THE IMPACT OF CLIMATE CHANGE INDUCED CATASTROPHE AFFECTING OFFSHORE WIND ENERGY: AN INSURANCE PERSPECTIVE

A Thesis submitted to the
University of Petroleum and Energy Studies

For the award of the degree of

Doctor of Philosophy
in
Management

By

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June 2023

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DECLARATION

I declare that the thesis entitled "**The impact of Climate change induced catastrophe affecting offshore wind energy: An Insurance Perspective"** has been prepared by me under the guidance of **Dr. Anil Kumar**, Professor of Energy Management, Domain Cluster, School of Business, UPES. No part of this thesis has formed the basis for the award of any degree or fellowship previously.

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ABSTRACT

Tackling climate change and keeping the global temperature below 1.5℃ require the support of renewable energy in the energy mix. Among the renewables, offshore wind Energy (OWE) is expected to play a crucial role in decarbonization and building energy security. Global OWE capacity is projected to reach 630 GW by 2050, owing to its exposure to steady and consistent wind. China, the UK, and Germany lead the global OWE development. India's extensive coastline and good wind resources are suitable for OWE generation. Considering this opportunity for clean energy development, the government notified National Offshore Wind Energy Policy (NOWE policy) in 2015. However, to date, the development of OWE on Indian coasts is nil due to significant barriers. This thesis aims to identify, classify, and rank the barriers in the Indian OWE sector, then draw a comparison of NOWE policy with schemes and approaches adopted by the leading players in the global OWE sector. Lastly, this thesis aims to suggest an optimal energy mix for creating energy security and mitigating insurance losses due to climate change-induced catastrophes.

Through extensive literature review supported by expert verification gave insights into the existence of 46 sub-barriers categorized into seven broad barriers that hinder the growth of OWE in India. These barriers were systematically prioritized using the Fuzzy Analytical Hierarchy Process (Fuzzy AHP). Results show that initial capital, social acceptance, visual and noise impacts, and the underdeveloped offshore industry are the top four barriers overall that need immediate attention. The United Kingdom, Germany, and China are the global front runners in OWE deployment. Therefore, these countries' policies and schemes must be examined, and lessons learned from their success can be implemented for the Indian OWE sector. The NOWE policy is compared with schemes and strategies adopted by the leading OWE countries in the financial, infrastructural, and environmental aspects. Some of the key findings include NOWE policy ignored the offshore wind-specific incentives and subsidies while China, Germany, and the UK provided OWE-specific financial support schemes at their early stages of OWE development. Further, NOWE policy ignored the scope for demonstration projects to build investors' confidence and limited attention in risk mitigation strategies, especially climate change-induced catastrophes.

The exposure of OWE to climate change-induced catastrophes is higher compared to onshore wind. Indian OWE sector faces the risk of cyclones, and insurance will play a crucial role in transferring the risk. On the other hand, insurance companies should diversify their portfolio to minimize losses. A diversified energy portfolio can build energy security and reduce losses due to the negative correlation between the energy sources in variability, cost, and risk to peril. A diversified energy mix includes the combination of OWE turbines, solar panels, lithium-ion batteries, grid connections, and diesel generators. Both grid-connected and off-grid solutions are proposed to find an optimal solution for minimizing insurance losses because of climate change-induced catastrophes. Simulations are run through Hybrid Optimization of Multiple Energy Resources (HOMER). From 24 options that are shortlisted from the simulation, four (optimal grid-connected, optimal off-grid, a diversified energy portfolio, and 100% renewable energy solution) are selected and ranked based on their techno-economic and environmental characteristics. Results suggest that the optimal grid-connected option has the lowest economic features. 100% renewable energy solution has zero emissions, signifying its environmental benefits. Sensitivity analysis is used to validate the simulation results. This study furthers the existing knowledge of OWE, its barriers, policy recommendation, and optimal solution suggestion for reducing the risks and insurance losses and building energy security.

ACKNOWLEDGMENT

The completion of this thesis would not have been possible without the guidance, support, and encouragement of my supervisor Dr. Anil Kumar. In the initial years of my Ph. D. journey, his constant advice and direction helped me to reach the goals in publishing, writing, reading and all aspects that are crucial for developing a comprehensive thesis. My initial doubts and the fear of whether dropping the corporate job for pursuing my quest for answers to my curiosity was right or not, needed special attention and a delicate approach. Dr. Anil Kumar with his patience and composure guided me through my most anxious days with panache. His approachability to any issue, not just concerning my professional work, made him my closest ally for the rest of my life. He once said, "the output of this journey is not a thesis, rather it is you". Today, I see a different me, wiser, mature, patient, dedicated, humbled, confident and many more qualities that I was missing from when I started the journey, I give full credit to Dr. Anil Kumar for transforming me.

This study does not just belong to me, it belongs to the School of Business, UPES. I recall 30 plus DRF seminars that I presented in front of some of the top academicians of the country have resulted in redirecting my work into heights and quality. Dr. Tarun Dhingra has mentored me in all the research aspects. I am lucky to have worked with a wonderful man with astonishing passion towards research. His presence in my journey, I value priceless!

The first person I interacted with before deciding on becoming a researcher was Dr. Mohammad Younus Bhat. I cannot thank him enough for the support he provided. He is one of the most hard-working person I have ever seen, I got inspired by him and I started to replicate his style by burning the mid night oil on regular basis, asking questions which the research community is yet to find answers for and developing a enthusiasm towards exploration. Dr. T. Bangara Raju is a pillar of my strength through this journey. The conversation I had and continue to have with him has pushed my intellectual boundaries far ahead. The opportunity I got to work with Dr. Anita Sengar helped me in understanding key research tools and opened my horizons of knowledge.

I want to extend my thanks to Dr. Neeraj Anand, Dr. P.C. Bahuguna, Dr. Pankaj Kumar, Dr. Binod Kumar Singh, Dr. Rajesh KS, Dr. Hiranmoy Roy, Dr. Sumeet Gupta, and Rahul Nainwal who helped me in various stages of my intellectual growth. I am also extending my gratitude to all my fellow scholars who have inspired, encouraged, motivated, and stood like a rock though out this wonderful journey. The emotional support from my parents and brother is monumental.

I started my Ph.D. journey in confusion, but in the end, I realized this was the best decision I have taken in my life, the credit must go to my wife Dr. Aswani RS. The reason why I left my comfort zone to an all-new world was because of her. Thanking her in a few sentences will never do justice to the hard yards she put in, the sacrifices she made, the energy and excitement she had for every single moment of this journey.

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LIST OF ABBREVIATIONS

RE	Renewable Energy
GHG	Greenhouse Gas
OWE	Offshore wind energy
CO_2	Carbon Dioxide
SO_2	Sulfur Dioxide
NO_2	Nitrogen Dioxide
FIT	Feed-in Tariff
UK	United Kingdom
GW	Gigawatt
MNRE	Ministry of New and Renewable Energy
NIWE	National Institute of Wind Energy
NOWE Policy	National Offshore Wind Energy Policy
EEZ	Exclusive Economic Zone
USA	United States of America
MW	Megawatt
NIMBY	Not in my back yard
CfD	Contract for Difference
OWF	Offshore wind farm
COP	Conference of the parties
GBS	Gravity based structures
MSP	Marine Spatial Planning
PV	Photovoltaic
IPCC	Intergovernmental Panel on Climate Change
FOWIND	Facilitating offshore wind energy in India
CAT Modeling	Catastrophe Modeling
OWZ	Offshore wind zones
GIS	Geographic information system
O&M	Operations and Maintenance
WT	Wind Turbine
LCOE	Levelized Cost of Electricity
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
ANP	Analytic network process
ELECTRE	ELimination and ChoiceExpressingREality
DEMATEL	Decision making trial and evaluation laboratory
AHP	Analytic Hierarchy Process
PROMETHEE	The Preference Ranking Organization METHod for Enrichment of Evaluations
THB	Technical Barriers
FIB	Financial Barriers
R&PB	Regulatory and Political Barriers
SOB	Social Barriers

SUCB	Supply chain Barriers
INB	Institutional Barriers
GEB	Geographical Barrier
HRES	Hybrid Renewable Energy Solutions
COE	Cost of Energy
MPT	Markowitz’s Modern Portfolio Theory
RPS	Renewable Portfolio Standards
MCDM	Multi Criteria Decision Making
FAHP	Fuzzy Analytic Hierarchy Process
HOMER	Hybrid Optimization Model for Electric Renewables
NREL	National Renewable Energy Laboratory
NPC	Net Present Cost
DOD	Depth to discharge
DG	Diesel Generator
DC	Direct current
AC	Alternate current
SGRE	Siemens Gamesa Renewable Energy
STP	Standard temperature and pressure condition
TNPC	Total net present cost
SLR	Systematic Literature Review
PPA	Power purchase agreement
TGC	Tradable green certificate
EIA	Environmental impact assessment
NID	National Infrastructure Directorate
IOR	Indian Ocean Region
OSOG	Optimal Solution Off-grid Solution
DPG	Diversified Portfolio with Grid
OSG	Optimal Solution Grid-connected Scenario
$N_2 0$	Nitrous oxide
RES	Renewable energy sources

CHAPTER 1

INTRODUCTION

Sustainable Development Goal (SDG) 7 points out the use of clean, reliable, and affordable energy for all by 2030 as an action to mitigate climate change. Shifting from fossil fuels and investing in renewables will reduce Greenhouse Gases (GHG) and hold global temperature below 2° C above pre-industrial levels. Renewable Energy (henceforth RE) made up 29 % of global electricity generation in 2020 (IEA et al., 2020). Global investments in energy need to be doubled to reach the SDG target. The global population lacking access to electricity stood at 13 %, which is equivalent to 570 million as of 2020 (Bhat et al., 2022) The energy investments must be at $55 million to expand energy access. The investments in RE must be at $600 million to be in line with SDG. Efficiency can be improved with a minimum investment of $700 million between 2018 and 2030 (IEA et al., 2020). Shifting to 100% RE is unrealistic since the current market architecture. Scalability and cost are among the most discussed challenges (Blazquez et al., 2018).

