Semarak International Journal of Chemical Process Engineering

Journal homepage:
https://semarakilmu.my/index.php/sijcpe/index
ISSN: 3083-8916

Establishing True North for Decision-Making in Offshore Wind Technology: Insights from Global Implementation Experiences in Advanced Economies

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ARTICLE INFO

Article history:
Received 25 March 2025
Received in revised form 23 April 2025
Accepted 24 May 2025
Available online 20 June 2025

Keywords:
Offshore wind technology; renewable energy; SWOT analysis; PESTEL analysis; sustainable

ABSTRACT

Offshore wind technology is emerging as a game-changer in the renewable energy sector, providing robust and sustainable solutions for renewable energy generation. While advanced economies have been extensively exploiting this technology, most emerging markets or developing economies are still in their infancy stages of adoption. This study provides insight into decision-making of offshore wind technology from global implementation using systematic analysis which is strength-weakness-opportunity-threat (SWOT) and political-economic-social-technological-environmental-legal (PESTEL). Key insights derived from successful implementations in advanced economies reveal that while sustainable growth, policies and strategic locations offer advantages, challenges persist in areas of high capital costs, conflicted policy frameworks, and unaligned legal structures. The interrelation between these factors creates a complex decision-making process that requires sensible and reliable choices, particularly concerning safety and social issues. While the outcomes of this study may help countries to make quicker decisions on the implementation of offshore wind technology, tailored to their specific contexts and benefits, validation from experts and industry stakeholders remain essential. Additionally, adopting the proposed framework/guideline as a living document is necessary to ensure the information stays updated and adapts to evolving times and technological advancements.

1. Introduction

As forecasted, global CO2 emissions are set to reach a new high in 2024, reflecting a 2% increase over 2023 levels, despite having plateaued over the past decade [1]. This trend falls far short of the reductions needed to achieve net-zero emissions and to limit global temperature rise in alignment

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https://doi.org/10.37934/sijcpe.3.1.5270

with the Paris Agreement's targets, which aim to reduce emissions to 40 gigatonnes or limit warming to 1.5°C above preindustrial levels [2]. While renewable energy has made significant progress in recent decades, reliance on fossil fuels, especially coal, remains substantial. For the second consecutive year, global electricity generation from coal power plants reached peak levels in 2022 [3], following a decline during the COVID-19 pandemic in 2020. This rebounds, driven by elevated natural gas prices following Russia's full-scale invasion of Ukraine, has culminated in unprecedented global levels of coal utilization and production as well as electricity generation from coal-fired plants [4].

To safeguard the climate system, countries worldwide must collectively halt the expansion of new fossil fuel production and wisely phase out existing fossil fuel infrastructures. Thus transforming "dirty" energy sources to clean energy via renewable alternatives is essential for this transition. Despite significant advancements in renewable technologies (onshore), the development of alternative technology/energy solutions remains critical to ensure energy security, environmental sustainability, and social wellbeing across varying geographical and economic contexts. To facilitate this crucial transformation, IRENA's 1.5°C scenario acknowledges the importance of offshore renewables in the energy transition and forecasts significant expansion in offshore wind, ocean energy, and floating photovoltaic installations over the next decade [5].

Oceans represent a vast and largely untapped source of renewable energy, with the potential to drive the growth of a sustainable blue economy [6,7]. Offshore renewable energy (ORE) features a game changer that can significantly mitigate the anthropogenic CO2 emissions while becoming the primary provider of energy demand in various industries [8]. ORE technologies such as offshore wind (fixed-bottom, floating, and airborne systems) [9,10]), floating solar photovoltaics (FPV) [11,12]) and other emerging ocean energy technologies can play a critical role in decarbonizing the power sector and supporting various end-use applications, including maritime transportation, district cooling, and seawater desalination.

Currently, Europe and Asia lead in ORE technology deployment, particularly in offshore wind [13-15]. This trend highlights the influence of geographical and topographical factors on the uneven development of ORE technologies, with advanced economies, such as those in Europe, leading the sector, while emerging market and developing economies, primarily in Asia, have started to expand their offshore renewable initiatives [16]. Most offshore wind farms are typically located within territorial waters (12–14 nautical miles from the coast) or within a country's exclusive economic zone (EEZ), which can extend up to 200 nautical miles [17-19]. Several large-scale and commercially successful offshore wind projects have been developed in these zones, including Dogger Bank (5.6 GW, United Kingdom), Hollandse Kust Zuid (1.5 GW, Netherlands), Seagreen (1,075 MW, Scotland), Qingzhaou (1 GW, China), and Greater Changhua (900 MW, Taiwan) [20]. These projects demonstrate the growing global adoption and scalability of offshore wind energy within designated maritime zones, with significant projections toward 2050, as depicted in Figure 1.

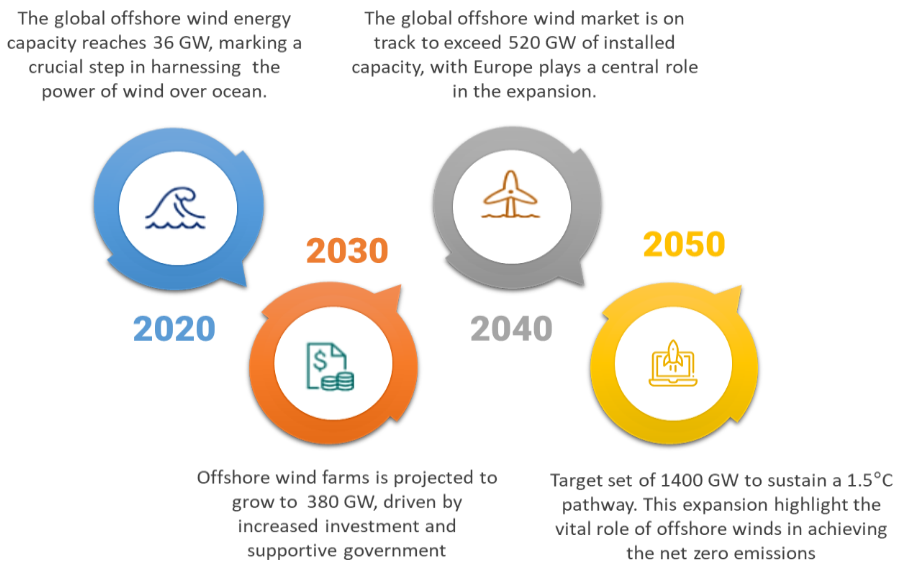

Fig. 1. Contemporary and projected installed capacity of global offshore wind technology [21-24]

