossil fuels and mitigate environmental impacts [21].

Onshore wind projects are often selected based on the accessibility of suitable land, wind speeds, and the overall cost-effectiveness of installation [22]. Factors such as local topography and land use regulations also play a significant role in determining the feasibility of onshore wind farms [23]. On the other hand, offshore wind projects are considered when there is a need to tap into wind resources over bodies of water, where wind speeds tend to be higher and more consistent [24]. Despite the higher installation and maintenance costs associated with offshore wind, the potential for increased energy production and the mitigation of land-use conflicts make it an attractive option in certain contexts [7]. Ultimately, the choice between onshore and offshore wind installations involves a careful consideration of these factors to optimize the efficiency and sustainability of wind energy projects [25].The utilization of wind energy has a rich historical legacy that extends over several millennia. The initial significant advancement in harnessing wind power for generating electricity occurred in 1888 with the development of a 12 kW turbine in Cleveland, Ohio, United States [26]. The primary adoption of onshore wind energy as a sustainable energy source can be primarily attributed to the abundant availability of wind resources and the comparatively advanced state of wind energy technology, as depicted in Figure 2 [27]. The significance of wind energy in fulfilling the obligations specified in international agreements, such as the Kyoto Protocol, is pivotal [28]. Yet, the successful fulfillment of these commitments requires the concurrent adoption of diverse measures, including the promotion of the construction of offshore wind farms [29].

Figure 2 depicts the flow diagram of the whole paper. This paper introduces a unique approach by conducting a comprehensive review of onshore, offshore, and floating offshore wind turbines for sustainable energy generation. The analysis delves into their distinctive features, encompassing factors such as installation procedures, size considerations, wind conditions, accessibility, and visual impact. A thorough understanding of each type of turbine is presented. The paper further conducts a comparative assessment to evaluate the

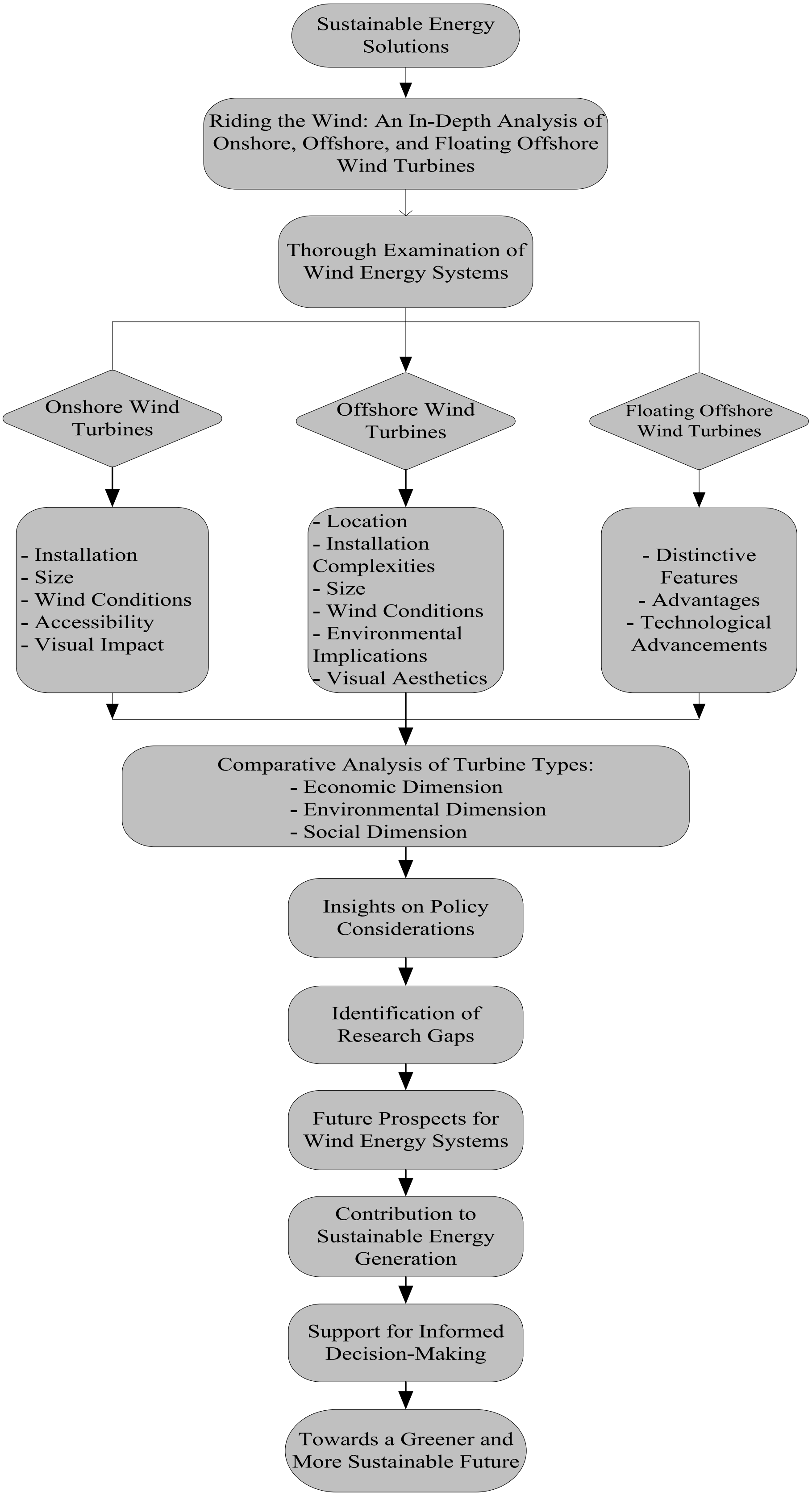


FIGURE 2. Flowchart of the research.