The Asia-Pacific region produced 17.74 billion CO_2 emissions in 2021. China reported 60% of Asia-Pacific emissions and 27% globally. With the massive urbanization and investments in Belt and Road Initiatives (henceforth BRI) demanding more energy than ever before. Coal contributes to most of China's power and is responsible for 70% of dust emissions, 67% of NO_2, 70 % of carbon, and 90% of SO_2 (Wang et al., 2016). China's economic growth at the expense of environmental degradation needs to be addressed through effective policies that could reduce the emissions and consumption of fossil fuels (Zhang, 2010). However, the use of clean coal in China has a particular negative bearing, such as low legal liability for pollution and a lack of laws relating to the use of coal. The policies are also in the incumbent stages (Tang et al., 2015). China is committed to improvement in RE with targets and promoting legislation and regulations to enlarge the production of RE (Hua et al., 2016). China has been developing RE since 2000 actively, with an annual average growth rate of 62.5% over the previous decade. China has plans to achieve 16% RE by 2030, while studies point out the plans can be exceeded by 26% by 2030 and 86% by 2050 (Yang et al., 2016). Investments in new energy sources are critical for these achievements, massive power projects that could boost the energy mix through R&D for efficient, affordable, and cleaner energy sources. The contributions from the government in support of such projects are vital, the RE law was passed in 2005, and further amendments were made in 2009. Subsidies and incentives formed the backbone of the initial policies to enable RE investments. Subsidies and incentives are financial support granted by the government to help the industry to keep the prices of commodities or products low. China established a policy on RE targets, a mandatory purchase and connection policy, feed-in tariffs (henceforth FIT) system, and arrangements for cost-sharing and incentives for funding RE (Schuman & Lin, 2012).

Germany is proactive with its ambitions in RE policies, even though the nuclear phase-out has created more energy insecurity, and coal was removed from remaining as a substitute due to the emergence of the climate change debate. In 2011, the conservative German government announced Energiewende (Energy Transformation), and a decision was taken to reduce the fossil fuel supply constituting 80% to 20% by 2050 (Renn & Marshall, 2016).

Renewable energy policies in the UK until 2003 were concentrated on cost-limiting caps, opportunism, and lack of clarity arising from continuous adjustments. Non-fossil fuel obligation failed deployment, failed to deliver diversity, and benefited large corporates. The UK government published visionary statements in 2003 to reduce CO_2 emissions by 60% in 2050 (Mitchell & Connor, 2004). The government introduced low carbon policies supporting renewable heat initiatives and FIT, which promoted solar energy production by 2010. The principal mechanism driving RE growth is Renewable Obligation in the electricity sector to meet the targets to reduce emissions (Anandarajah & Strachan, 2010).

India's commitment to combat climate change need an active deployment of RE technologies. Now, fossil fuels, particularly coal, make up the majority of the installed power capacity. India had an installed generating capacity of 407.8 GW as of September 2022. This installed generating capacity is powered by fossil fuels to a degree of over 58%. India has the fourth largest onshore wind installed capacity in the world. Wind energy is a sustainable energy source for meeting rise in energy demand, and Offshore Wind Energy (henceforth OWE) is identified as a stable renewable source with significantly higher capacity factor of 40-50%. The Government of India has taken measures to tap into Indian coastal wind resources. India's target is to reach 30 GW of OWE by 2030. India has a 696 GW OWE potential at hub heights of 120 meters. Tamil Nadu, Gujarat, Karnataka, Andhra Pradesh, Maharashtra, Rajasthan, and Madhya Pradesh are the states with the most potential. India's 7,600 km of coastline has excellent prospects for developing OWE. Considering the natural resources, the National Offshore Wind Energy Policy (henceforth NOWE policy) was drafted in 2015 to enable the employment of OWE in Indian territorial waters. The Ministry of New and Renewable Energy (MNRE) will be the nodal agency for the development of OWE, responsible for the monitoring of OWE and working in coordination with other entities to develop Marine Space within the Exclusive Economic Zone (NMRE, 2015). The National Institute of Wind Energy (NIWE) will carry out resource assessment, demarcate blocks for OWE and conduct studies and surveys in India's Exclusive Economic Zones. The cost of OWE has seen a steady decline with new foundations and structures which make the wind generation in an efficient manner. MNRE set a target of 5 GW of OWE installation by 2022 and to reach 30 GW by 2030 to build confidence among the developers and investors. However, the sector is yet to take off owing to significant barriers. Thus, it is vital to understand why India's OWE sector is yet to take off. A critical analysis of the NOWE policy compared to policies adopted by leading countries in the OWE sector may eliminate the existing barriers.

1.1 Wind Energy

With the looming energy crisis, wind energy can step in to meet the energy demand and provide steady clean energy. Wind energy can substitute non-renewables, and with favorable policies from the government, more investments can be brought in, adding to the energy mix. Wind energy has limitations, but a careful application with grid integration, feasibility assessment with wind speed, consistency assessment, and effective wind farm design can reduce them (IRENA, 2019). Most of the wind farms are located far from energy-demanding populous regions. The transmission of electricity from the mountainous areas (having excellent wind resources) to the plains faces up to 10% transmission losses. The Inner Mongolian region in China produces steady onshore wind energy. Still, its location is 2500 kms away from the most populated area of the southeastern coast of China, the transmission of power is cost-intensive, and transmission losses are the challenges faced (Han et al., 2009). Developing wind energy from the coastal region is a solution for steady, predictable, and consistent wind for countries with extensive coastlines and high energy demand. Offshore wind energy is constructed and installed in the Exclusive Economic Zone (EEZ) to capture the steady wind and connect it to the grid to deliver to the energy-demanding population.

1.2 Need for Offshore wind energy

1.2.1 Safe for Ecosystems

The impact of wind farms on local wildlife and the ecosystem has been analyzed by many studies previously. For example, approximately 75,000 birds die in collision with wind turbines in the USA alone. However, only a handful of studies prove the negative impacts of OWE on the marine ecosystem. But most studies conclude the benefits of wind turbines and their foundations as a breeding platform for a new ecosystem (Furness et al., 2013).

1.2.2 Few Natural Resources Required

The energy generated per kilometre of OWE wind farms is lower than its onshore counterparts. The land availability in the onshore wind sector has hindered progress in many Asian countries such as India, Japan, and China. For the latest technologies, such as floating turbines, the changes that must be made to the sea surface are limited. Onshore wind farms require clearance of vegetation, moving wildlife, piling, levelling, and making an alteration to the landscape.

1.2.3 Efficiency

The wind in the oceans is more consistent and frequent than onshore wind. The wind power generation and its output are obstructed by mountains, buildings, and hills. On the other hand, shoreline turbines are installed in the open sea. An average onshore wind turbine of 1 MW capacity produces electricity for 500 households (Guo et al., 2022). However, an offshore wind turbine of the same capacity can provide energy for over 920 households annually.

1.2.4 Noise and Visual Effects

One of the most significant shortcomings of wind turbines is that they can by noisy. It produces broadband noises due to the revolving rotor blades contending with air turbulence. Not In My Backyard (NIMBY) protests in Europe sparkled around the visual and noise impacts of land-based wind farms, have gained attention, and caused severe losses for energy producers. In contrast, OWE farms are constructed within 200 nautical miles from the shoreline causing limited distress to human activities (Pires et al., 2022).

1.3 Global Offshore Wind Outlook

The offshore industry has taken off in recent years, with Europe leading with 84% (15,780 MW) of the installations in 2017; China accounts for the remaining 16%. The United Kingdom has the largest wind market in the world, accounting for 36%, followed by Germany at 28.5% (Herzig, 2022). Europe's net addition to offshore capacity in 2019 stood at 3,623 MW, increasing the total capacity to 22,072 MW with 5,047 grid connected OWE turbines across 12 countries. In 2019 alone, 502 grid-connected turbines were added. It is predicted to grow by 19.1% yearly to reach 150 GW of OWE installed capacity by 2030 (Mikami et al., 2022). At the end of 2019, the UK had 40 wind farms with 9,945 MW of cumulative capacity run by 2,225 grid-connected turbines. The UK has created a procedure for single-window clearance, which has eased the procedural difficulties in offshore project developments (Mani & Dhingra, 2013). Contract for difference (CfD), a scheme that was introduced in the Energy Act of 2013, echoed Feed-in Tariffs (FIT) with cost control during auctions, and fluctuating electricity prices were in operation in auction round 1 in 2014 and auction round 2 in 2017. A CfD can be defined as an incentivized investment of RE by providing project developers with an upfront cost and protection against volatile wholesale prices. The CfD was perfect for OWE in the UK and its progress; however, the design of the auctions increased speculative bidding. The auctions were designed for a one-shot, preventing bidders from effectively using the information. The German offshore wind industry has matured with innovation and had the world's first *subsidy-free* bids. This resulted in tremendous confidence in the technology and opportunities for the investors to compete with fossil fuel counterparts on the wholesale price of electricity (Fig. 1.1).

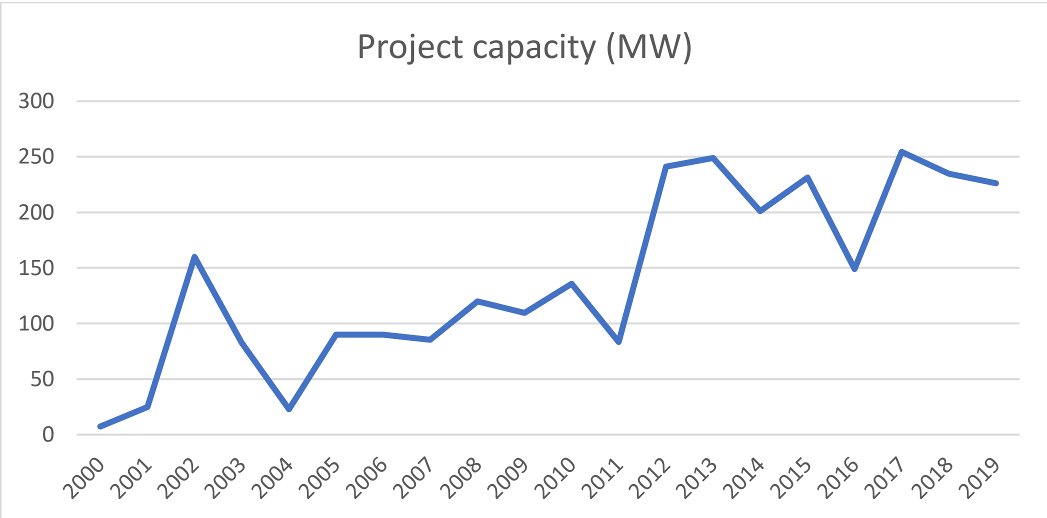

Fig 1.1 Global offshore wind project capacity in MW (2000-2018) (Herzig, 2022)

Germany currently has 7,445 MW of cumulative capacity, 559 turbines connected to the grid, and 28 wind farms. The total addition in 2019 was 1,111 MW with 160 grid-connected turbines. The offshore wind policies adopted by the German government are framed in a futuristic perspective in the Renewable Energy Act, 2014; more precise segregation in offshore and onshore was drafted, and more robust support schemes were provided for the former, considering the cost involved. Erneuerbare-Energien Gesetz 2017 (EEG, 2017) offered the “paradigm shift” from FIT to a system based on auction remuneration. Every renewable is designed to get a tailor-made auction, and this is a significant change in the electricity system allowing it to be market-driven (WWEA, 2018). In Denmark, offshore wind farms (OWF) are commissioned in a competitive tender process, and the cost of production of electricity is reflected in a FIT (DEA, 2015). The global offshore wind turbine rating has mainly increased over the last two decades, largely due to European governments' financial and technological support (Fig. 1.2).