2. Research Gap and Contributions

Essentially, the large-scale deployment of onshore wind farms can significantly alter natural landscapes, potentially leading to land-use conflicts [14]. This technology often faces social acceptance challenges, particularly in areas with high aesthetic value, where residents oppose the said development due to concerns about property value depreciation [25]. Offshore wind technology has emerged as a game changer due to its capabilities and stands as a promising option to substitute for or retrofit conventional energy sources. This is primarily due to its low greenhouse gas emissions, increasing cost-effectiveness, and the abundant wind resources available at sea [26]. Consequently, offshore wind technology is capable of significantly contributing to meeting the 2050 net-zero greenhouse gas emission targets [27].

Advanced economies such as those in Europe and the United Kingdom (UK) have pioneered few of the most commercially successful offshore wind technologies. Due to their technological and operational maturity, they have emerged as some of the most cost-effective energy projects in Europe, with a significant decrease in the levelized cost of electricity [28]. In contrast, countries that are latecomers to ORE development, particularly offshore winds, face numerous risks that must be carefully considered. Most of these latecomers (as generalized in this study) are emerging or developing economies, which often encounter unique technical, financial, and policy challenges.

Therefore, it is crucial to provide a clear and structured framework/guidelines to support the successful implementation of offshore wind technology in those countries. To support this, we combine strengths, weaknesses, opportunities, threats (SWOT) framework to assess internal capabilities, and the political, economic, social, technological, environmental, and legal (PESTEL) framework to provide a comprehensive analysis of both internal and external factors. Currently, only Kansongue *et al.,* [29] have applied the SWOT-PESTEL analysis to evaluate renewable energy development in Togo. Their findings suggest that better outcomes can be achieved by implementing strategies that address high capital costs and promote local participation. Notably, their analysis identified the absence of ORE as a significant weakness in Togo’s renewable energy system.

This study systematically gathers insights from global implementation experiences in advanced economies related to offshore wind projects. Such approach enables latecomers to learn lessons from existing projects and make informed decisions about adopting offshore wind technology in their own contexts. Building on this study hypothesizes that integrating SWOT-PESTEL framework provides a more robust, context-aware approach to support effective offshore wind technology adoption in emerging markets.

3. Data And Methodology

This study employs qualitative data analysis guided by the SWOT-PESTEL framework to establish a clear true north, ensuring reliable and focused decision-making insights for offshore wind technology implementation. The analysis draws from a comprehensive review of existing literature available on platforms such as Science Direct, Scopus, Web of Science, Springer Link, IEEE Xplore, and Non-Scopus Indexed Journals. To enhance the study's findings, we consulted supplementary sources, including gray literature comprising policy documents, online newspapers, statistical studies, and reports from governmental and non-governmental organizations. Through the SWOT analysis framework, internal and external factors imposed in the offshore wind projects are identified. While PESTEL analysis is used to examine broader factors affecting the offshore wind deployment. To ensure methodological rigor, the SWOT-PESTEL conceptual framework is designed to avoid overlapping criteria and prevent bias in decision-making in Figure 2. The element categorization follows strategic analysis tools adopted from Njoh [30] and methodology is adapted from Kansongue *et al.,* [29] to ensure transparency and replicability in present approach.

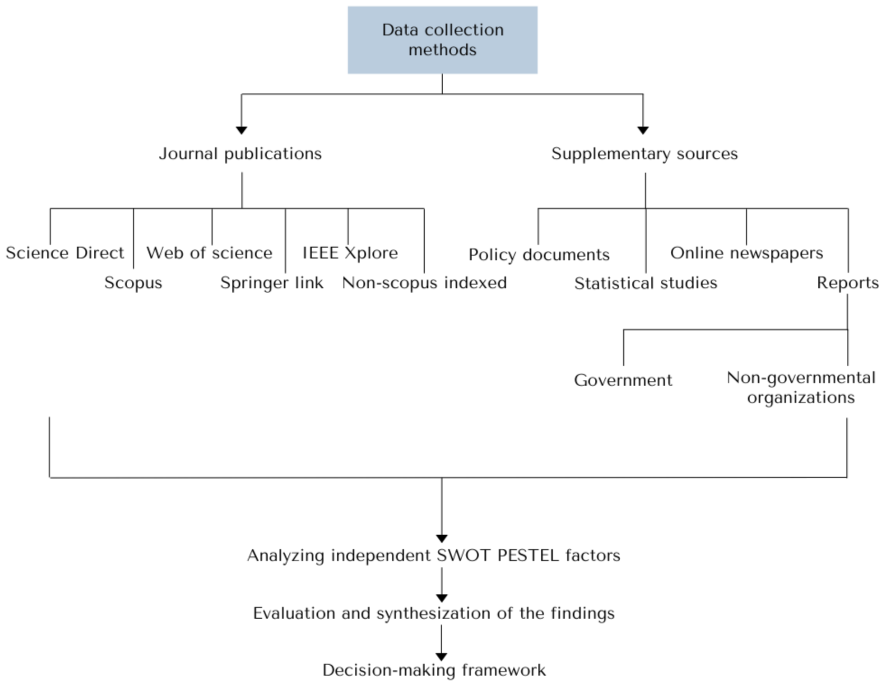

Fig. 2. Flowchart illustrating the integration process of the study

As shown in Figure 2, the study proceeds in two distinct stages: first analyzing independent SWOT-PESTEL factors in advanced economies. The findings are then evaluated and synthesized to develop a decision-making framework that establishes a "true north" for offshore wind implementation for latecomers. A decision framework is proposed for latecomers by infiltrating the

SWOT criteria in the PESTEL framework. This systematic approach helps to identify successful practices and derive better strategies for offshore wind technology development, ultimately enhancing socioeconomic and positive safety-environmental impact.