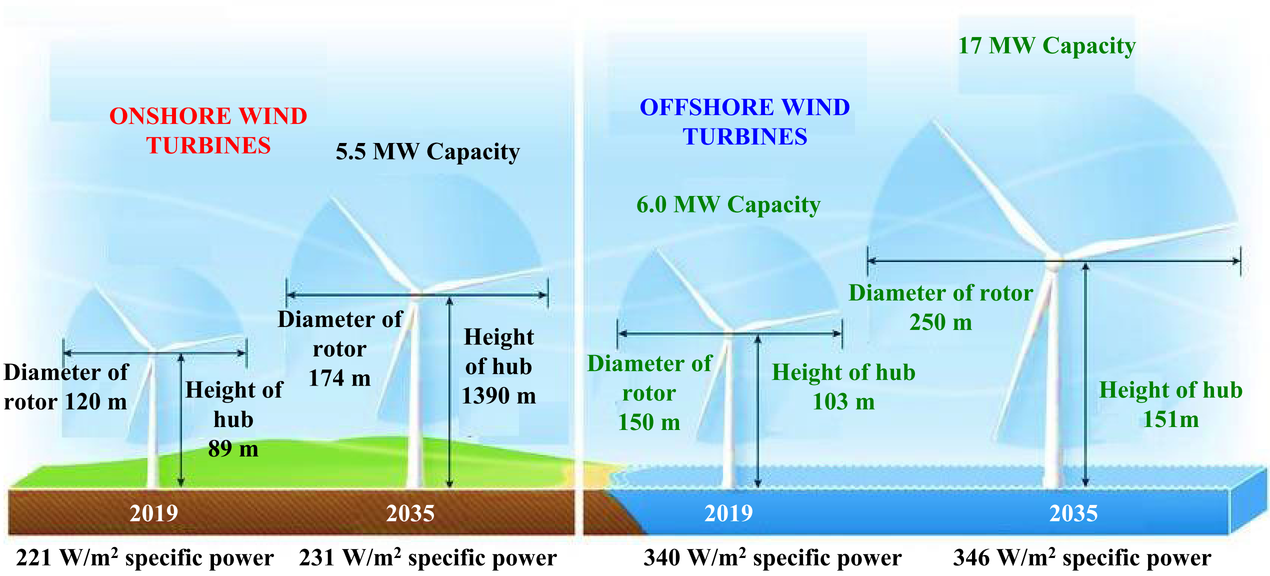


FIGURE 3. Global wind power forecast (2019-2035) [30].

economic viability, environmental consequences, and social acceptability of these wind energy systems. This evaluation encompasses costs associated with installation, operation, and maintenance, aiming to gauge competitiveness in the energy market. Additionally, the study investigates policy frameworks and financial incentives, exploring their roles in wind energy projects. The paper examines technology, components, design, and power generation aspects of wind turbines. It explores environmental and social impacts, along with government policies and incentives. Through a comparative analysis, the paper identifies strengths, weaknesses, opportunities, and threats. Scalability, energy potential, and integration are also taken into account in the assessment.

II. OFFSHORE WIND TURBINES

A. TURBINE DESIGN, FOUNDATION TYPES, AND INSTALLATION TECHNIQUES BASED ANALYSIS OF TECHNOLOGY RELATED TO OFFSHORE WIND TURBINES, COVERING ASPECTS

Offshore wind turbines can capture abundant wind resources found in oceanic seas. The technology for these turbines is attracting considerable interest as a potential renewable energy source [31]. Turbine design for offshore applications involves considerations such as larger rotor diameters [32], higher hub heights, and specialized design features to withstand harsh marine conditions illustrated in Figure 4 [33].

Offshore wind energy represents a recent and significant challenge in the worldwide wind industry, as illustrated by the current global installations totaling 8.76 GW, as indicated in Figure 5. This accounts for 2.4% of the total wind power capacity [34]. Europe emerges as the dominant player, contributing 8.1 GW (92.5% of the capacity), generating an annual output of 29.6 TWh. Among the fourteen nations engaged in offshore wind, the top five include the UK (4.49 GW), Denmark (1.27 GW), Germany (1.05 GW), Belgium (0.71 GW), and China (0.66 GW). Japan occupies the eighth position with a capacity of 50 MW [35].

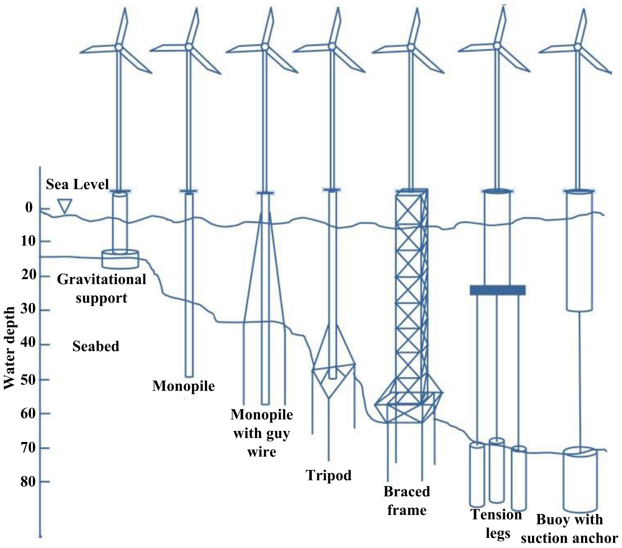


FIGURE 4. Options for the support structure or foundation of Offshore Wind Turbines [33].

Offshore wind energy boasts superior capacity factors, typically ranging from 20% to 40%, attributable to the enhanced wind speeds found at greater distances from the shore [36]. The challenges posed by deeper waters lead to escalated development and operational costs, counteracting the benefits in energy yield [37]. The economic feasibility of offshore projects aligns with their onshore counterparts, characterized

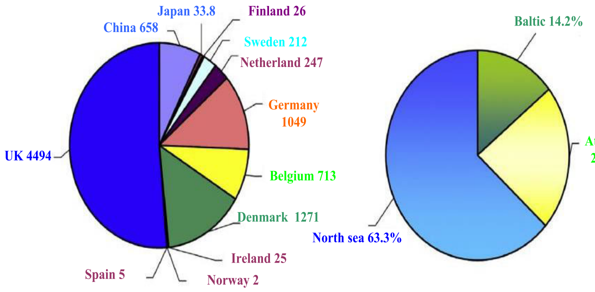


FIGURE 5. Global offshore capacity growth and the accumulated distribution by country [34].

by heightened capital and maintenance expenditures [38]. Progress persists in the pursuit of enhanced efficiency and cost-effectiveness within the wind energy sector. Ongoing research focuses on achieving higher turbine capacities, refining designs for increased reliability, and developing next-generation support structures [39].

B. OFFSHORE WIND TURBINES POTENTIAL AND ENVIRONMENTAL IMPACTS ON MARINE ECOSYSTEM

Assessing the environmental effects of offshore wind turbines is essential for promoting sustainability. Offshore wind farms play a crucial role in mitigating emissions, creating habitats, and contributing to the global effort to combat climate change [40]. While there are similarities in the effects of offshore wind farms compared to onshore counterparts, distinct differences warrant careful consideration. Uncertainty surrounds the impact of offshore installations on both plant and animal life, as the marine environment introduces unique challenges that necessitate specialized micro-siting analyses [41]. The construction and operation phases of offshore wind projects entail unique environmental implications. Encouragingly, the ecological consequences can prove beneficial for marine species, as these projects have the potential to create habitats and artificial reefs [42]. Nonetheless, detrimental impacts such as noise, toxic spills, and electromagnetic fields pose risks to marine organisms, as depicted in Figure 6.