China is currently ranked third in OWE; however, the projections look promising for China for 2031, as its total installed capacity will rise to 39 GW, the UK will have the second spot with 19 GW, and the entire Europe combined will have 49 GW (Musial & Nunemaker, 2018). The growth of China’s offshore wind power sector was slow from 1996 to 2005. However, the growth picked up after a series of incentive schemes and formulating of a structure favorable for OWE in production and consumption until 2013 (Fig. 1.3).

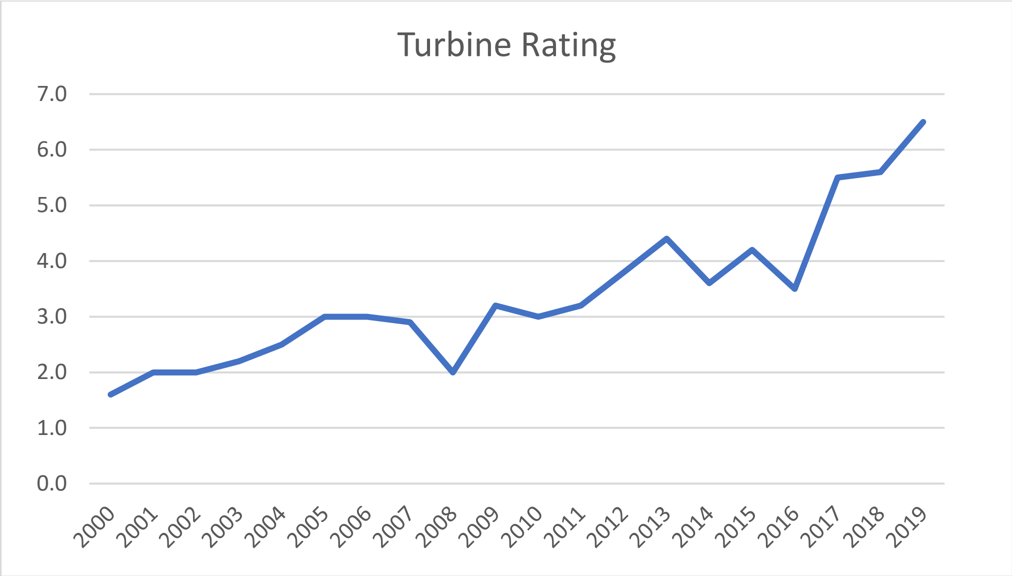

Fig 1.2 Global Offshore wind turbine rating (2000-2018) (Herzig, 2022)

After 2014, China saw a drop in its patents in OWE with regulations and rising quality standards bar by the government (H. Zhang et al., 2018), (Surana & Anadon, 2015). China set its tariff for OWE at 0.85 yuan per KWh, which is generous and reliable for wind farm developers to invest in OWE. During the same period, coal-fired power plants received an average of 0.42 yuan/kWh (Wei et al., 2021a). The CO_2 emissions have increased despite the introduction of new technologies that can generate energy without emissions, which is a result of increased coal consumption, along with oil and natural gas imports (Pan et al., 2021).

1.4 The need for offshore wind in India

Economic growth and energy consumption have a positive correlation in most countries. Energy consumption through non-renewables incurs carbon emissions, which degrade the environment. Renewable energy is clean, abundant, and relatively untapped. India relays heavily on imported coal, oil and gas to meet its energy needs. The dependence on foreign fossil fuel imports has left India with energy insecurity. The war in Ukraine is a strong example, Germany's over-dependence on Russian gas has left the former with no option but to go back to coal consumption to meet their energy requirements. Such as, an increase in coal consumption will diminish the chances of meeting climate goals set in Paris COP 21.

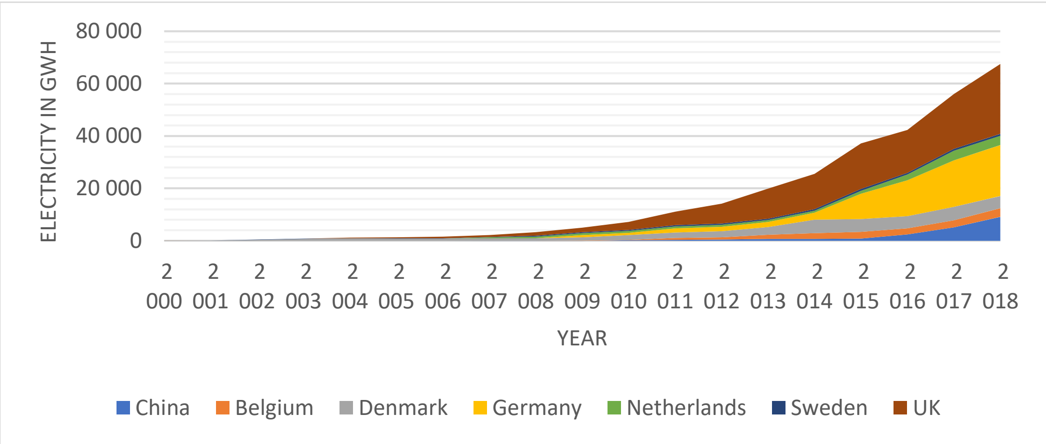

Fig 1.3. OWE generation among the leading producers (GWEC, 2021)

The advancement in technology and fall in cost has encouraged more countries to OWE investments. As a result, OWE is a front runner in policy formulation in reaching the SDG 7 target of accessible, affordable, and cleaner energy solutions. However, the percentage share of OWE in total RE generation is only 1.3% as on 2020 (Fig. 1.4).

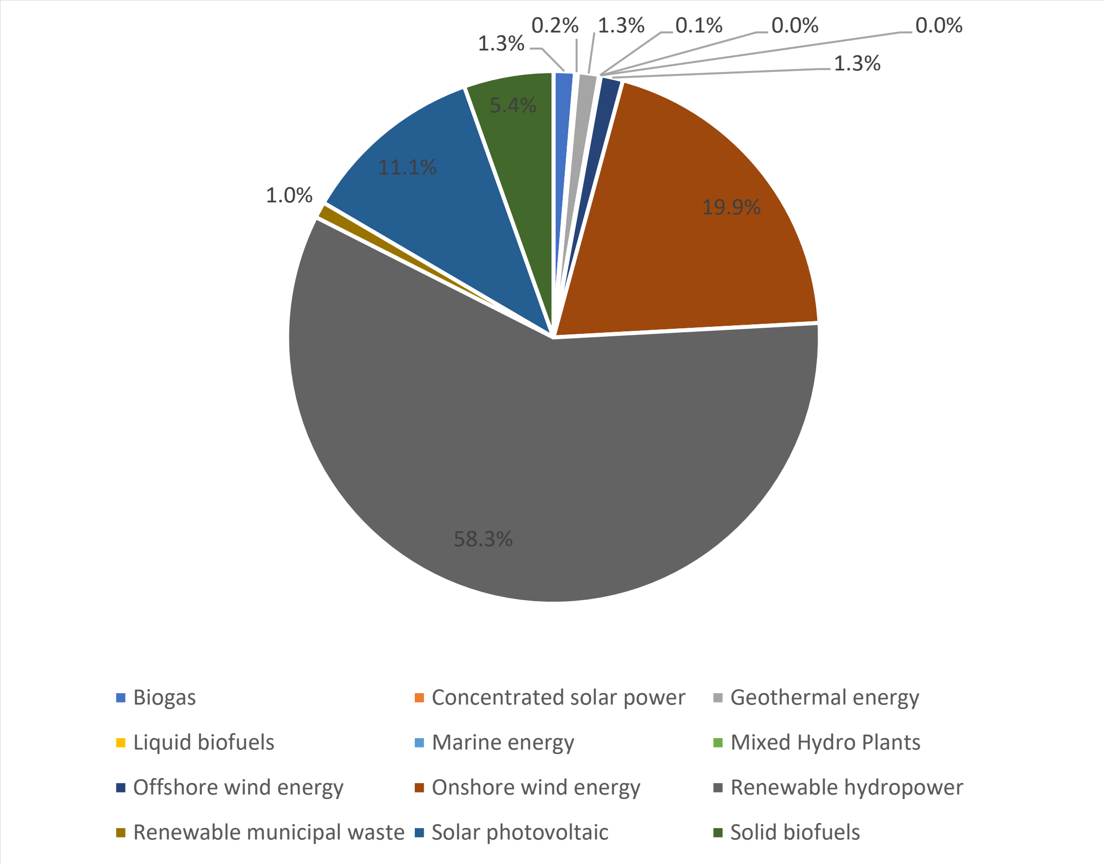

Fig. 1.4 Global share of Renewable energy technologies (GWEC, 2021)

India's energy demand is projected to rise by 50 % between 2019 and 2030, and sustaining this demand requires a significant rise in renewable energy (henceforth RE) sources (Bhat et al., 2021). India, in COP26, pledged to reach net zero by 2070 and meet the energy demand of 2030 with 50% renewable energy sources. As of 2021, India is ranked third in the renewable energy attractive index, the target is to reach 175 GW of RE by 2022 and expand to 500 GW by 2030 (Bhat et al., 2022). India's RE capacity has increased by 286% during the period 2013-2021, which is 39% of total power (investindia, 2021). India has the fourth-largest installed capacity of wind energy globally, constituting 40.08 GW as of December 2021. The growth of wind energy in India is restricted to onshore wind energy, while India is yet to start its energy generation from OWE. The worldwide offshore wind capacity as of 2020 was 35.3 GW, and China, the UK, and Germany formed 75% of the global installed capacity (IRENA, 2021).