4. Results And Discussion

This work is focused on experiences from the largest offshore wind [20] that have successfully operated. Insights from these experiences of global implementation are used to anchor the true north for decision-making in offshore wind technology which benefits countries with emerging markets and developing economies (latecomers). Figure 3 and 4 summarize the significant factors from the individual SWOT and PESTEL analyses.

4.1 SWOT Analysis Based on Successful Offshore Wind Operation
4.1.1 Strengths

Strategic location emerges as a fundamental strength across successful offshore wind projects worldwide. The robustness of grid infrastructure at onshore connection points significantly reduces curtailment risk, as evidenced in Australia where strategic grid planning enhances offshore wind project viability [31,32]. Comprehensive site evaluation, particularly regarding wind characteristics, remains essential for accurate energy potential assessment and production forecasting. The offshore environment inherently provides advantages over terrestrial sites, with sea surfaces generating more frequent and powerful winds due to reduced surface friction while minimizing visual landscape impacts [33]. This scenario has been evidently proven in actual project case studies in Taiwan. The world's premier offshore wind development demonstrates how location-specific advantages drive project success. The UK's Dogger Bank project exemplifies this through its optimal North Sea positioning, which provides consistent wind patterns resulting in exceptional capacity factors [34]. In contrast, the Netherlands' Hollandse Kust Zuid capitalizes on relatively shallow water depths (18-35m) which substantially reducing foundation costs (capital) [19] and simplifying installation processes [35]. Scotland's Seagreen project demonstrates viable deployment in deeper waters (up to 55m), where effectively expanding potential installation zones for future offshore developments globally [36].

Besides geographical advantages, such flagship ventures are backed by strategic joint venture alliances that blend niche area expertise with robust capital bases. Dogger Bank's trilateral partnership of SSE Renewables, Equinor, and Eni [37] brings various energy sector experience and financial muscle. Similarly, Hollandse Kust Zuid's development partnership headed by Vattenfall, BASF, and Allianz [38] brings energy production expertise with industrial and financial muscle. TotalEnergies and SSE Renewables' Seagreen partnership is another risk-sharing and knowledge-transfer model for success in the offshore wind sector [39].

Progressive policy settings also underpin offshore wind expansion globally. For instance, in the UK, policies simultaneously promote energy security, encourage research and development of new offshore renewable technology, and ensure protection of marine environments. Such comprehensive policy approaches significantly contribute to national energy security objectives while advancing global climate goals. This scenario is reflected in the UK and Dutch offshore development experiences [40], with detailed analysis of policy support strengths for offshore wind across various countries can be found in [32].

4.1.2 Weaknesses

Supply chain constraints represent a significant weakness in the offshore wind sector globally. Dependence on specialized installation vessels with limited availability affect projects across all regions. Such challenges have been faced by Denmark's offshore wind farms. Where, if more vessels are not commissioned to meet the upcoming demand, the offshore wind industry will have to deal with widespread project delays [41]. The shortage of specialized vessels for offshore wind operations is a clear indicator of the precarious state of Europe's wind energy supply chain. The European wind industry is currently facing an unprecedented combination of overlapping challenges. Recent analysis indicates that the impending global shortage of specialized offshore wind vessels poses a substantial risk for project execution not only in Poland but worldwide [42]. These supply chain bottlenecks create schedule uncertainties, increase costs, and potentially compromise project/operational viability.

Skilled workforce shortages in technical areas further complicate development and operations of offshore wind projects. The sector is projected to experience rapid workforce growth, with a 79% increase in technicians required by 2027 compared to 2022 levels. This urgent need for a skilled and sustainable workforce underscores the critical role the offshore wind industry plays in driving the energy transition to renewable sources [43]. However, a significant skills gap already exists, with heightened demand for workers possessing relevant experience in key areas of integrated energy sectors, including oil and gas, hydrogen, offshore wind, and carbon capture and storage. Industry projections indicate substantial challenges in balancing the supply and demand for appropriately skilled personnel over the next 10 to 15 years [44].

Despite the environmental benefits of renewable energy, offshore wind technology presents certain ecological challenges. The installation and anchoring of floating wind turbines can disrupt sensitive marine ecosystems, including coral reefs, seagrass beds, and migratory routes for marine species [45]. Noise and sediment disturbance during installation phases can also cause adverse impacts on marine ecosystems [46]. Such environmental concerns necessitate good site selection, strict impact assessment, and at times costly mitigation measures, adding several levels of sophistication and expense to project planning.

Additionally, human safety threats are the significant structural and operational threats to offshore wind technology, particularly in areas subject to repeated extreme weather conditions like tropical storms and high winds. Crosswind oscillations caused by wave loading and misalignment of wind turbulence can potentially influence the fatigue life of offshore wind turbine foundations [47]. These technical problems need sophisticated engineering solutions and robust monitoring systems, contributing to the cost and complexity of the project.