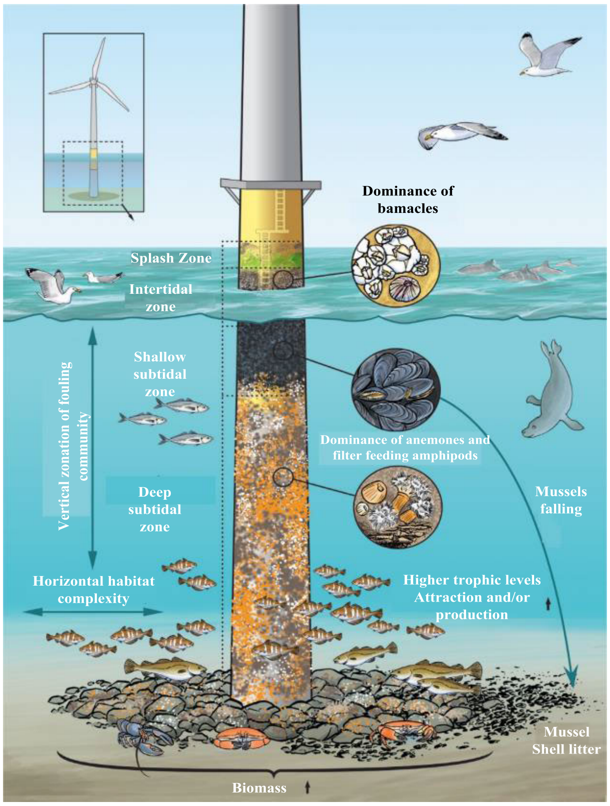


FIGURE 6. Effects of offshore wind installations on the marine. environment [43].

The influence of human-generated noise on marine species is contingent on factors such as the propagation of underwater sound, frequency characteristics, the hearing abilities of marine mammals, and the duration of noise exposure [44]. The evaluation of impacts on diverse species at different distances requires a comparison of received noise levels, spectral composition, hearing thresholds, and local ambient noise levels [45]. In extensive offshore wind farms, electricity is conveyed to an offshore substation through interconnected turbine cables, forming a collection circuit. Subsequently, the power is transmitted to the mainland grid through export cables [46]. The submarine cables carrying currents generate electromagnetic fields, potentially impacting marine organisms based on transmission methods, materials used, and water conductivity [47]. The construction phase has a notable impact on marine mammals and fish, primarily attributable to elevated noise levels. Pile-driving for foundation installation, a major contributor to this noise generates substantial sound during the construction of wind farms [48]. As an illustration, measurements taken during the construction of a wind farm in the UK indicated peak noise levels from pile hammering, reaching 260 dB at a depth of 5 meters and 262 dB at a depth of 10 meters [49]. In contrast, operational wind turbines generate minimal noise that is unlikely to harm marine hearing [50].

Public opinions regarding offshore installations vary depending on the location, making it challenging to arrive at definitive conclusions. This section highlights the societal and environmental impacts of offshore wind facilities, emphasizing the importance of thorough assessments to address potential drawbacks [51]. The issue of construction noise, which has adverse effects on marine life, requires the implementation of effective mitigation strategies [52]. To minimize the risk of bird and bat collisions with turbine structures, careful consideration of siting and designs is essential. Concerns related to benthic habitats and sediment can be managed through the application of control measures and regular monitoring [53]. Moreover, addressing the introduction of electromagnetic fields necessitates a comprehensive understanding and the formulation of effective mitigation measures [54]. By conducting thorough impact

TABLE 1. **Environmental impact of offshore wind turbines [56], [57], [58], [59].**

Environmental Considerations	Potential Impacts	Mitigation Strategies
Human-Generated Noise	The impact on marine species depends on factors like underwater sound propagation, frequency characteristics, marine mammals' hearing, and noise duration. Assessing effects on different species at varying distances involves comparing received levels, spectral composition, hearing thresholds, and local noise levels.	Monitoring and controlling noise levels during construction phases, using quieter installation methods, and implementing underwater noise reduction technologies.
Electromagnetic Fields	Submarine cables carrying currents create electromagnetic fields, potentially affecting marine organisms based on transmission, materials, and water conductivity.	Employing cable designs and materials that minimize electromagnetic field emissions, implementing monitoring programs to assess impacts on marine organisms, and exploring technologies to mitigate electromagnetic field exposure.
Construction Noise	Pile-driving for foundation installation, a major contributor, generates substantial noise during wind farm construction. Measurements during a UK wind farm's construction revealed peak pile hammering noise levels of 260 dB at 5 m depth and 262 dB at 10 m depth.	Implementing noise mitigation measures such as bubble curtains, and acoustic barriers, and scheduling construction activities to minimize noise impacts on marine life.
Operational Noise	Operational wind turbines produce minimal noise unlikely to harm marine hearing. Seals and porpoises were affected during construction, while operational phases showed no significant adverse effects. Fish studies suggest turbine operational noise poses minimal risk of hearing impairment.	Conducting ongoing monitoring of operational noise levels and their potential impacts on marine life, implementing noise-reduction technologies if necessary, and considering operational noise levels in future turbine designs.

assessments, continuous monitoring, and fostering collaboration, offshore wind farms have the potential to minimize adverse effects on marine ecosystems and maximize the benefits of renewable energy generation [55].

Table 1 summarizes the environmental considerations, potential impacts, and mitigation strategies related to offshore wind turbines' effects on marine ecosystems [56], [57], [58], [59].

C. DEVELOPMENT OF OFFSHORE WIND ENERGY BASED ON GOVERNMENT REGULATORY POLICIES

Governments are instrumental in establishing a supportive framework through the implementation of policies, regulations, and incentives for offshore wind energy [60]. Vital elements of this framework include the establishment of unambiguous licensing and permitting processes, the designation of offshore zones for wind energy development, and the assurance of transparent procedures for project approval [61]. Additionally, governments play a crucial role in promoting the development of grid connection and transmission infrastructure, thereby facilitating the seamless integration of offshore wind power into the broader electricity system [62].

In crafting forward-looking policies, governments can set ambitious yet attainable offshore wind targets, providing a clear roadmap for the industry's growth. By establishing concrete goals, policymakers not only inspire confidence within the sector but also create a framework for sustained progress and innovation [63]. Establishing a conducive environment for the growth of offshore wind energy requires a comprehensive suite of supportive policies. These measures encompass feed-in tariffs, renewable energy targets, tax incentives, and financial mechanisms strategically designed to allure investments and alleviate project risks [41]. Environmental regulations and thorough impact assessments are equally pivotal, serving as guardians against potential ecological repercussions and ensuring a trajectory of sustainable development [64]. Feed-in tariffs, as a supportive policy tool, guarantee a fixed payment to renewable energy producers for the electricity they generate. This incentivizes private investments in offshore wind projects, providing a stable and predictable income stream that fosters financial feasibility [65]. Tax incentives play a crucial role in reducing the financial burden on developers, making offshore wind projects more economically attractive. By offering tax credits and deductions, governments encourage private sector participation and facilitate the growth of the offshore wind industry [41].

D. CASE STUDIES BASED ANALYSIS OFFSHORE WIND PROJECT TOWARD SUSTAINABLE ENERGY GENERATION

Examining successful offshore wind projects underscores their pivotal contributions to sustainable energy generation [66]. The Block Island Wind Farm in the United States, operational since 2016, has been a trailblazer as the nation's first offshore wind farm, supplying clean electricity to over 17,000 homes annually and setting a precedent for future U.S. offshore wind developments [67]. Similarly, Denmark's

Horns Rev 3, one of the world's largest offshore wind farms since 2019, exemplifies the scalability and efficiency of such projects, annually providing electricity to approximately 425,000 Danish households and significantly contributing to the country's clean energy goals [68]. These case studies not only demonstrate the feasibility and impact of offshore wind ventures but also underscore their transformative role in advancing sustainable and renewable energy sources on a global scale [69].