1.5 Types of Offshore Wind Energy Foundations

1.5.1 Monopile technologies

Monopile technologies are designed for shallow waters with depths not exceeding 30 m. The maximum power that can be generated in 4 MW. The smaller size of the foundation brings the advantages of low cost, simplified design, rapid fabrication, flexibility in installation, and vast offshore deployment (Fig. 1.5). At the same time, the proximity to land increases visual impacts and noise while piling. The turbine requires heavy lift vessels and frequent maintenance. The ideal location for a monopile foundation is mainly soft soil or surfaces which need driving and drilling. The diameter of the foundation ranges from less than 6 m to and mass that does not exceed 650 tonnes. It consists of a single steel pile embedded into the ocean surface.

1.5.2 Gravity-based structures (GBS)

This structure is installed at a depth not more than 40 m, with a structured mass of 2000-3000 tonnes and a ballast mass of 1500-2500 tonnes. GBS is constructed in a barge or yards and transported to the site. GBS requires the seabed to be flat, firm, and unsuitable for soft soil (Fig. 1.6). Concrete is the dominant material used in GBS foundations. Thus, fatigue and corrosion risks are lower than in monopile technologies. These foundations are best suitable for the sea floor with a rich marine ecosystem.

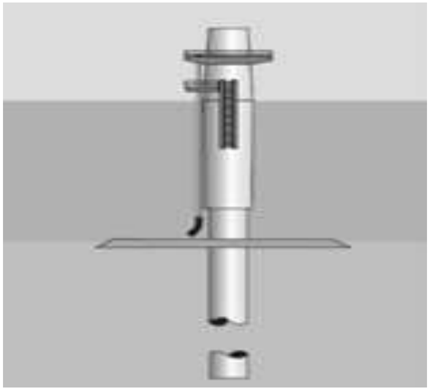

Fig. 1.5 Monopile turbine foundation

Gravity-based structures need specialized vessels for their transportation and installations. Due to their massive size, the construction is a lengthy process, fabrication will be slow, and requires a skilled workforce with experience in deep-water. In addition, preconstruction works such as sea-bed preparation may add to the construction period.

1.5.3 Jacket

Jackets have four metal piles connected to a lattice, providing strength and stability to the structure (Fig. 1.7). In addition, they have thinner individual sections better suited for mass fabrication and automation. The jacket can be installed in the ocean with a water depth of fewer than 50 m and can generate 4-8 MW. However, jackets with many welds and joints often require expensive casting. In addition, jackets often encounter frequency constraints and high pile tension loads.

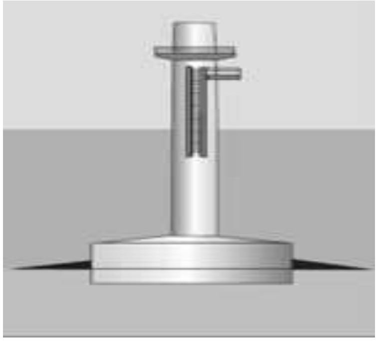

Fig. 1.6 Gravity based turbine foundation

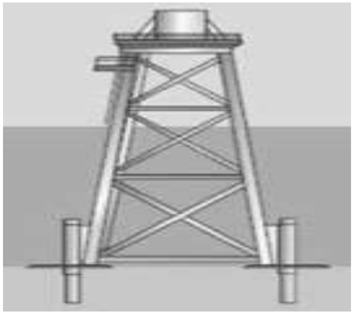

Fig. 1.7 Jacket OWE foundation

1.5.4 Tripode Foundations

These are three-legged foundations made of cylindrical steel tubes. Tripode is well suited for depths between 20 and 40 m producing 4-6 MW (Fig.1.8). The base width can be altered to suit the sea surface conditions. In comparison with Jackets, tripode reduces welds and requires no transition sections. However, they limit the ability to fabricate in sections. They are typically higher in mass and cost in comparison to jackets. Tripode requires large vessels and creates pile tension problems. In addition, they need thick plates and significant welds, making automation difficult.

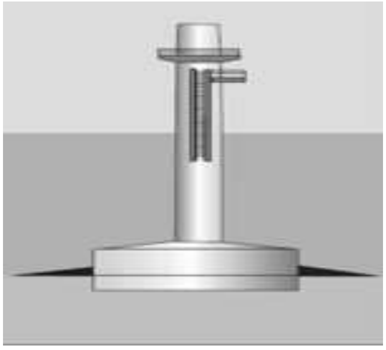

Fig. 1.8 Tripode OWE foundation

1.5.5 Tripile

Like tripode foundations, tripiles consist of individual steel tubes which carry a crosspiece. The wind turbine is held on the crosspiece above sea level (Fig.1.9). The steel mass is more extensive than the jacket generating 3-6 MW. A typical transition piece connects piles. It has a standard transition piece for a range of water depths from 25-40 m. It is an extensive structure visible above sea level. The pile diameter is usually larger than a jacket.

Fig.1.9 Tripile OWE foundation

1.5.6 Pile Cap

The pile cap comprises 8-16 small diameter raking piles driven to a considerable depth (Fig. 1.10). It is suitable for soft soils, and its depth can be up to 15 m, generating less than 4 MW. The vessels required can be smaller, and the welding required is relatively less. However, pile caps face risks of wave run-up on a pile cap and high wave loading.

Fig. 1.10 Pile cap OWE foundation

1.6 Risk of offshore wind energy

Offshore wind energy is exposed to many risks, essentially its location in hostile ocean conditions. The risk of inconsistency in maintenance and servicing may shorten the lifespan of the turbines. Another danger involved in the smooth operation of wind farms is the possible conflict with different stakeholders who share the marine space. The risk of collision of ships, if the turbines' location is near famous shipping lines, and damages to cables when ships are anchored are risk projections. However, these kinds of risks can be mitigated by employing Marine Spatial Planning (MSP). MSP is a public process of identifying and allocating marine locations based on the temporal and spatial distribution of human activities to achieve economic, social, and ecological objectives and maintain equilibrium among the stakeholders. The displacement of marine habitats and the impact on marine mammals on wind turbines' very existence is not a sustainable practice. Thus, careful assessment of the risk that OWE exposes to various stakeholders needs further analysis. Bird migration is affected after the installation of offshore wind turbines. The bird collision with the turbines has raised concerns about their endangerment (Hüppop et al., 2006). The size of the turbines has a significant impact on marine mammals and their migration. Construction of offshore wind turbines includes high sound pressure, with pile-driving being the nosiest. This can cause close-range hearing impairment in shallow marine mammals (Madsen et al., 2006). The underwater sounds and electromagnetic fields do impact the marine ecosystem while positive effects on functioning as artificial reefs and acting as a no-take zone for the aquatic species, with possible spillover effect (Punt et al., 2009)

Technical risks such as design, innovation, infrastructure, and curtailment risks affect the energy generated and transmitted to the grid. Such variation may cause losses to the producer and distribution companies. Unfortunately, the options to mitigate those risks are also limited. However, the recent technological advancement and sharing of best practices have improved the technical quality. As a result, most issues relating to operation and maintenance activities have been reduced in the past decade.

Financial risks of capital availability, price volatility, and credit accessibility caused stagnation in project development. These risks can be mitigated through effective policy intervention. Germany's initial policy to provide subsidies for OWE has given rich dividends and the fast expansion of OWE sector. The harsh environmental conditions, along with the higher probability of damage due to storms, should be a key consideration in the risk modelling of offshore wind farms.

1.7 The variability nature of renewable energy

Variable renewable energy such as wind and solar are inconsistent in their supply. Wind and solar depend on natural forces which cannot be controlled. At the same time, hydropower and bioenergy are controllable renewable energy sources. An energy provider who depends largely on variable energy may risk meeting the demand and the possibility of supply exceeding demand. Storage systems and demand responses will play a critical role in balancing demand and supply.

Offshore wind has a capacity factor of 40%-50%, doubling solar PV, exceeding onshore wind, and matching capacity factors of coal-fired power lands and gas-fired power plants in some regions (Fig. 1.11). In addition, the hourly variability of OWE is lower than that of solar PV. OWE fluctuates within a narrow band, less than 20% from the hour-to hour ; in comparison, solar PV fluctuates up to 40%.

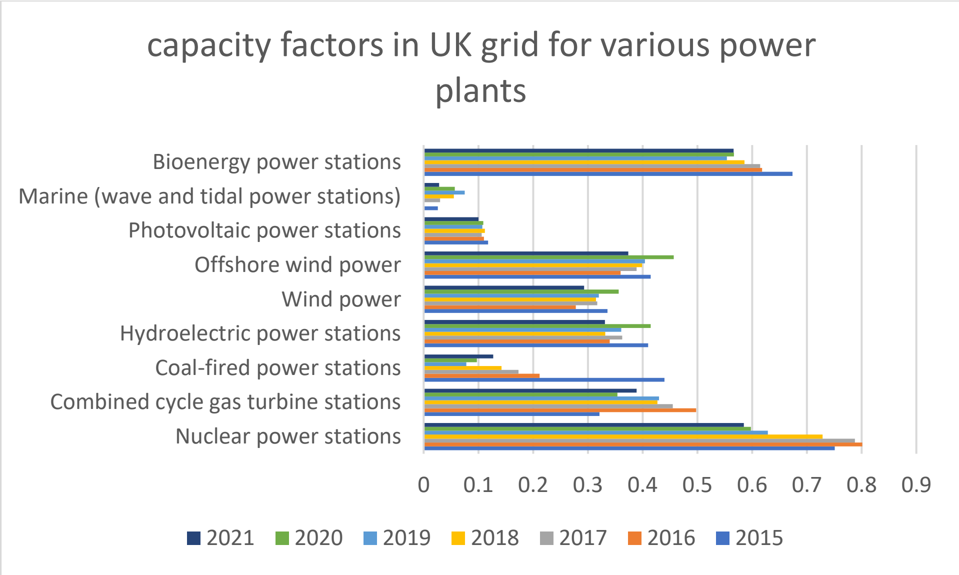

Fig. 1. 11 capacity factors in UK grid for various power plants (IEA) (GWEC, 2021)

1.8 The Vicious Circle of Climate Change

Climate change induced catastrophes such as windstorms can cause damage to wind turbines causing energy insecurity. The demand for energy is met by coal consumption which in turn amplifies global warming due to more GHG in the atmosphere. As result of climate change windstorms increase their intensity, frequency, and impact. These changes in weather patterns are not irreversible unlike climate change induced sea level rise. Limiting the global temperature below 2°C above pre-industrialization can keep the windstorms in manageable levels. For this objective a large-scale deployment of renewables along with carbon capture and storage technologies are needed.