While strategic joint ventures can fortify offshore wind ventures with shared experience and assets, they are also riddled with immense organizational complexity. This dual capability is exemplified by Shanghai Electric's public announcement at the 2014 China Wind Power conference in Beijing; that complicated joint venture structures resulted in operational issues, excessive administrative cost, and loss of efficiency [48]. Shanghai Electric reiterated such sentiments in other public platforms [49], highlighted how inefficiency in the bureaucratic nature present in multi-entity alliances can invert their theoretical advantage. Such organizational inefficiencies may ultimately undermine project outcomes by creating administrative bottlenecks, compromising decision-making procedures, and impairing accountability between the partners.

4.1.3 Opportunities

Strategic sites for offshore wind farms are among the most significant aspects of achieving various opportunities for the renewable energy industry. Sites for wind farms, typically located within areas of high-quality wind resources, also provide the potential to share infrastructure with adjacent schemes or developments, so that efficiency of operation is optimized and widespread cost savings are obtained. For example, shared transmission grids and ports reduce capital expenditures by allowing multiple projects to use the same facilities, and economies of scale and avoiding duplication of infrastructure are obtained [50]. A novel hub-and-spoke concept developed by the North Sea Wind Power Hub (NSWPH) consortium takes it a step further by coupling offshore transmission of electricity from an ensemble of wind farms to land with interconnectors between countries. This system can provide a unified energy system for the North Sea, featuring enhanced grid stability, enhanced flexibility in power delivery, and multinational collaboration in energy transition goals. It has significant advantages through its focus of power transmission and facilitating concentration of resources, reducing the need for each wind farm to support an independent transmission system, which can save money and improve system reliability [51,52].

In addition, the integration of technology in offshore wind farms has some prospects. Of the most promising among these technologies is green hydrogen generation and incorporation into offshore wind power. Green hydrogen generated through renewable electricity from wind farms, offers a solution to the perennial issue of energy storage that has held back the growth of renewable energy. Offshore wind technology, with their constant and high energy output capacities, are ideal candidates for green hydrogen production as they can provide a consistent source of electricity to the electrolyzers that convert water into hydrogen. This synergy is able to address the energy intermittency issues and provide a mechanism for storing excess energy to be used during low wind generation or peak demand challenges [53-56]. Moreover, this mixture would create new markets for hydrogen as a clean fuel for application in transportation, industry, and heat, to support the decarbonization of many industries simultaneously.

The expanding of the corporate Power Purchase Agreement (PPA) market for renewable energy offers new revenue streams. The PPA market has grown by an average of 33% since 2015, catalyzing hundreds of billions of dollars in investment into the global energy transition [57]. In the context of energy transition policies, the findings shed light on the vulnerability of each domestic economy to energy price shocks and highlight the critical need for countries to invest in renewable energy sources to ensure long-term energy security [58].

4.1.4 Threats

Most of the offshore wind form projects face threats from market and environmental factors. Supply chain disruptions and material cost inflation are negatively impacting project economics [42]. The findings indicated that since the mid-2010s, supply shocks have become the primary drivers of inflation. Following the Global Financial Crisis, commodity price shocks severely impacted inflation in Germany, the U.K., and the U.S., while the influence of global supply chain disruptions on inflation in these countries surged after the COVID-19 pandemic [58]. Grid integration challenges, coupled with aging infrastructure, pose technical risks to project operations. The intermittent nature of wind power creates balancing requirements, which must be addressed through comprehensive grid modernization. The variability in wind generation further exacerbates these challenges. Over the past few years, daily wind generation in the U.K. has fluctuated significantly. During winter months, generation averaged between 8 and 10 GWh/h, while in summer when wind speeds are typically lower and demand decreases, generation has ranged between 4 and 6 GWh/h ([59].

Additionally, extreme weather events, exacerbated by climate change, present increasing operational risks. Offshore wind farms are vulnerable to various climate change impacts, including changes in wind speed, wave height, and the formation of sea ice. Reports indicate that by 2100, global temperatures are expected to rise by 2 - 4 degrees Celsius, sea levels will likely rise by 1 meter, and extreme weather events such as cyclones and tsunamis will intensify [60,61]. With climate change, offshore wind technology (i.e. the turbine) will face more frequent exposure to extreme weather events beyond the design limits of current turbines, potentially leading to reduced operational performance and structural damage to the turbines [60].