Exemplifying the viability and scalability of offshore wind technology, the London Array offshore wind farm in the UK stands out as one of the world's largest projects of its kind [70]. Boasting an impressive 630 MW installed capacity, this initiative is a key player in curbing greenhouse gas emissions and driving the widespread adoption of clean energy [71]. Across the Atlantic, the Block Island Wind Farm in the United States holds its significance as the nation's pioneering offshore wind farm. Generating 30 MW, it not only supplies clean energy to numerous households but also plays a crucial role in advancing the state's renewable energy objectives [72]. These projects collectively showcase the tangible impact of offshore wind ventures in the global pursuit of sustainable and environmentally friendly energy sources [73].

III. FLOATING OFFSHORE WIND TURBINES

Utilizing floating platforms in deep waters, floating offshore wind turbine technology situates turbines in areas where fixed-bottom turbines are impractical, thereby expanding the potential of wind energy [75]. These platforms exploit more robust winds in deeper waters, aligning with objectives for clean energy. Accurate predictions become essential for location-specific design due to the continual evolution of technology [76]. Floating Offshore Wind Turbines (FOWTs) are increasingly capturing attention for their capability to harness the stronger and less turbulent winds found in deeper waters, thus creating opportunities for renewable energy generation in novel areas [77]. This growing interest is propelled by the increasing emphasis on integrating clean energy sources into the overall energy mix. Given the ongoing development of FOWT technology, precise forecasts of their performance are critical, particularly considering the necessity to customize their design for each specific location [78]. Upcoming turbine configurations prioritize stability over load-driven models, integrating advanced elements such as composites, flexible blades, smart structures, and rapid-response controls. Nevertheless, these enhancements might lead to instabilities due to intricate aero-servo-elastic interactions [79].

Identified instabilities encompass pitch-flap flutter and rotor-shaft whirl. The susceptibility to instabilities could be heightened for offshore turbines due to the supplementary hydrodynamic interactions introduced by ocean currents and surface waves [80]. The presence of instabilities, even marginal ones, poses the risk of swift failure or prolonged oscillations, which can induce fatigue or ultimate-load failure [81]. The key challenge lies in devising design and control strategies that eliminate these instabilities while simultaneously improving loads, performance, and cost-effectiveness [82]. In response to this demand, conceptual tiers were introduced in Table 2, with progress seen in the wind industry. Leading this, the world's first floating wind farm, Hywind, was established off the coast of Aberdeenshire, Scotland, in 2017 [83]. These innovative floating platforms are designed to maintain stability and secure anchoring through versatile mooring systems, allowing turbines to operate efficiently in challenging offshore conditions. The potential advantages of floating offshore wind turbines include access to more powerful and consistent winds in deep-water areas, resulting in increased energy generation and improved capacity factors [84].

TABLE 2. **Concepts of different levels.**

Concept	Year	Relevant literature
Hywind	2005-2009	[85]
WindFloat	2009-2022	[86-88]
DeepCwind	2010-2013	[89, 90]
Sway	2012-2016	[91, 92]
Blue H	2009-2019	[93, 94]

In the pursuit of advancing offshore wind technology, Figure 7 showcases three distinct designs with varying static stability strategies [74]. The Spar-buoy relies on ballast, the tension leg employs mooring lines, and the barge distinguishes itself by utilizing inherent buoyancy. This study focuses on the aeroelastic stability of the barge platform, which relies on its straightforward design, cost-effectiveness, and ease of installation as key motivators for exploration. It is crucial to note that aeroelastic instability, as discussed in the following section, is distinct from vibrations [95].

A. OFFSHORE WIND FARMS' SUITABILITY BASED ON DIFFERENT CLASSIFICATIONS OF FLOATING FOUNDATION

A significant portion, ranging from 25% to 35%, of the overall development cost of offshore wind power production is allocated to the foundations [96].

The selection of an appropriate foundation type is a complex decision influenced by a myriad of factors. These include site-specific conditions such as water depth and seabed characteristics, operational considerations like turbine size, loading characteristics, maintenance requirements, and access considerations [98]. The choice is intricately linked to available construction technologies for transport and installation, and crucially, economic costs. This overview aims to elucidate the spectrum of foundation solutions implemented over the past two decades, as illustrated in Figure 8 with brief descriptions of each [97].

Table 3 provides a detailed overview of various foundation types used in offshore wind energy projects. Each type has distinct advantages and considerations, making it essential for informed decision-making during wind farm planning and

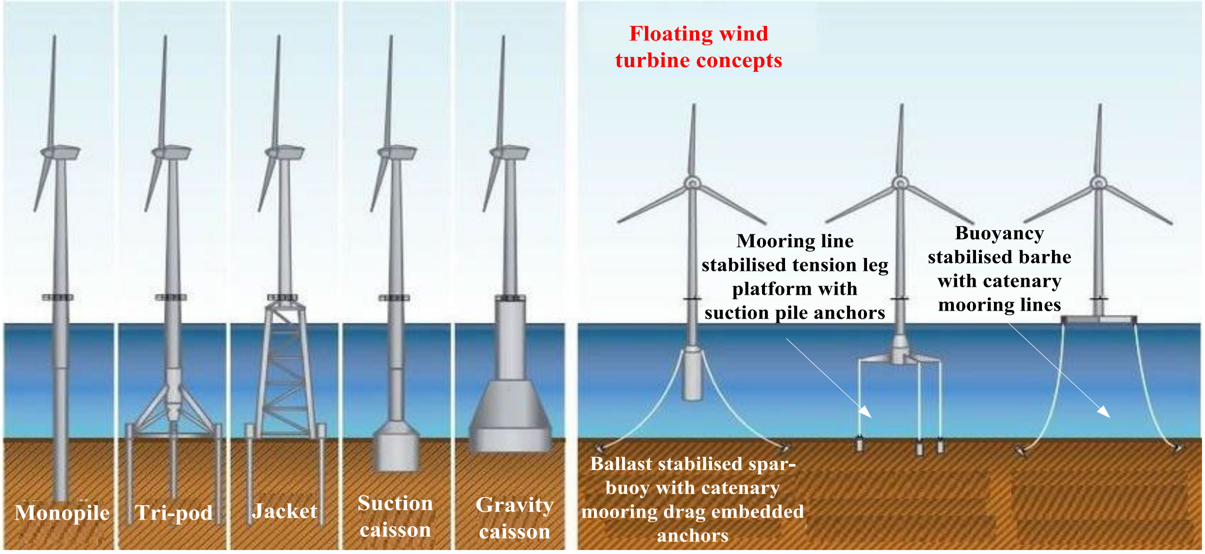


FIGURE 7. Floating wind turbine ideas [74].