Offshore wind energy is exposed to a wide range of risks, that can be classified into environmental risk, infrastructure risk and financial risks. These risks need to be mitigated through an effective diversification strategy or risk transfer mechanisms such as weather bonds or insurance. Insurance is a solution in risk mitigation for all the above risks in exchange for a premium quoted by the insurance provider. Diversification of offshore wind farms creates an opportunity for insurance companies to mitigate risks (Table 1). However, there exists a gap for alternative risk-mitigating strategies apart from insurance and diversification (Gatzert & Kosub, 2016).

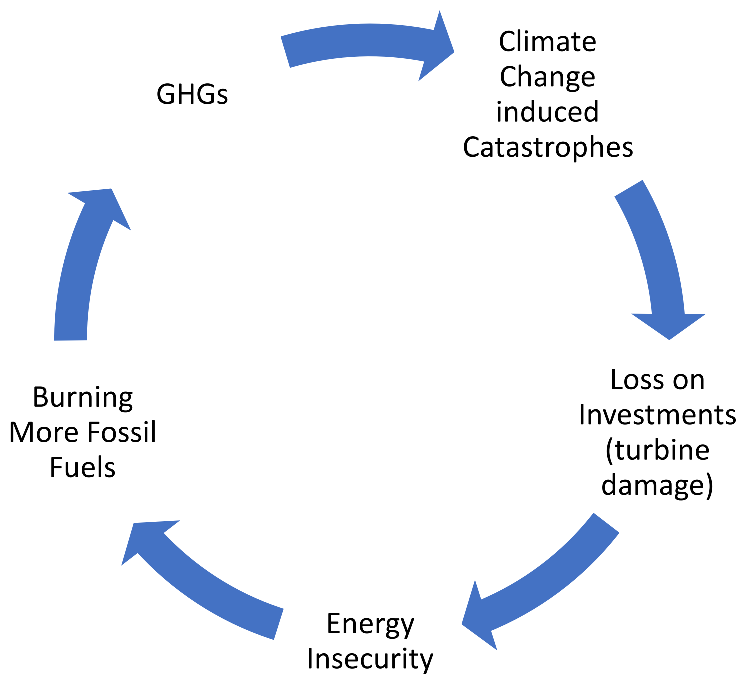

Fig 1.12 The vicious circle of climate change

Table 1.1 Risks offshore wind energy turbine/generation is exposed to

Si No	Risks	Classification	References
1	Weather related risks	Environmental Risk	(Gintautas & Sørensen, 2017; Yue et al., 2020)
2	Maritime environment	Environmental Risk	(van Hal et al., 2017)
3	Risk of conflict with maritime traffic, fishing zones and marine protected regions	Environmental Risk	(Ashley et al., 2014)
4	Risk of offshore wind turbines to marine habitat	Environmental Risk	(Pezy et al., 2020)
5	Geopolitical Risk	Environmental Risk	(R. Aswani et al., 2021a)
6	Policy Risk	Financial Risk	(Mani & Dhingra, 2013c)
7	Complex and long approval procedure	Financial Risk	(Chung, 2021)
8	Instability in subsidies and incentives	Financial Risk	(Dhingra et al., 2022)
9	Security risk	Infrastructural Risk	(R. Aswani et al., 2021b)
10	Construction delay	Infrastructural Risk	(Leontaris et al., 2017)
11	Design flaws	Infrastructural Risk	(Feld, 2004)

12	Innovation Risk	Infrastructural Risk	(Reichardt & Rogge, 2016)
13	Curtailment Risk	Infrastructural Risk	(X. Sun et al., 2012)
14	Infrastructure Risk	Infrastructural Risk	(Díaz & Guedes Soares, 2020a; Oh et al., 2018a)
15	Lack of Repair	Infrastructural Risk	(Carroll et al., 2016)
16	Maintenance Risk	Infrastructural Risk	(Ren et al., 2021)
17	Replacement and decommissioning	Infrastructural Risk	(McAuliffe et al., 2019; Topham & McMillan, 2017)
18	Wear and tear	Infrastructural Risk	(Yeter et al., 2015)
19	Capital Risk	Financial Risk	(Mani & Dhingra, 2013c)
20	Insufficient access to credit	Financial Risk	(Dhingra et al., 2022)
21	Uncertainty of revenue due to price volatility	Financial Risk	(R. Aswani et al., 2021b)
22	Absence of Risk Transfer (Absence of Insurance, diversification)	Financial Risk	(Liao et al., 2021)

1.9 Climate Change-induced Catastrophes

The catastrophes linked to weather extremes are part of the Earth's system. However, the increased human activities by burning fossil fuels have led to a rise in temperature, causing widespread draughts, heatwaves, and storms (cyclones, typhoons, and hurricanes). These catastrophes have increased their frequency, intensity, and impact in recent years, causing widespread damage to life and property as never experienced before (United Nations Climate Change, 2018). Now, about 90% of weather-related disasters are caused by climate-related or climate change-induced catastrophes. The damage is accounted to be $520 billion in 2021, pushing 26 million people into poverty (Russo et al., 2022). Understanding the trend and making room for policy changes in mitigation and adaptation becomes increasingly important for countries. The new global economic order should be for increasing the green growth initiatives, unplugging carbon-intensive consumption practices, and developing adaptive measures to reduce the impact of climate change-induced catastrophes.

In the last decade, the frequency of catastrophes recorded in the Emerging Events Database has shown a threefold increase (Fig. 1.13). The increase was from 1300 in 1974-84 to 3900 events in 2005-14. The annual category five storm increased three times between 1980 and 2014. The increase in hydrological and meteorological events are significant during this period. Investments towards disaster reduction are relatively low, especially in developing countries. Japan faces larger risks in geophysical and hydrological disasters, and the country invests 5% of its national budget in risk deduction measures. The global average is $0.40 cents spent on disaster risk deduction for every $100 in total development aid. Studies previously have identified a 1%-2% is the ideal budget for risk reduction, but the question is its spending effectiveness in the developing countries.

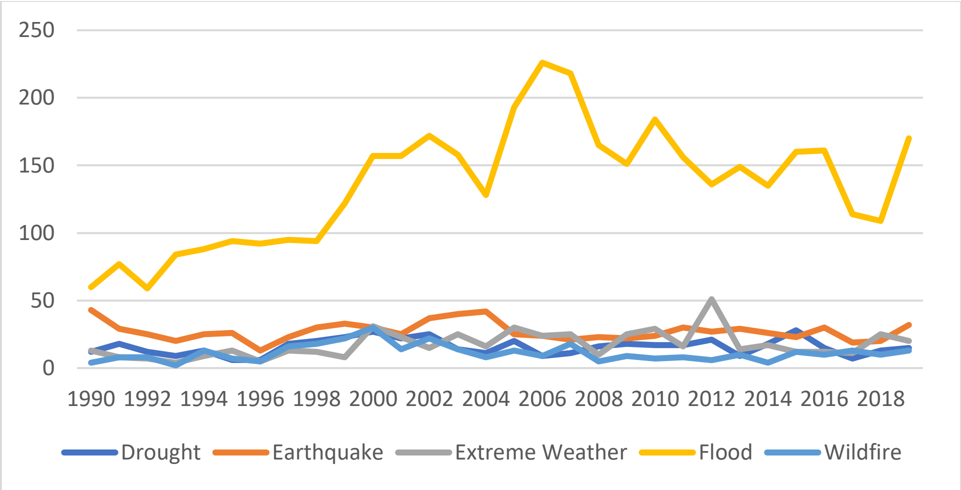

Fig. 1.13 Frequency of catastrophes by type from 1990 to 2018 (IPCC, 2021)

The IPCC disaster risk framework exhibits the following linkages affecting climate change-induced catastrophes.

- The temperature and precipitation are affected by climate variables that re-altered by the emission of greenhouse gases (GHG).
- The changes in climate variables due to emissions increase the frequency of catastrophes
- The frequency of catastrophes increases the chances of risk of natural disasters.

The relationship between greenhouse gas (carbon dioxide, nitrous dioxide, methane, and hydrofluorocarbons) emissions and global warming are of considerable discussion. The ocean surface temperature rises with the earth's temperature as the GHGs increase (Fig. 1.14). As a result, the ice melts, and the sea level rises to flood the low-lying islands. This temperature rise is a threat to coral bleaching, impacts fish migration, ocean acidification, and dawning wetlands, and sends across an alarming, dangerous feedback loop that intensifies the disastrous effect.