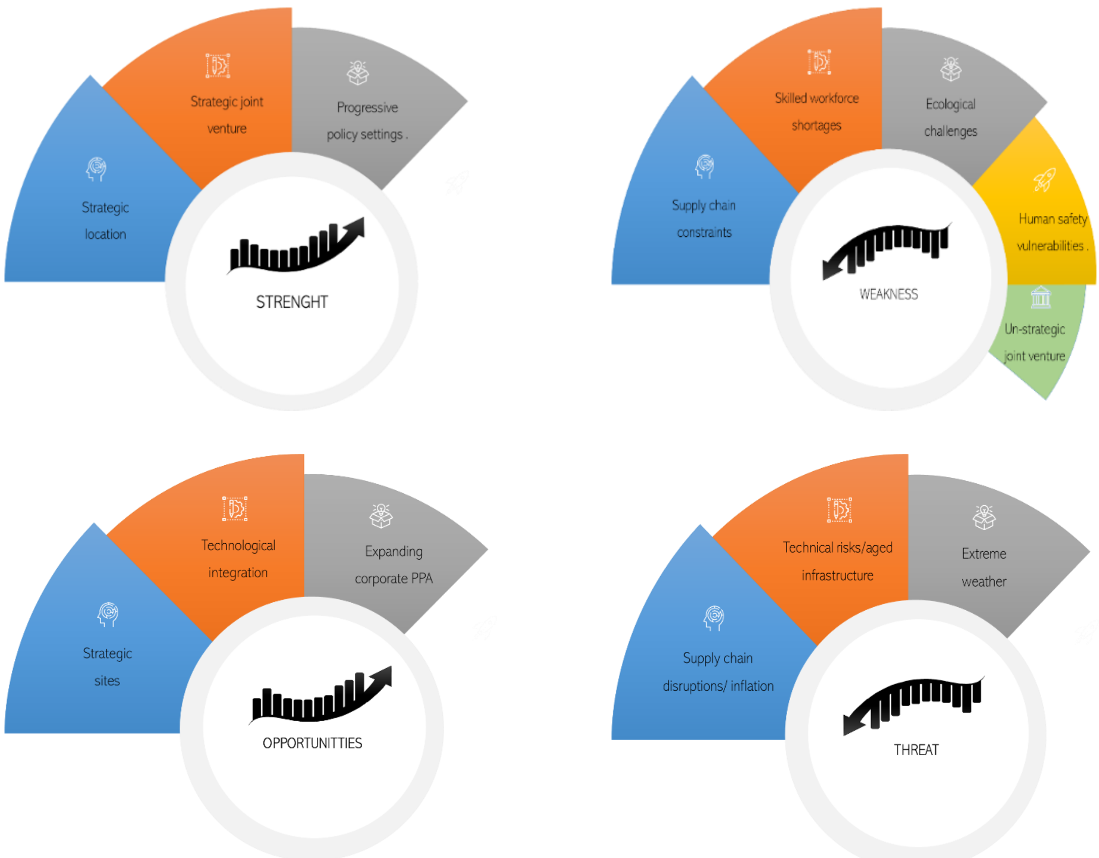

Fig. 3 Insight from global implementation experiences in advanced economies based on the SWOT framework

4.2 PESTEL Analysis Based on Successful ORE Operation
4.2.1 Policy

Supportive policy environments have played a crucial role in the development of the offshore wind technology. For instance, the UK's target of 50 GW of offshore wind capacity by 2030 and the North Sea Transition Deal are central to supporting major projects like Dogger Bank [62,63]. As part of the North Sea Transition Deal, an integrated People and Skills Plan has been developed to ensure the transferability of skills from the oil and gas sector to offshore wind, helping to build the workforce needed for this growing industry [63]. Similarly, the Dutch Climate Agreement sets an ambitious target of 11.5 GW of offshore wind by 2030, with three designated wind farm zones namely Holland Coast (West), North of the Wadden Sea Islands, and IJmuiden Far Offshore, paving the way for this additional capacity [64]. This agreement also has ambitious short-term targets by reducing emissions to 75% by 2030 and 90% by 2040, below the 1990 levels. In line with the 2015 Paris Agreement's objectives, it shows a worldwide commitment to capping the rise in temperature at 1.5 degrees Celsius or less [65].

Among the most powerful policy instruments to support the growth of offshore wind is the Contracts for Difference (CfD) regime [66,67]. CfDs help to remove the volatility of revenue for renewable-based projects, which appeals to investors. While effective at triggering growth, CfDs can cause market distortions. For example, they can encourage a "produce-and-forget" culture, where generators prioritize generating as much as possible without responding completely to market signals, leading to inefficiencies [66].

The CfD auction system, introduced by the UK's Electricity Market Reform (EMR) in 2013, has been instrumental in driving the decarbonization of the electricity industry. These auctions have promoted competitive bidding, reducing the cost of low-carbon technology significantly offshore wind, thereby making such projects cost-effective [68].

Financing arrangements vary between projects. For example, the Dogger Bank Wind Farm secured a CfD for the whole of three phases of the project, including 1.2 GW of low-carbon electricity generation. On the other hand, Seagreen secured a CfD for 454 MW prior to its Final Investment Decision in June 2020, to be expanded to 1,075 MW. Under the CfD regime, all successful wind farms are required to meet some milestones prior to securing the corresponding contracts. In accordance with the UK's Low Carbon Contracts Company (LCCC), a company responsible for running the CfD scheme, they have pledged to make sure that the projects of Dogger Bank and Seagreen have reached their critical CfD milestone requirements [63]. Furthermore, under the National Policy Statement for Energy (EN-1), in effect as of 17 January 2024, energy infrastructure development projects are more solicited to be in line with environment and sustainability objectives.

The policy calls for Nationally Significant Infrastructure Projects (NSIPs), both offshore and onshore, to benefit, protect, and enhance the natural environment. Particularly, it calls for these projects to secure net gains in biodiversity and broader environmental benefits, emphasizing the integration of environmental considerations into each step of energy infrastructure planning and development [64].

4.2.2 Economic

Offshore wind farms have sizeable economic impacts. The creation of employment is among the key socio-economic benefits of renewable energy (RE) and energy efficiency (EE) technologies. The ability of RE and EE sectors to generate new job opportunities exerts a substantial impact on public policy and on resource allocation for such sectors [71]. The combination of economic, societal, and policy considerations highlight the importance of prudent decision-making in the deployment of offshore wind technology, ensuring that the three aspects are reconciled based on fair judgement.

The Dogger Bank project, for example, is expected to contribute £6 billion to UK GDP [72]. Similarly, the construction of Seagreen, Scotland's largest offshore wind farm, has already delivered a £1 billion economic boost to the Scottish economy through SSE Renewables [73]. Employment creation is one of the major economic advantages in all offshore wind developments. The Dogger Bank project alone create thousands of direct and indirect jobs, supporting approximately 107,700 UK jobs annually from 2017 to 2048 [66]. Additionally, the £1 billion contribution of SSE Renewables to Scotland's GDP has been supporting approximately 4,000 Scottish jobs in the previous year [73]. The European Wind Energy Association (EWEA) has approximated that more than 520,000 people were employed in the wind energy sector within the EU by 2020, and this is expected to rise to around

800,000 by 2030. Of these, 62% will be in the offshore sector [74]. Job creation in offshore wind includes direct employment in construction and operations and maintenance of offshore wind technology, as well as indirect jobs within the supply chain and induced employment [75,76].