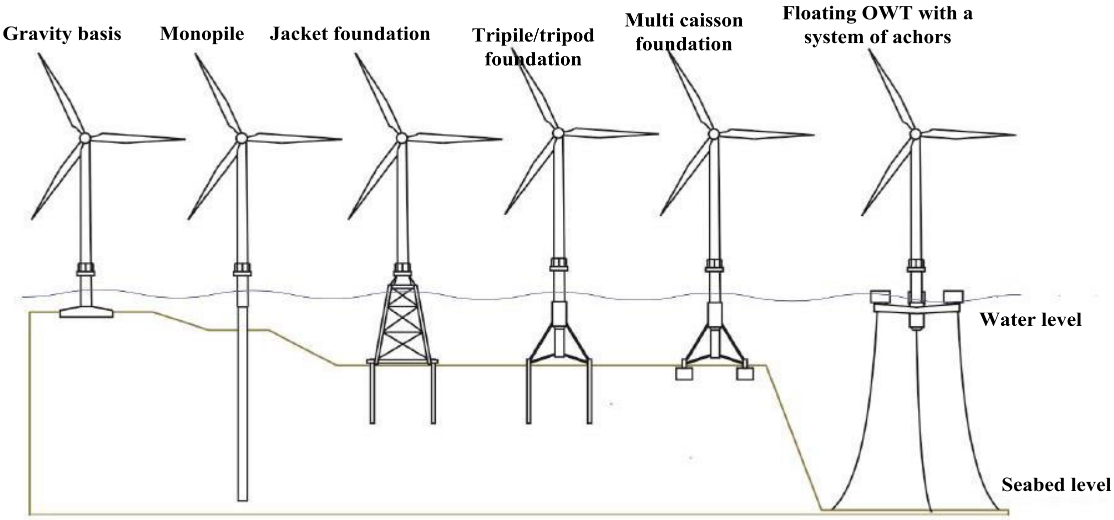


FIGURE 8. Typical offshore wind turbine foundations [97].

construction [84], [99], [100]. Various foundation systems play a pivotal role in supporting wind turbines offshore, offering diverse solutions to address specific environmental and operational challenges. The range includes fixed gravity base foundations (GBF), tripod structures, jackets, suction caissons, monopiles (MP), and buoyant fixed structures [101], [102]. Given the initial ambiguity about the foundation's geometry, an assumed size is typically chosen, and subsequently, the foundation response is evaluated. Should the assumed geometry fall short of meeting the ultimate or serviceability limit states, a new geometry is proposed. This iterative loop persists until an optimal foundation geometry is achieved, emphasizing the dynamic and adaptive approach inherent in the development of offshore wind projects [101], [103].

B. ANALYSIS OF THE CONTINUOUS RESEARCH AND DEVELOPMENT ENDEAVORS AIMED AT ENHANCING THE EFFICIENCY AND COST-EFFECTIVENESS OF FLOATING WIND TECHNOLOGIES

The ongoing exploration of research and development initiatives in the field of floating wind technologies marks a pivotal stage in the progression of offshore renewable energy. As scientists and engineers delve deeper into the possibilities of harnessing wind power in offshore environments, the advancements in floating wind technology hold great promise for the sustainable generation of clean energy. This critical phase underscores the industry's commitment to overcoming challenges and optimizing the efficiency of offshore wind farms, paving the way for a more resilient and environmentally friendly future. The continuous efforts

TABLE 3. Comparison of offshore wind turbine foundation types.

Foundation Type	Description	Suitable Water Depths	Advantages	Disadvantages
Monopile	Single cylindrical steel pile driven into seabed	Shallow water depths	• Cost-effective, widely used • Minimal site preparation	• Limited to shallow water • Not suitable for very deep water
Tripod/Truss	Three-legged base with a central column	Medium-to-deep water depths	• Stable, minimal site preparation • Ideal for certain soil conditions	• Not suitable for very deep water
TLP (Tension Leg Platform)	Multiple columns and pontoons anchored with mooring system	Deeper water depths	• Ideal for deep water • Good stability • Minimal seabed disturbance	• Complex installation and expensive • Challenging maintenance
Semi-submersible	Partially submerged structure with buoyant pontoons	Various water depths	• Versatile, adaptable to different conditions • Suitable for various seabed types	• Requires specialized construction • Challenging maintenance
Spar	Vertical cylinder that floats in water	Deep water depths	• Suitable for larger turbines • Good stability • Minimal seabed disturbance	• Requires specialized construction • Complex installation and expensive • Challenging maintenance

in this domain exemplify a collective dedication to shaping a sustainable energy landscape and mitigating the impact of climate change [104]. Dedicated researchers and industry professionals are actively focused on elevating the performance and cost-effectiveness of floating wind platforms. Their concentrated efforts span various fronts, encompassing the pursuit of innovative materials capable of withstanding the harsh conditions of marine environments. Additionally, there is a keen exploration of novel structural designs aimed at enhancing stability, coupled with advancements in mooring systems to ensure heightened reliability. This comprehensive approach reflects a commitment to pushing the boundaries of technological advancements, addressing challenges, and ultimately fostering the sustainable growth of floating wind technologies. Through these endeavors, the aim is to create resilient and efficient solutions that contribute significantly to the expansion of offshore renewable energy sources [105].

Operational strategies within the floating wind technology sector are currently undergoing meticulous examination with the goal of optimizing maintenance procedures and diminishing overall operational costs. The industry is actively exploring hybrid solutions, merging floating wind platforms with other renewable sources, as well as implementing cost reduction initiatives through streamlined construction and installation processes. These concerted efforts reflect a strong commitment to enhancing the efficiency and economic competitiveness of floating wind technologies. The ongoing research and development initiatives in this realm paint a promising picture for the future, solidifying floating wind's potential as a sustainable and viable contributor to the global energy landscape. This forward-looking approach signals a positive trajectory for the industry, emphasizing its dedication to advancing and integrating innovative solutions for a more sustainable energy future [106].

C. ASSOCIATED WITH FLOATING OFFSHORE WIND TURBINES FACES TECHNICAL AND OPERATIONAL CHALLENGES

Floating offshore wind turbines indeed face various technical and operational challenges despite their potential benefits. Here are some key challenges associated with floating offshore wind turbines [107].

1) DYNAMIC ENVIRONMENTAL CONDITIONS

Floating turbines operate in dynamic and harsh marine environments with varying wind, wave, and current conditions. This requires robust engineering to ensure stability and reliability [108].

2) MOORING SYSTEMS

Developing effective and durable mooring systems capable of withstanding strong winds and waves is crucial. The anchoring systems must be able to support the weight and movements of the turbine while maintaining stability [109].

3) STRUCTURAL DESIGN AND MATERIALS

The design and construction of the floating platforms need to consider the structural integrity of the entire system. Materials must be durable and resistant to corrosion in a corrosive marine environment [110].

4) INSTALLATION AND MAINTENANCE

Floating turbines pose challenges in terms of installation and maintenance. Accessing and servicing turbines at sea can be complex, requiring specialized vessels and equipment. Maintenance costs can be higher compared to fixed-bottom turbines [75].

5) GRID CONNECTION

Connecting floating offshore wind farms to the electrical grid involves challenges in terms of transmission infrastructure. The distance from shore and deep-sea conditions may require innovative solutions for power transmission [111], [112].