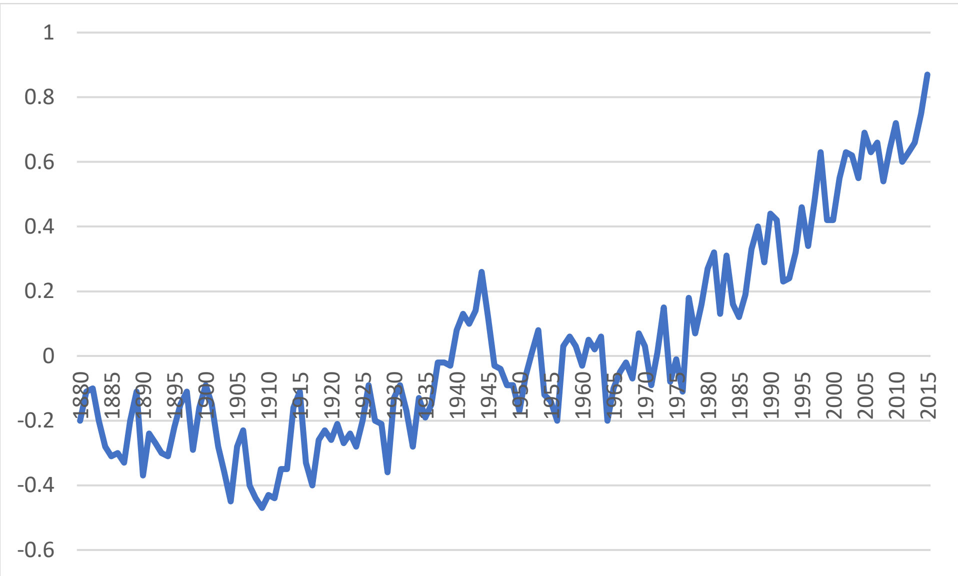

Fig. 1. 14 Global temperature change from the pre-industrial period (IPCC, 2021)

The Indian Ocean is the warmest of all oceans, and storms strive on warm water (Fig. 1.16). The continuous increase in the global temperature amplifies sea level rise. It increases the chances of high-intensity storms (Fig. 1.15, Table

1.2). Initial wind resource assessment in the FOWIND report suggests that two of three favorable locations (Rameshwaram and Kanyakumari) fall in Indian Ocean Region (Fig. 1.16). Even though the scope for better wind resources with consistency with shallow depth in the ocean is expected in this region, the risk of the cyclone is higher.

In such a scenario, the investors will look for risk transfer options. The presence of risk transfer options is limited in the NOWE policy. Insurance, contractual agreements, and waiver of subrogation are some of the risk transfer options commonly used. Insurance companies seize the liability of the OWE developers in the construction and operation phase in exchange for a premium.

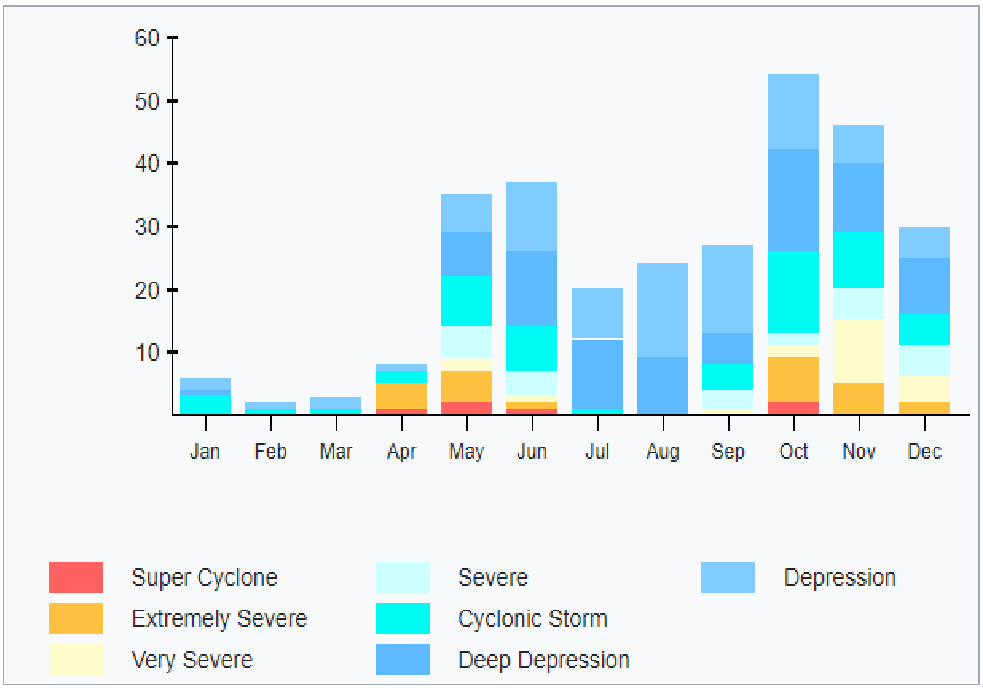

Fig.1.15 Historical storm formation by month for the period 1990-2020 (Mohanty et al., 2020)

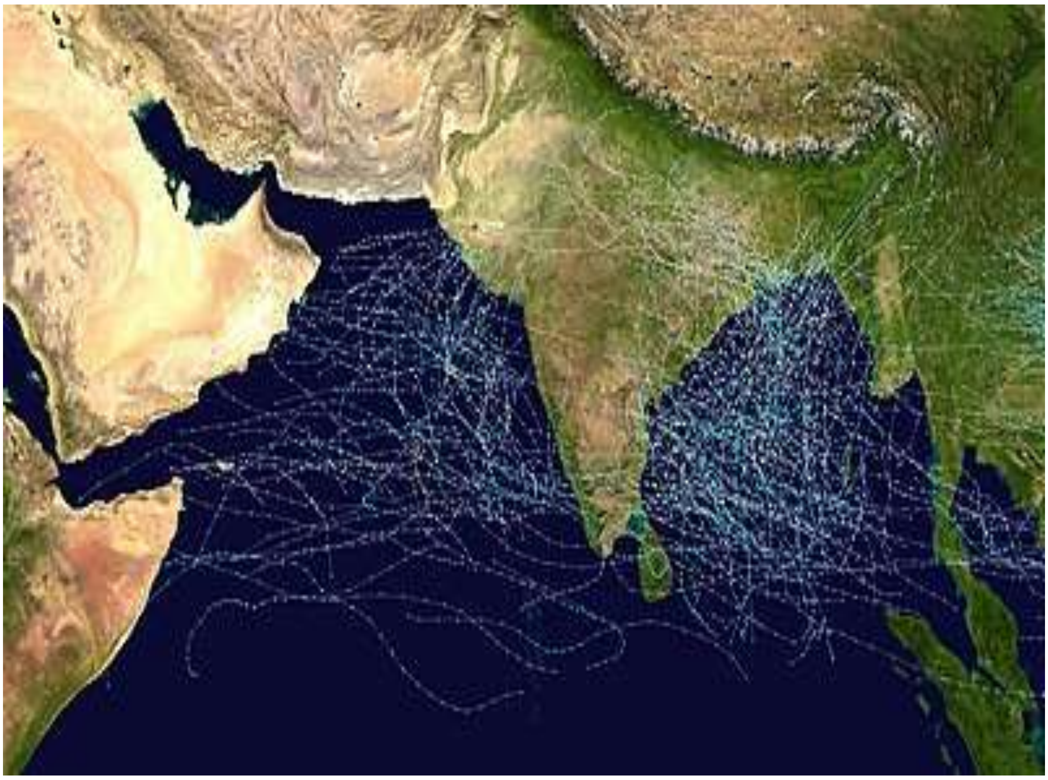

Fig. 1.16 Cyclone patterns in the India Ocean Region (Mohanty et al., 2020)

Table 1.2 List of strongest storms with damage to life and property

Year	Strongest Storm	Deaths	Damages in USD
2010	ESCS Giri	402	$2.99 billion
2011	VSCS Thane	360	$277 million
2012	CS Nilam	128	$56.7 million
2013	ESCS Phailin	323	$1.5 billion
2014	ESCS Nilofar	183	$3.4 billion
2015	ESCS Chapala	363	$358 million
2016	VSCS Vardah	401	$5.4 billion

2017	VSCS Ockhi	834	$3.65 billion
2018	ESCS Mekunu	343	$4.33 billion
2019	SuCS Kyarr	173	$11.5 billion
2020	SuCS Amphan	269	$15.8 billion
2021	ESCS Tauktae	230	$5.31 billion
2022	SCS Asani	3	None

1.9.1 Catastrophic Modeling

Catastrophic modeling (CAT Modeling) is a computer-assisted calculation based on the losses that may occur because of a catastrophic event such as an earthquake, windstorm (hurricane, cyclone, or typhoon), flood, wildfire, terrorism, etc. CAT modeling is especially applicable for analyzing risk for insurance companies. The inputs for a practical risk assessment include information on the vulnerable to catastrophic risk exposures. The exposure consists of geocoding, physical characteristics of the exposure, and financial terms of the insurance coverage. CAT modeling would help guide an insurer's underwriting strategy and help in decision-making in premiums, deductibles, limits, and re-insurance purchases.

1.9.2 Reinsurance

Reinsurance is a stop-loss strategy; it is a strategy of insuring the insurer. Reinsurance transfers risk portfolios to other parties to reduce the probability of losses resulting from an insurance claim. As a result, reinsurance reduces the net liability on risk/perils, especially on catastrophic events. By covering the insurer, reinsurance gives the insurer more financial security by increasing its ability to face financial losses on perils of lower probability and higher insured value. In addition, this practice will allow ceding companies to increase their underwriting capacity in size and risk exposure.

1.9.3 Co-insurance

The insurance party or co-insurers have agreed to underwrite a share of the risk. The co-insurers include the lead insurer (insurance party that conformed to the highest or majority share of risk) and the 'follower' co-insurer (contributing the rest of the share or a portion of the total insured value). Co-insurance is generally expressed as a fixed percentage and the insured must pay toward a covered claim after the deductible is satisfied.

1.10 Renewable energy against climate change

Energy production and use account for two-thirds of global greenhouse gas emissions. The global CO_2 levels should be reduced by 85% by 2050 to keep global temperature below 1.5℃. The switch to renewables and better energy efficiency practices can reduce 90% of the emissions fulfilling the Paris Agreement to limit the earth's temperature below $2°C$ above the pre-industrial revolution. This monumental transition from fossil fuel use to renewables may avert catastrophic climate change impacts such as catastrophes in the form of cyclones, draughts, heatwaves, and wildfires.

Renewables are argued to be first in line for solutions for global warming. This is because renewable energy technologies are virtually inexhaustible and abundant. However, “renewable” does not mean sustainable, large hydropower dams and corn-based ethanol are examples. The renewable energy sector faces the challenge of variability and uncertainty in energy generation. Solar and wind energy are categorized as variable energy sources due to their intermittent nature. Hydropower and biomass are classified as controllable energy sources, and geothermal is a constant energy source. Offshore wind energy under variable energy sources must be complemented with other sources to meet the energy needs. The battery industry is relatively immature, and energy generated from OWE in most of the last decade was unutilized and curtailed. The recent developments in Energy Storage Systems (ESS) have improved the potential of large-scale RE systems to match the energy generated and used.