4.2.3 Social

The development of offshore wind technology has significant social and demographic impacts on coastal communities. One of the key effects is population instability, as skilled workers are often drawn to project areas, leading to demographic shifts within the energy workforce. These shifts can also have substantial impacts on local housing markets, community wellbeing and cohesion [77] and the possibility of devaluation of housing prices [78]. This is hypothetically due to the negative perspective and limited awareness with regards to the offshore wind projects. These impacts are accompanied by externalities, particularly for those who rely on the maritime space and seascapes for industries such as fishing, tourism and recreation (T&R). The expansion of marine renewables is expected to affect T&R, potentially leading to decreased local welfare and a reduction in visitor numbers, as some stakeholders have predicted [75,79].

In contrast, projects such as Dogger Bank and Seagreen have demonstrated positive contributions to economic growth by creating thousands of jobs and supporting local community development. For example, Dogger Bank Wind Farm has announced a £25 million commitment to coastal communities as part of its long-term legacy as a world-leading renewable energy project. This fund is aimed at strengthening science, technology, engineering, and mathematics (STEM) education for young people over the wind farm's 35-year operational lifespan, equipping future generations with the skills needed to thrive in a net-zero emissions economy [80]. This promotes a community social responsibility (CSR) or community benefits in offshore wind development. Moreover, community funds have been shown to deliver tangible positive impacts to local populations. However, such financial contributions are sometimes perceived as compensatory or even as bribes [75,76], raising questions about their long-term effectiveness. In the UK, the co-benefits of policies such as the Renewable Obligation Certificates (ROCs) for offshore wind extend beyond energy generation. These include greenhouse gas emission reductions, decreased dependence on energy imports, and job creation. Notably, the employment generated by offshore wind developments has been estimated to provide £1 billion in social benefits [81].

4.2.4 Technological

The offshore wind industry is experiencing significant technological advancements and strategic innovations. One standout example is the Dogger Bank Wind Farm, which boasts a remarkable 3.6 GW capacity and utilizes GE Haliade-X 14 MW turbines using the most powerful commercial turbines currently in operation [37,82]. Similarly, the Hollandse Kust Zuid project employs Siemens Gamesa 11 MW turbines, each featuring a 200-meter rotor diameter, specifically designed to optimize performance in the challenging conditions of the Dutch North Sea [83]. An industry breakthrough was achieved by Seaway7, which completed the world's first commercial monopile foundation installation in Dynamic Positioning (DP) mode. This innovative installation method significantly reduces both time and cost by eliminating the need to anchor at each location, thereby shortening installation cycle times and overall project duration. Furthermore, this breakthrough yields environmental benefits by reducing greenhouse gas emissions and minimizing the impact on the seabed and surrounding infrastructure [19].

In terms of operational innovation, most of the mature and successful offshore wind farms showcase the adoption of advanced digital technologies. Digital twin technology, in particular, is being utilized to optimize the operations and maintenance (O&M) of these offshore wind farms. Offshore turbines are subject to various loads that are uncommon onshore, and harsh wind and wave conditions often limit the operability of vessels required to access the turbines. As the scale of power generation continues to expand, it has become essential to implement advanced planning strategies for O&M to minimize downtime, optimize turbine availability, and maximize energy production [84].

In addition to digital twins, robotics and drone technologies are revolutionizing maintenance operations by improving safety and reducing costs. Drones, which are now routinely used for infrastructure inspection, offer substantial safety benefits by eliminating the need for workers to perform tasks at height. Moreover, drones help in reducing inspection times and eliminating the need for specialized access equipment and training, which further reduces costs [85]. The development of fully autonomous offshore wind farms is also on the horizon, supported by advancement in information and communication technology (ICT) and robotics. These innovations are key to optimizing the operation and maintenance of floating wind technology, offering significant potential for cost reduction and improving operational safety. The incorporation of remote operation via digital twins, autonomous underwater robots, and surface vehicles, could further drive down costs and enhance the efficiency of offshore wind farms technology [86].

4.2.5 Environmental

The carbon reduction benefits of offshore wind farms are substantial. Renewable energy has the potential to significantly reduce system-wide pollution emissions by replacing fossil fuel-based generation sources [87]. The emission reduction associated with offshore wind projects has contributed an estimated £4.4 billion in value. These values contributed by the co-benefits of the UK's ROCs offshore wind policy include emission reductions thus decrease the energy imports [81]. Seagreen Wind Farm, for instance, has the capacity to displace over 2 million tonnes of CO_2 annually, which plays a critical role in supporting Scotland's net-zero targets by 2045 [88].

Biodiversity considerations are also central to the development of offshore wind technology. Dogger Bank, for example, implements biodiversity net gain initiatives, aiming to leave the natural environment in a better state than before development. When a development impacts biodiversity, developers are encouraged to enhance ecological features and natural habitats beyond the affected area, thereby halting current biodiversity loss and restoring ecological networks [89]. Similarly, the Hollandse Kust Zuid project integrates biodiversity enhancements around its turbine foundations. This initiative focuses on the first-ever research into how wind turbine designs can actively contribute to developing nature on wind farms. By creating passages through the bases of turbines, the project allows marine animals, for instance, fish, to pass freely in and out, enabling them to contribute to a healthier marine environment [83].

Offshore wind farms have been shown to increase epibenthic biodiversity in the North Sea. Scour protection installed around wind farm turbines presents a hard structure favorable to epibenthic species that populate the otherwise sandy seabed at the southern North Sea. Studies have indicated incorporating scour protection translates to higher density and diversity of epibenthic species, opening up new possibilities for sea life [90]. In terms of lifecycle management, offshore wind technology is embracing circular economy (CE) principles in their environmental policies.