6) COSTS

Floating offshore wind technology is generally more expensive than traditional fixed-bottom systems. Research and development efforts aim to reduce costs, but as of now, the economic feasibility is a significant challenge [113].

7) SCALABILITY

While some floating wind projects are operational, scaling up to a large commercial project poses its own set of challenges. Achieving economies of scale and standardizing technologies are essential for widespread adoption [114].

8) ENVIRONMENTAL IMPACT

Floating turbines may have environmental impacts on marine ecosystems. Studies are ongoing to understand and mitigate potential effects on marine life, including seabirds and marine mammals [98].

9) REGULATORY AND PERMITTING HURDLES

Regulatory frameworks for floating offshore wind are still evolving, and navigating the permitting process can be challenging. Ensuring compliance with environmental regulations and addressing concerns from local communities is crucial [115].

IV. ONSHORE WIND TURBINES

Playing a vital role in the worldwide transition to renewable energy, onshore wind turbines contribute significantly by converting wind energy into electricity and thereby mitigating greenhouse gas emissions. These turbines comprise a range of essential components, as depicted in Figure 9, such as the rotor, blades, hub, nacelle, generator, gearbox, control systems, and tower [116].

The convergence between learning curves and expert perspectives reveals a certain degree of alignment; however, the proposed learning rate of 10%-12% in this context advises a cautious approach to anticipating cost reductions. This caution stems from factors not fully considered, such as project lifespan, operational expenses, and financial costs [117]. Taking these elements into account, and drawing on previous research, the anticipated long-term learning rate for the levelized cost of energy in onshore wind is estimated to be no less than 10%-12%, potentially exceeding this range with additional cost reduction incentives [118]. Nevertheless, external variables have at times disrupted cost projections. Achieving equilibrium amidst supply-demand dynamics, fluctuations in labor and material expenses, and financial shifts is crucial to translating learning effects into tangible market value [119]. Wind turbine and project costs have generally decreased, with temporary rises from the 1980s-2002 and 2009-2017 due to wind power-related factors (explained earlier). Power curve, capacity factor, power control, and grid interaction are crucial in optimizing turbine performance and power integration. Advancements in technology - larger rotors, taller towers, digital innovations, and trends promise more deployment, driving global sustainable energy generation [120].

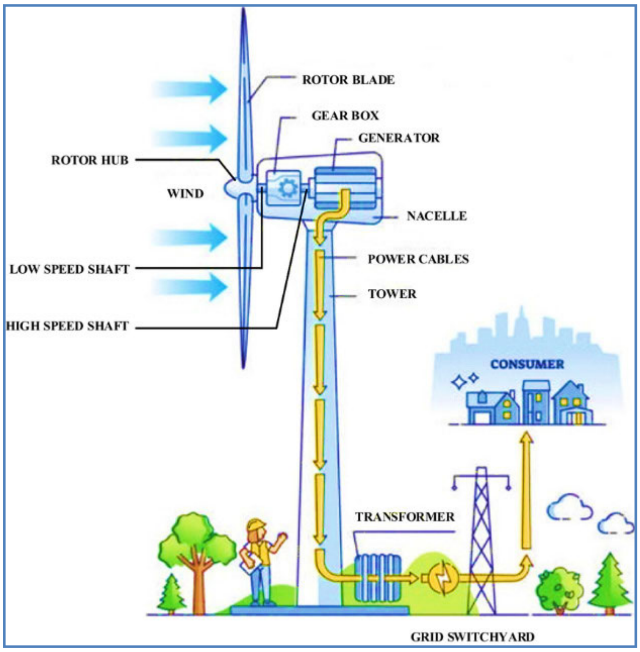


FIGURE 9. Different parts of wind turbine [116].

A. SOCIAL AND ENVIRONMENTAL CONSEQUENCES ON ONSHORE WIND FARMS

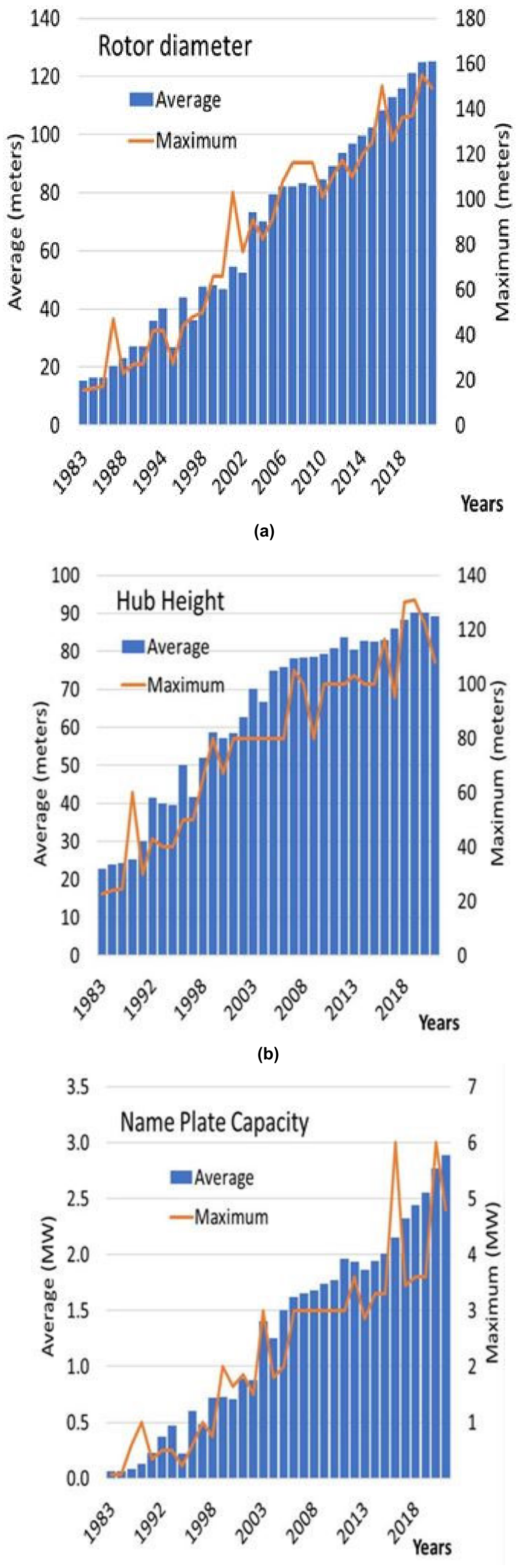
Wind energy, while heralded for its sustainability benefits, grapples with challenges that emanate from various fronts, including environmental groups, local communities, and stakeholders. Social resistance, often rooted in apprehensions surrounding wind farms, becomes a prominent hurdle [121]. Concerns over the ecological impact, particularly on local bird and bat populations, present significant challenges that demand careful consideration. Furthermore, the issues of visual and noise pollution fuel community opposition, underscoring the delicate balance between sustainable energy solutions and their societal implications [122]. The ecological footprint of wind farms extends beyond the immediate concerns, delving into potential impacts on soil quality and local temperatures. As such, comprehensive research becomes imperative to understand and address these nuanced challenges. In well-established wind markets like Germany and the United States, the management of turbine components post-lifespan emerges as a pressing issue, with a particular focus on the disposal of blades and electronic components [123].