1.11 The climate change-induced catastrophe's impact on renewables

Variations in wind speed can negatively impact electricity generation and ultimately affect the plant's profitability. The climate variations may increase operational costs and influence the efficiency of the turbine equipment. Incidents like drifting sea ice and a rise in sea level can cause damage to offshore wind foundations.

The rise in intensity, frequency, and impact of windstorms (hurricanes, cyclones, and typhoons) may cause larger damage to infrastructure, causing business interruption and impacting the lifespan of the turbines. The design of the offshore wind turbine will be altered by turbulence intensity, increase in wind speed, and direction. The inconsistency of wind speed prompts wind turbines to be shut down during extreme events to stop further damage. In addition, wind turbines will become vulnerable to catastrophes as they become larger and taller. Safety factors should be redesigned for climate change adaptability.

1.12 Business Problem

Climate Change induced catastrophes are considered the 3rd most significant risk (Barometer, 2015). With warmer oceans, more will be risk of windstorms, and offshore wind turbines are at high risk of damage (Gatzert & Kosub, 2016b). In addition, warmer oceans can shift the predicable windstorm patterns and affect locations with no storm history. Indian ocean is warming at 1.2 °C during the last century compared to 0.7 °C for the warm pool region (Roxy et al., 2014). The warmer ocean is exposed to more catastrophes (Edwards & Estes, 2006), which could affect the risk of insuring OWE. Risk mitigation strategies can prevent losses and encourage more investments. Insurance and diversification are strategies that can reduce or transfer the risk. The general business problem is that insurance companies lack experience providing insurance coverage in OWE and there is unavailability of data for catastrophe modeling. The specific business problem is that a diversified portfolio (a mix of different energy sources) that could help mitigate the risk caused by climate change-induced catastrophes is explored less. Such a solution may reduce the risk and improve investment since there exists a negative correlation between the energy sources in variability, exposure to a specific risk, and cost.

1.13 Business Problem Statement

Warmer oceans attract more windstorms and OWE is exposed to a higher risk of damage during such an event. Insurance and diversification are strategies that could reduce the risk of losses. However, there is a paucity of data on modeling risks especially related to climate change. Moreover, diversification with different energy sources can reduce risk and build energy security.

This section gave an outlook of offshore wind energy sector from global to Indian context. Further this section gave insights into the risks of OWE sector and the insurance strategies of meeting climate change induced catastrophes.

CHAPTER 2

LITERATURE REVIEW

The following sections classify the literature on various segments of offshore wind energy using a thematic literature review. Firstly, the holistic advantages and challenges of OWE are explored; second, the significant barriers of OWE through the literature, which is further classified, analyzed, and brought forward in seven broad categories. Finally, the opportunities for a hybrid environment are reviewed.

2.1 Opportunities of Offshore Wind Energy

2.1.1 Geographical Characteristics

India has a coastline of 7,600 km with excellent wind resources (strong and consistent wind resources). These resources are perfect for OWE deployment (Varghese et al., 2018). China has a similar geographical advantage, covering 18,400 km and backed by a large coastal population with an increase in energy demand (Poulsen & Hasager, 2017). China now accounts for 92% of OWE investments in Asia; currently, China has 21 offshore wind farms, while the UK is the global leader with 30 offshore wind farms (Díaz & Guedes Soares, 2020). China's OWE adoption and growth have their ups and downs; the first instalment came in 2001, and the sector was in slow growth till 2007. However, a series of active policies emphasizing removing financial and technological barriers saw a fast increase until 2014 (Wei et al., 2021b).

The distance from the shore is another critical variable contributing to the final energy output. The wind speed is stronger and more consistent in the open seas (Hong & Möller, 2012). Globally more than 87 % of the wind turbines are installed within a distance from the shore of 30 km (Lamy et al., 2020). However, OWE occupies large areas and is argued to have conflict in co-existence with navigation, fisheries, and marine protected locations (Haggett et al., 2020). Offshore wind zones (OWZ) effectively solve stakeholder disputes and provide an uninterrupted energy supply (Hou et al., 2016). OWZ was established after evaluations on sea-use status, distance from shore, depth, and wind resources assessment (Ou et al., 2018).

Several studies have used a combination of Multi-criteria decision-making (MCDM) techniques and Geographical Information systems (GIS) in selecting a suitable location for OWE (Genç et al., 2021). Germany has suggested an amendment to environmental impact assessment that includes effective marine spatial planning and conservation measures; this is expected to reduce conflicts and spread good practices (Lüdeke, 2017). The recent technological advancement has helped OWE developers to successfully increase the power nameplate without increasing the number of turbines and optimally utilizing the marine space (Pınarbaşı et al., 2019; Rodrigues et al., 2015).

Earlier studies have outlined the impact of OWE on the marine environment. For example, studies have pointed out the negative effect of OWE on marine mammals caused mainly by the noise from turbines, fish migration, and pollution as a result of an increase in traffic during the operations and maintenance activities (Hooper et al., 2015; Madsen et al., 2006). However, few studies have also given the positive side of the turbines in creating new habitats for smaller species which again gave potential for rebuilding a new food chain (Negro et al., 2020).

Denmark is an early adopter of both onshore and offshore wind in Europe, and its potential for cross-border interconnection capacity is also explored in existing literature (Ladenburg et al., 2020). Furthermore, cross-border interconnection with OWE can solve energy insecurity caused by European Union's gas dependency on Russia.

1.1.2 Economic Challenges of OWE

Operations and Maintenance (O&M) in marine conditions are a huge challenge in hostile marine conditions. The expertise and technologies required to carry out O&M should be specialized and tailor-made for each offshore condition. Forty per cent of the total cost involved in the lifecycle of a wind turbine accounts for maintenance (Ge et al., 2020). OWE turbines are 20% more expensive than onshore turbines, and the foundation and tower are 2.5 times more costly due to specialized equipment investments to support installations in the deep sea (Kitzing & Morthorst, 2015). It is found that Chinese offshore wind farms incur more expenditure than the farms in the UK due to the compensations that need to be provided to other stakeholders. In China, ecological compensation covers more than half of the total spending of the project, and these funds are utilized to create a similar ecosystem (Sun et al., 2017).

Chinese growth in wind power generation over the last ten years is due to doubling production and an effort to systematically reduce the cost (Wesseh & Lin, 2016). Over recent years, grid availability has replaced outdated technology as the critical factor that resists wind power development (She et al., 2019). Timely maintenance of wind turbines (WT) is crucial for extending their life span. After a service life cycle ends, WT can be re-manufactured into effective power-producing WT with the latest technology installation or recycling with economic benefits (Ortegon et al., 2013). Repowering the turbines started taking off late in China, which was common in Europe (Klinge Jacobsen et al., 2019). Replacing the smaller old turbines with larger installations may improve the output (Hayashi et al., 2018). The cost of technology appeared to be a significant roadblock to OWE growth in Germany (Wieczorek et al., 2013). However, OWE auctions in Germany are already subsidy-free, showing signs of the sector's competitiveness (Jansen et al., 2020) Cavazzi & Dutton, (2016) assessed the cost of energy from OWE with GIS in the UK. The study includes the estimation of capital expenditure, location-specific expenditure (based on wind speed and depth of ocean), and financial parameters (discount and incentives).

2.1.3 Incentives

Incentive schemes like Feed-in Tariffs (FIT) and relaxation in tax schemes encouraged Indian wind energy investments in the last decade. The onshore wind sector benefited from FIT in its early adoption years, coupled with energy development in rural regions and rapid industrialization in India (Thapar et al., 2018a). However, in China, a quota was set for the grid companies to have a reasonable amount of onshore and offshore wind purchases (Sahu, 2018). Five Year Plans aimed to build power plants near the eastern Chinese coast, demanding growing energy needs. Offshore wind energy appeared in five-year plans and drew much of energy investors' attention. Early-stage investors see the opportunity open by FITs and other incentive schemes, along with the experience from 25 years of operating onshore wind energy (Poulsen & Lema, 2017). The government tried rationalizing the industry and separating the incentive schemes from generation and installation (Da et al., 2011). The former was effective and encouraged megawatt-hour more than a megawatt. These schemes have increased many installed capacities and turbine production (Mani & Dhingra, 2013f). However, one of the drawbacks was subsidy cheating and frequent changes in subsidies in wind sector development (She et al., 2019).

China's FIT is expected to fade in the coming years; this will not be a good sign for investors in wind energy since the levelized cost of electricity (LCOE) is more than coal, which is not promising for sustainable development. The addition of new coal power plants in China is an example of China's move not to fast-track the adoption of new renewable energy technologies, especially offshore wind (Global Energy Monitor, 2020). The recent introduction of carbon pricing and trading in Europe is a positive sign. Soon, China and India may follow in their footsteps to penalize coal and other fossil fuel consumption and reward renewable energy generation. The major challenge here is the timing of introducing carbon pricing and the gradual decline of FITs (Tu et al., 2018). Studies have proved carbon credit trading can contribute to the producer's revenue but do not significantly impact financial security or reduce investment risks (Aquila et al., 2016). While considering the external cost and cost of CO_2 equivalent emissions the renewable energy in most of the G20 countries are lower than coal and fossil fuels, and this socioeconomic benefit will encourage the development of renewables (C. Yao et al., 2015). By 2030, even without the external cost and CO_2 equivalent cost, the renewables will be much cheaper than their conventional energy counterparts (Ram et al., 2018).

Germany relied heavily on subsidies for renewables in the early stages of OWE growth. Germany implemented FIT schemes to boost investments in OWE in its early stages of adoption (Liou, 2015). Still, the recent years, OWE auctions have been conducted on a subsidy-free basis, an encouraging sign since investors feel the competitiveness of OWE with other renewable energy sources. The nuclear phase-out in Germany came at the wrong timing, with the war in Ukraine that forced Germany to take steps to sanction Russia and much of its gas imports along with the Nord Stream 2 pipeline. Germany's excess dependence on Russian gas has caused a severe energy crunch and shortages. The need to fasten the installation of OWE in the Baltic Sea and the North Sea may help Germany to meet its energy requirement in the long term (Schmidt, 2017).