Seagreen, for instance, incorporates end-of-life recycling planning into its environmental strategy. Siemens Gamesa has pioneered the development of the RecyclableBlade, the world's first wind turbine blade designed for recycling at the end of its lifecycle. This innovation enables the separation and recycling of materials in the blades, which can be repurposed for new applications, marking a significant step forward in sustainability [91]. This focus on recycling during end-of-life is aligned with the need to adhere to the Environmental Protection Agency's (EPA) Waste Management Hierarchy, which favors practices that minimize waste and optimize recycling and reuse [92]. Besides the benefits, there are also ecological concerns regarding the impacts of floating offshore wind farms that focus on the environmental consequences that are likely to follow, e.g., habitat disturbance and underwater noise effects, primarily in the case of deep-water floating wind farms [86].

4.2.6 Legal

Offshore renewable energy development entails navigating a complex network of national and global laws designed to protect territorial sovereignty, environment, and the interests of various industries in the marine jurisdictions [14]. Offshore wind energy, one of the pillars of the world energy transition, was a priority that was met with the passing of the Offshore Wind Energy Act in 2015 and its revision in 2021. This Act was the foundation for the Netherlands' initial Offshore Wind Energy Roadmap, which aimed to increase the country's offshore wind capacity to 4.5 GW by 2023. The roadmap also established a clear timeline for tenders and project development. According to this scheme, three areas for offshore wind farms such as Borssele, Hollandse Kust (Zuid), and Hollandse Kust (Noord) were formally designated to be developed. Notably, the Hollandse Kust (Zuid) project, which includes 1.5 GW at four locations, was the first in Europe to be developed unsubsidized.

A major catalyst for the development of such projects is government support, namely in terms of regulatory assurance, effective approval processes, and fiscal or tax incentives. By the absence of these, Brazilian offshore wind projects face prolonged delays and uncertainties. Industry stakeholders emphasize the difficulties of having consistency in policy at federal, state, and local government levels, and therefore the requirement for integrated and harmonized legal frameworks to be crucial for successful offshore wind project development [32]. In contrast, the UK's renewable energy pledge has also been backed by the adoption of different legal mechanisms, such as the Offshore Wind Capital Grants Scheme devised by the Department of Trade and Industry (DTI) in 2001. The scheme provided direct financial support for trailblazing offshore wind farms in favor of the development of essential infrastructures such as the North Hoyle and Burbo Bank wind farms [94].

In addition to that, the subsequent Crown Estate rounds of licensing have continually developed offshore wind power capacity. The UK's legal framework has further been strengthened by legislative measures taken pursuant to international commitments, such as the EU Renewables Directive under which the UK was required to generate 15% of its energy through renewable energy in 2020. Offshore wind was recognized as a significant technology to achieve these goals [95]. These regulatory measures have been instrumental in the growth and stability of the UK's offshore wind sector, and the importance of a well-established and enabling legal framework for offshore wind development is underscored.

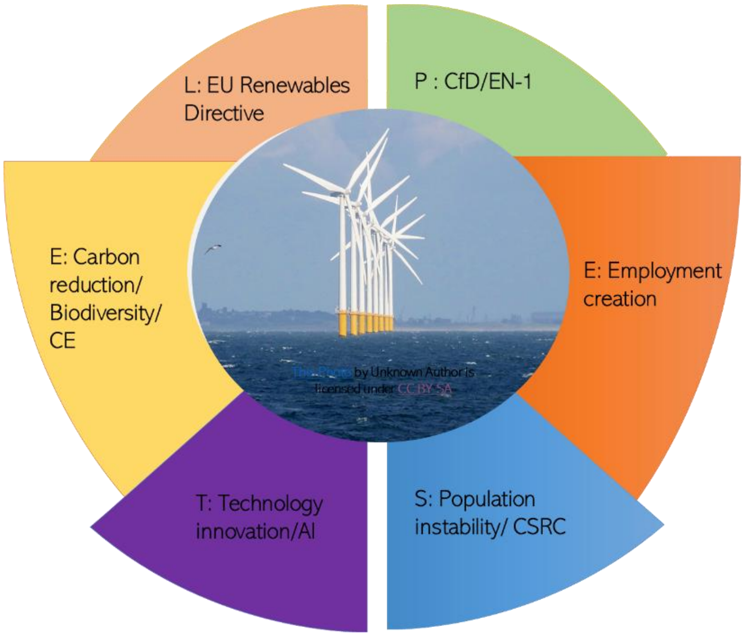

Fig. 4 Insights from global implementation experiences in advanced economies based on the PESTEL framework

4.3 Decision-Making Framework for Offshore Wind Technology: Insight

Constructing real north for application of offshore wind technology requires thorough analysis crossing multiple domains. With the holistic application of SWOT and PESTEL methods, stakeholders will be in a position to address complex trade-offs without straying from strategic objectives. Balanced technique ultimately enables the application of offshore wind technology to achieve their maximum capacity as keystone technology in energy transition globally and offers clean energy on a global scale. Table 1 rigorously outlines the criteria of PESTEL by decomposing the components of SWOT for each criterion. This proposed decision-making framework/guideline is a novel approach adopted to avoid conflicting criteria in decisions, since traditional individual SWOT-PESTEL analyses might overlap in their findings. This study is believed to be the first work to infiltrate SWOT analysis into the PESTEL approach.

Insights from global implementation experiences in advanced economies demonstrate that politically, while sustainable growth policies are advantageous, conflicted policy frameworks across jurisdictions present challenges. Economically, strategic locations offer optimized capital costs, though high initial investment requirements pose barriers. Social perspectives highlight the importance of public confidence through strategic partnerships, while managing community perceptions that funds may be viewed as bribes. Technologically, rapid adaptation and AI innovation create opportunities, alongside challenges related to operational safety and grid infrastructure. Environmental considerations demonstrate strong biodiversity targets but face issues with installation noise and extreme weather vulnerabilities. Legally, the protection of territorial sovereignty supports implementation, though unaligned frameworks across different governance levels may hinder progress. These insights from successful offshore wind implementations worldwide provide valuable guidance for latecomers considering similar developments. Figure 5 depicted the flashcard as the decision guideline for the implementation of offshore wind technology.