The imperative for thorough environmental and social impact assessments stands as a cornerstone in the pursuit of sustainable onshore wind farm development, an acknowledged clean and renewable energy source [124]. Onshore wind farms not only contribute significantly to the global shift towards clean energy but also bring about crucial environmental benefits [125]. By generating electricity without emitting greenhouse gases or air pollutants associated with fossil fuels, these wind farms play a pivotal role in reducing carbon emissions, addressing climate change, and enhancing air quality. The roots of this environmental consciousness trace back to the late 1960s, a transformative period that saw the emergence of a widespread environmental movement culminating in Earth Day 1970 [126]. This pivotal moment galvanized millions of individuals for national action and laid the foundation for the creation of the Environmental Protection Agency (EPA) and federal laws in the 1970s, fostering the growth of grassroots environmental groups [127]. In this evolving landscape, renewable energy sources, including wind power, gained favor, becoming integral components of sustainability efforts worldwide [128].

B. TRANSFORMATIONS IN WIND TURBINE SPECIFICATIONS: ROTOR DIAMETER, SIZE, HEIGHT, AND NAMEPLATE CAPABILITY

Evolution in wind turbine technology has brought about notable changes in key parameters such as nameplate capability, size, height, and rotor diameter. The nameplate capability, indicating a turbine's maximum power output, has seen significant advancements as turbines become more efficient and capable of generating higher amounts of electricity [129]. In tandem, the physical dimensions of wind turbines have transformed, with larger sizes becoming more prevalent. Height has seen an increase as turbines reach greater altitudes, tapping into stronger and more consistent wind resources [130]. Moreover, rotor diameter, a critical factor influencing a turbine's energy-capturing capacity, has expanded, reflecting advancements in aerodynamics and design [131]. These changes collectively represent a dynamic landscape in wind energy technology, marked by continuous innovation and improvements to enhance overall efficiency and productivity [120].

Figures 10 (a), (b), and (c) demonstrate the exponential increase in hub height, nameplate capacity, and rotor diameter of WTs installed in the United States [132]. In the last decade, turbine size has grown for greater energy harvesting, intensifying wakes and necessitating equipment separation, expanding occupied areas. For wind-speed-dominant directions, crosswind separation might be smaller [132]. The vertical axis averages data for each year, with the secondary axis showing the highest yearly value. For example, Figure 10 (a) indicates 2015 average rotor diameter at 102.42 m and the maximum at 125 m. Technological strides in wind farms, including larger efficient equipment, site optimization, and refined configurations, enhance capacity factors (CF). Figure 10 illustrates Texas' CF growth over two decades [133]. In 1999, all farms averaged CF under 0.25; in five years, 60% exceeded 0.35. By 2014, 77% surpassed 0.4, 33% exceeded 0.45. In 2015, >5%



(a)

(b)

(c)

FIGURE 10. Wind turbine growth throughout time, taking into account: (a) rotor width, (b), hub altitude, and (c) nameplate capacity [132].

new farms hit CF >0.5; 2016 saw 14% reach this [134]. Advancements bolster equipment performance, but location and local winds impact generation. Lower speeds reduce CF, and below-average wind years affect CF due to wind speed variability.

C. ASSESSMENT OF THE CURRENT CHALLENGES AND FUTURE PROSPECTS FOR ONSHORE WIND TURBINES

Onshore wind turbines, while encountering challenges, hold promising prospects in the evolving landscape of renewable energy. Presently, a primary hurdle for onshore wind turbines is the escalating competition posed by emerging renewable energy sources, particularly the affordability and accessibility of solar power [135]. This competitive environment necessitates a continual push for innovation and cost reduction in onshore wind turbine technology to maintain competitiveness. Furthermore, the quest for suitable onshore sites with optimal wind resources faces constraints, urging developers to explore more intricate terrains and regions with lower wind speeds [136]. Grid integration emerges as another challenge, as the increasing capacity of wind farms introduces intermittent power generation, impacting grid stability and reliability. Addressing this requires the incorporation of energy storage systems, smart grid technologies, and improvements in grid infrastructure for seamless integration of onshore wind power into the existing electricity grid [137], [138]. Looking ahead, onshore wind turbines hold significant potential. Ongoing innovations in turbine design, exemplified by larger rotor diameters and taller towers, contribute to increased energy production and heightened efficiency. The advancement of sophisticated control systems and anticipatory maintenance techniques further strengthens the dependability and operational effectiveness of onshore wind turbines [139]. As the renewable energy landscape continues to evolve, overcoming current challenges and capitalizing on these advancements will play a crucial role in shaping the sustainable future of onshore wind energy [140].

The expansion of wind turbines poses multifaceted challenges in transportation, installation, maintenance, and safety, prompting concerns among stakeholders. Logistics grapple with the considerable size of blades and towers, complicating their transport [141]. Traditional truck transportation faces limitations due to the sheer scale, necessitating the use of rail for larger loads. However, adapting narrow paths and accommodating heavy equipment for rail transport introduces complexities, restricting potential deployment areas [142]. The increased dimensions of wind turbines, necessitating greater separation between components to counteract turbulent air flows, impact the internal pathways within wind farms [143]. These typically narrower and unpaved roads now must facilitate the movement of elongated and bulkier equipment from the primary roadway or rail intersection to specific turbine sites, resulting in heightened expenses and more intricate technical specifications [144]. Table 4 succinctly outlines the challenges and prospects for onshore wind turbines, underscoring the imperative for continuous innovation and enhanced infrastructure to effectively address existing challenges and leverage future opportunities for sustainable energy generation [137], [145], [146].

TABLE 4. Assessments of onshore wind turbine challenges and prospects [137], [145], [146].

Challenges	Prospects
Competition from other renewables like solar power	Ongoing innovation and cost reduction to maintain competitiveness
Limited availability of optimal wind sites	Exploration of complex terrains and regions with lower wind speeds
Grid integration challenges for stability and reliability	Implementation of energy storage systems, smart grid technologies, and improved infrastructure
Transportation, installation, maintenance, and safety concerns	Advancements in logistics, technology, and safety measures

V. COMPARATIVE ANALYSIS BETWEEN OFFSHORE, FLOATING AND ONSHORE WIND TURBINES

Onshore wind turbines exhibit notable scalability, adaptable to varying sizes based on the availability of land and wind resources. They excel in generating substantial energy, boasting capacities that extend into the megawatt range. The integration of onshore wind turbines into the energy grid is marked by its simplicity, seamlessly connecting to local electrical grids and minimizing the need for extensive infrastructure upgrades [147]. Furthermore, their proximity to populated areas proves advantageous, facilitating efficient energy distribution and mitigating transmission losses. In contrast, offshore wind turbines offer scalability over expansive open waters, whether in shallow or deep areas, featuring larger and more powerful turbines [148]. Harnessing the consistent and robust energy yields from sea winds, offshore installations present a promising avenue for renewable energy generation. However, this comes with its set of challenges, particularly in grid integration [149]. Overcoming these challenges necessitates the use of specialized subsea cables and grid connections. Despite these challenges, the potential for offshore wind energy remains significant, offering a valuable contribution to the broader renewable energy landscape [150]. Table 5 shows the comparative analysis between offshore, floating and onshore wind farms based on particulars. Floating offshore wind turbines innovatively tap deep-water winds, scalable across extensive offshore regions [151].

Whereas, floating offshore wind turbines harness superior wind resources, offering an innovative approach to enhance energy generation in deep-water environments [152]. The integration of these floating turbines with existing energy systems proves to be intricate, necessitating the use of specialized mooring and cabling for efficient electricity transmission [153]. Despite these challenges, there is ongoing progress in advancing suitable grid connections and infrastructure tailored specifically for floating turbines. This

TABLE 5. Comparative analyses of the strengths, weaknesses, opportunities, and threats for onshore, offshore wind turbines [154], [155], [156].

Offshore Wind Farm	Floating Wind Farm	Onshore Wind Farm	Particulars
Scalability across expansive open waters.	Innovatively tap deep-water winds, scalable across extensive offshore regions.	Display scalability, diverse sizes based on resources.	Scalability.
Larger and more potent turbines, consistent yields.	Access superior wind resources for enhanced energy generation	Substantial energy generation, reaching megawatts.	Energy Generation.
Challenges in grid integration, specialized subsea cables and connections.	Intricate integration with existing energy systems requires specialized mooring and cabling for electricity transmission.	Straightforward integration into local grids.	Grid Integration.
Potential challenges in grid integration with higher costs, demand specialized subsea cables, and connections.	---------------------------------	Facilitates energy distribution, curbing transmission.	Proximity to Populated Areas.
Involves higher costs and complexities in developing offshore substations and transmission networks.	Advancing suitable grid connections and infrastructure for floating turbines is underway, holding promise.	Minimizes infrastructure upgrades.	Infrastructure Upgrades.

ongoing development holds promise for the continued growth and successful integration of floating offshore wind technology into the broader renewable energy landscape [75].

VI. CONCLUSION

This research provides a comprehensive and insightful exploration of the crucial role played by offshore, onshore, and floating offshore wind turbines as cornerstones for sustainable energy generation and environmental stewardship. The study has meticulously examined the unique attributes, advantages, and challenges associated with each type of wind turbine technology. From the scalable and visually integrated onshore turbines to the expansive energy yields and environmental considerations of offshore installations, and the innovative solutions brought by floating turbines in deep waters, each technology contributes significantly to the global transition towards sustainable energy practices.

The comparative analysis undertaken in this research has shed light on the economic, environmental, and social dimensions of these diverse wind energy systems. Each technology brings its own set of benefits and challenges, underscoring the importance of considering various factors in decision-making processes. The nascent technology of floating offshore wind turbines, in particular, holds promise for addressing challenges associated with deep-water locations and expanding the potential for offshore wind energy. As the world strives for a greener and more sustainable future, the insights provided in this exploration can serve as valuable guidance for policymakers, researchers, and industry stakeholders. By addressing research gaps and outlining prospects, this study contributes to the ongoing efforts to seamlessly integrate and advance diverse wind energy systems. Ultimately, “Winds of Progress” aims to foster informed decision-making and accelerate the transition towards a more sustainable and environmentally conscious energy landscape.

VII. FUTURE WORK

While this research paper has provided valuable insights into onshore, offshore, and floating offshore wind turbines for sustainable energy generation, there are several avenues for future research and development in this field. The following are some potential areas of future work.

A. ADVANCED WIND TURBINE TECHNOLOGY

As technology continues to advance, there is a need to explore and develop innovative designs and materials for wind turbines. Future research could focus on improving turbine efficiency, reducing maintenance requirements, and enhancing reliability through the integration of advanced sensors, control systems, and materials.

B. INTEGRATION WITH ENERGY STORAGE SYSTEMS

Energy storage is a critical component for the effective utilization of wind energy. Future research could explore the integration of wind turbines with advanced energy storage systems, such as batteries or hydrogen storage, to enhance the stability and reliability of wind power generation.

C. OFFSHORE WIND FARM DESIGN AND OPTIMIZATION

Offshore wind farms have immense potential, but their design and optimization can be complex. Future research could focus on developing advanced optimization algorithms and tools to determine the optimal layout and configuration of offshore wind farms, considering factors such as wind patterns, sea conditions, and environmental impact.

D. ENVIRONMENTAL IMPACT ASSESSMENT

While wind energy is considered a clean and renewable energy source, it is essential to continue assessing and mitigating its potential environmental impacts. Future research could focus on conducting comprehensive environmental impact assessments, studying the effects on marine ecosystems, bird migration patterns, and underwater noise, and developing strategies to minimize any adverse effects. By addressing these areas of future work, researchers and industry stakeholders can further enhance the understanding, efficiency, and sustainability of wind energy systems. This will contribute to the overall goal of achieving a greener and more sustainable future powered by clean and renewable energy sources.

VIII. LIMITATIONS

Despite the comprehensive review provided in this research paper, some limitations should be acknowledged. These limitations are as follows.

A. SCOPE AND DEPTH OF ANALYSIS

Due to the vastness and complexity of the topic, it is important to note that this research paper offers a broad overview of onshore, offshore, and floating offshore wind turbines. While it provides valuable insights into their characteristics, advantages, and disadvantages, a more detailed and in-depth analysis of specific aspects, such as turbine design, efficiency, and cost analysis, could be explored in future research.

B. GEOGRAPHIC LIMITATIONS

This research paper primarily focuses on wind energy systems in specific regions, such as Pakistan, China, India, United Arab Emirates, Saudi Arabia, and Egypt. The findings and conclusions drawn may not fully represent the global context and could be influenced by the unique characteristics and conditions of these regions. Future research could consider a more diverse range of geographical locations to provide a more comprehensive understanding of wind energy systems worldwide.

C. DATA AVAILABILITY AND RELIABILITY

The analysis and comparisons presented in this research paper heavily rely on the availability and reliability of data from various sources. It is important to acknowledge that data collection and standardization can be challenging, and variations in data quality and accuracy may exist. Future research could address this limitation by conducting primary data collection and employing rigorous data validation techniques.

D. EVOLVING TECHNOLOGY AND POLICY LANDSCAPE

The field of wind energy is constantly evolving, with advancements in technology and changes in policy frameworks. This research paper is based on the knowledge and information available up until January 2024, and there may have been significant developments or shifts in the industry since then. It is important to consider the dynamic nature of the wind energy sector and ensure that the findings and conclusions of this research paper are regularly updated and aligned with the latest advancements and policy changes. By acknowledging these limitations, it is important to recognize that this research paper serves as a starting point for further exploration and investigation in the field of wind energy. Addressing these limitations in future research can contribute to a more comprehensive understanding and provide more accurate and up-to-date insights into the various aspects of onshore, offshore, and floating offshore wind turbines for sustainable energy generation.

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