Table 1
Proposed decision-making framework of offshore wind technology based on insight from emerging economies

Perspective	Factor	Criteria for offshore wind technology decision-making
Policy	S	Policy Support: Enabling Sustainable Growth
	W	Conflicted policy framework across partnerships
	O	Green energy investment
	T	Undetermined
Economic	S	Strategic location and partnership: Optimize capital cost
	W	High capital/foundational cost
	O	Power Purchase Agreement (PPA)
	T	Undetermined
Social	S	Strategic partnership: Boost confident from public
	W	Conflicted partnership: Lost trust from the public perspective
	O	Enhance job creation and skill workers
	T	Negative perception: Community fund as a bribe
Technology	S	Strategic location: Speed technological adaptation and AI
	W	Supply Chain Vulnerabilities: Massive demand
		Safety challenge: Operational and structural risk
	O	Strategic grid infrastructure with the onshore/nearby development (green hydrogen)
	T	Incompatible technology/grid integration
Environment	S	Environmental target and biodiversity
	W	Ecological challenge: Installation and noise
	O	Decrease energy import, circular economy
	T	Extreme weather event: Climate change
Legal	S	Protect territorial sovereignty
	W	Unaligned legal framework across all levels
	O	Encouragement to others: Subsidy free
	T	Undetermined

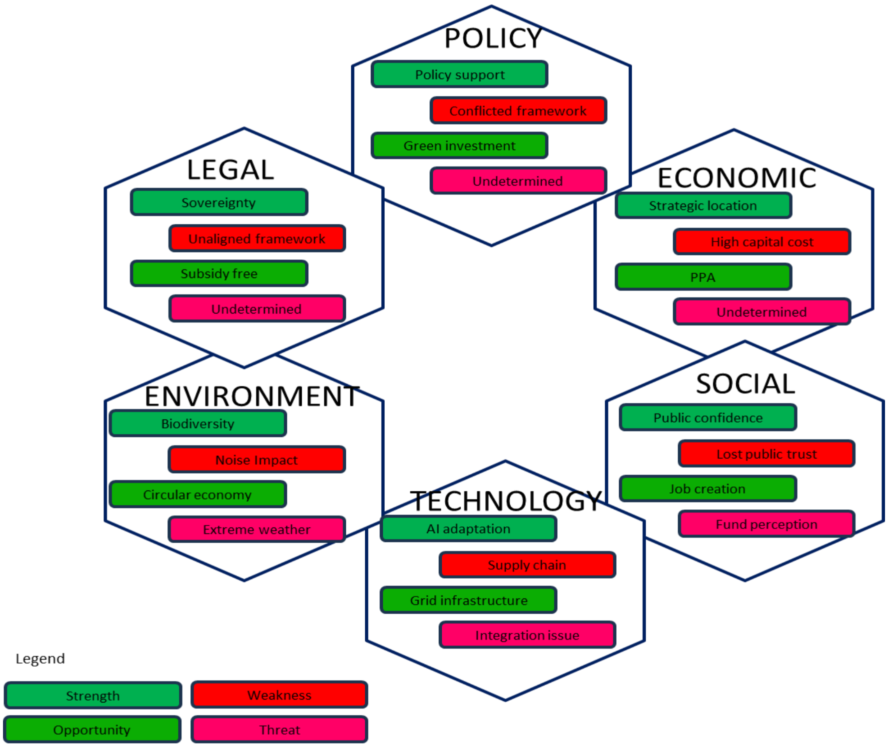

Fig. 5. A flashcard for decision-making of offshore wind technology

4.4 Disaster Risk Management insight

Crucially, the analysis highlights disaster risk management (DRM) as an often overlooked yet critical factor, given offshore wind infrastructure’s vulnerability [96] to extreme weather under the environment aspect (e.g., hurricanes, typhoons) and long-term climate risks. The interrelation of these factors demands decision-making that prioritizes resilient design, adaptive risk assessments [97], and emergency response protocols, particularly in disaster-prone regions. While this study accelerates context-specific offshore wind deployment, expert validation remains essential to address site-specific DRM gaps. The proposed framework should also in future consider integrating evolving DRM strategies (e.g., AI-driven hazard modelling [98], redundancy in grid connections) to safeguard investments and ensure operational continuity amid growing climate uncertainties.

5. Conclusion

Offshore wind technology holds transformative potential for developing countries or emerging economies’ renewable energy sector (this study considers as latecomers). While this technology can enhance energy security, biodiversity, and climate resilience, challenges such as environmental impacts, installation risks, and technological limitations must be mitigated. Effective stakeholder collaboration and regulatory frameworks are critical to overcoming barriers and ensuring sustainable development in offshore wind technology. Fostering international collaboration is essential for the latecomers to advance their offshore renewable energy capabilities. By engaging with global experts, the country can leverage cutting-edge technological advancements and establish the best practices for safety and environmental management. Partnerships with experienced nations and organizations will also facilitate knowledge exchange and enhance the technical expertise of local stakeholders. Investing in research and development (R&D) is crucial to overcoming the challenges associated with offshore wind installations. Priority should be given to developing eco-friendly materials, innovative monitoring systems, and disaster-resilient designs to ensure long-term sustainability and reliability. The decision-making framework proposed in this study enables emerging economies to apply valuable lessons from advanced economies' experiences. While this research focuses primarily on qualitative outcomes, future work should include industry validation and quantitative evaluation to address the limitations of the current study.

Acknowledgement
The authors declare no competing financial interests

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