Croonenbroeck & Hennecke, (2020) argues the German renewable energy support schemes might be somewhat off target. The authors point out that increasing hub heights generally does not improve profitability. The financial systems, political stability, and matured supply chain gave OWE a good breeding ground in the early years in the UK (Higgins & Foley, 2014). The financial schemes included incentives and subsidies to encourage investments (Mani & Dhingra, 2013). Planning policy on OWE is distinctive for its rational, 'criteria-based' approach, which appears to favour OWE development (Toke, 2011). Later the UK introduced Carbon Price Support (CPS), a unilateral tax on emissions from the power sector (Gugler et al., 2021).

Energy policy in Denmark focuses on energy efficiency, diversification, and independence, giving ample opportunity for the growth of wind energy (Johansen, 2021). Regulatory factors in Denmark promote certainty in the deployment of OWE (Toke, 2015). While large financial subsidies flow to foreign markets from Denmark with power exports, this creates inverse cost-benefit ratios (Hu et al., 2013).

2.1.4 Operational Aspects of OWE

The initial years of adopting OWE were driven by common technical knowledge, and the focus was more on quantitative expansion, thus compromising the quality (Grafström, 2019). In addition, grid availability was also a challenge since the grid companies did not expose their technology to low-quality power (Karltorp et al., 2017).

Low production cost in China adds to the competitive advantage in the domestic market since China's wind turbines are better adapted to domestic conditions, and the price is lower than the imported turbines (Elia et al., 2020a). Chinese state-owned turbine manufacturers supply smaller turbines at a lesser quality, while foreign manufacturers supply efficient and larger ones, generating more power. The Chinese policies hardly helped improve turbine size and quality between 2005 and 2012 (Hayashi et al., 2018).

The quality of grid connection provided by transmission system operators appears to be a major challenge for OWE operators in Germany (Ferdinand et al., 2018). Few studies have pointed out challenges related to corrosion (Plagemann & Momber, 2018), the support structure (Colmenar-Santos et al., 2016), decommissioning (Kruse, 2020), and fitness testing (Preisser et al., 2019) Limited grid infrastructure has been a significant challenge for OWE in the United Kingdom. The fragmented policies and poor alignment of the regulatory framework have stood as an obstacle in the early years of OWE adoption (Wieczorek et al., 2013). It is noted that there is an increase in unbalanced figure loads and unequal distribution of fatigue offshore wind turbines in Danish OWFs. Zhao et al., (2020) classified the drawbacks of conventional turbine fatigue and proposed an improved fatigue definition, including wind speed, electric power generator, and wind wake turbulence. The stakeholders in the OWE sector are less willing to share critical technical information for operations and maintenance (Ahsan & Pedersen, 2018).

2.2 Barriers to OWE

A thorough review is conducted on the challenges and barriers that affect OWE in India; the literature also considers the OWE challenges that other countries face. Table 2.1 lists studies on offshore wind using Multi-Criteria Decision Making (MCDM) techniques. The list of barriers is shown in Table 2.2. The identified barriers and challenges are divided into classified into seven segments. The list of barriers comprises of 46 sub-factors.

2.2.1 Technical Barriers

The energy generated from OWE fluctuates within small time frames largely due to the variability, causing grid instability (Jiang, 2021). The turbines manufactured in India are based on European standards. Therefore, there is a possibility of a mismatch between components used by Indian and foreign manufacturers (Kulkarni & Anil, 2018). Onshore wind turbines used today are of induction types, operating asynchronously, and are considered ineffective reactive energy control capability (Jiang, 2021). Moreover, the turbines are expected to undergo constant maintenance and servicing, and the local operations and maintenance facilities may find it challenging to work with European design and important components (Cevasco et al., 2021). The constant exposure of offshore turbines to air, seawater, and salt sprays may cause corrosion and reduce their lifespan. Therefore, they need consistent fatigue examinations and identify long-term corrosion behaviours (Mehmanparast & Vidament, 2021).

The risk of cable damage is higher the wind farms are co-located with shipping lines since emergency anchoring can cause damage to cables (Cevasco et al., 2021; Jiang et al., 2019) Studies have modelled and selected locations best suited for OWE turbines using a combination of geographical information systems (GIS) and MCDM tools to reduce the risk of accidents and conflicts that may cause energy interruption (Obane et al., 2021; Sarker & Faiz, 2017).

2.2.2 Financial Barriers

One of the primary reasons why Indian offshore wind energy has not taken off is because of the existence of financial barriers (Lange et al., 2013). The high installation cost and need for huge initial investments need to be addressed soon. These issues were the main barriers to OWE adoption in the UK, Germany, and China in the early 2000s (Reichardt & Rogge, 2016). However, these countries have introduced incentives and subsidy schemes to support the investors (Graziano et al., 2017). In the Indian context, with lessons learned from other high capital-intensive RE sources, it can be concluded that some of the financial barriers Indian OWE will face are funds availability, regulations governing project funding, limited income, and insufficient support schemes (Al-Sumaiti et al., 2020). The OWE-deployed countries used a variety of financial instruments and monetary supports such as capital subsidies, feed-in tariffs, tradable green certificates (TGC), mandatory standards, tax concessions, and grid access guarantees (Timilsina et al., 2013). New schemes such as e-reverse auctions are fast replacing FITs to discover the lowest tariff in the RE sector (Bose & Sarkar, 2019). In addition, the cost of electricity from OWE generation is brought down with recent technological advancements and knowledge shared with experienced OWE developers (Lerch et al., 2018). This is again backed by excellent research and development funding provided by countries in location selection and zoning to enable designated regions for OWE turbines (Myhr et al., 2014).

Further, some risks amplify the financial risks and act as barriers to its implementation and growth, such as lack of availability of insurance and diversification options to transfer the risks such as business interruptions, catastrophes in the form of storms, fire caused by lightning, and tsunamis (Gatzert & Kosub, 2016).

Table 2.1 List of studies that used MCDM technique on OWE sector.

Author	Methodology	Objective	Site
(Kolios et al., 2010)	TOPSIS	Selection of OWE foundation	EU
(Fetanat & khorasaninejad, 2015)	ANP, ELECTRE, DEMATEL	Site selection of offshore wind farm	Iran
(Mytilinou et al., 2018)	TOPSIS	Location Selection	UK
(Collu et al., 2014)	TOPSIS	Design of Floating wind turbines	UK
(Shafiee & kolios, 2015a)	ANP	Operational Risks	UK
(Abdel-basset et al., 2021)	AHP, PROMETHEE	Location Selection	Egypt
(Güner et al., 2021)	AHP	Sustainability of OWT	Turkey
(Lo et al., 2021)	Grey DANP	Site selection	China
(Ma et al., 2021)	ANP	OWT selection	China
(Deveci et al., 2020)	Interval type-2	Site Selection	Ireland
(Narayanamoorthy et al., 2021)	NWHF-MAUT, NWHF-CRITIC	OWT Selection Process	India
(Y. Wu et al., 2020)	PROMETHEE, ANP	Site Selection	China

Table 2.2

List of challenges in OWE growth

S No.	Barriers/ Challenges	Code	Sub-categories	Reference
1	Technical Barriers (THB)	THB1	Grid connection issues	(Weißensteiner et al., 2011)
		THB2	Insufficient technology	(Meier, 2014; Willis et al., 2018)
		THB3	Lack of maintenance services	(Ren et al., 2021)
		THB4	Lack of standardization and Insufficient testing	(Brennan, 2013; Du et al., 2017)

		THB5	Cable connection	(Sedighi et al., 2018)
		THB6	Inadequate energy storage and battery system	(Fan et al., 2016)
		THB7	Offshore wind zones (OWZ)	(Ou et al., 2018)
		THB8	Innovation Risk	(Bento & Fontes, 2019a)
2	Financial Barriers (FIB)	FIB1	High Initial Capital	(R. Aswani et al., 2021c)**,**
		FIB2	Finances availability	(Tseng et al., 2017)
		FIB3	Inadequate subsidies and incentives	(Mani & Dhingra, 2013b)
		FIB4	Unfavorable Pricing scheme	(Levitt et al., 2011)
		FIB5	High cost of engineering facilities	(James & Ros, 2015a)
		FIB6	Insurance and diversification	(Gatzert & Kosub, 2016b)
		FIB7	Lack of consistency in feed-in tariff schemes	(Thapar et al., 2018b)

		FIB8	High levelized cost of electricity (LCOE)	(Aldersey-Williams et al., 2019)
3	Regulatory and Political Barriers (R&PB)	R&PB1	Institutional framework	(Willsteed et al., 2018)
		R&PB2	Lack of political commitment and consensus	(Tsouri et al., 2021)
		R&PB3	Bureaucratic permit	(Vann, 2011)
		R&PB4	Entry barriers	(Lehtovaara et al., 2012)
		R&PB5	Irrelevant standards	(Lehtovaara et al., 2012)
		R&PB6	Insufficient monetary policy support	(Bice et al., 2017; Mani & Dhingra, 2013e)
		R&PB7	Inadequate wind-energy targets	(Mani & Dhingra, 2013a)
		R&PB8	Corporate PPAs	(Barradale, 2010; Mani & Dhingra, 2013b)

		R&PB9	suppliers' agreement	(Poujol et al., 2020)
4	Social Barriers (SOB)	SOB1	Lack of awareness	(Rasmussen et al., 2018)
		SOB2	Public Acceptance	(Firestone et al., 2009)
		SOB3	Noise and Visual impacts	(Thompson et al., 2013a)
		SOB4	Low consideration of environmental safety	(Bush & Hoagland, 2016)
		SOB5	Lack of knowledge and experience	(Crabtree et al., 2015)
5	Supply Chain Barriers (SUCB)	SUCB1	Absence of heavy-duty machinery and technology	Sarker & Faiz, 2017)
		SUCB2	Unreliable turbine vessel carriers	(Halvorsen-Weare et al., 2013)**,**
		SUCB3	Lack of port facilities	(Irawan et al., 2017)
		SUCB4	Facilities for assembly	(Umoh & Lemon, 2020)

		SUCB5	Lack of large vessels	(S. J. Kim et al., 2021)
		SUCB6	Lack of alignment in tooling facilities	(James & Ros, 2015b)
6	Institutional Barriers (INB)	INB1	Lack of skilled human resource	(Heidenreich, 2018)
		INB2	Lack of formal coordination	(MacKinnon et al., 2021)
		INB3	Absence of institutional capacity	(Wei et al., 2021b)
		INB4	Lack of infrastructure	(Wieczorek et al., 2015)
		INB5	Corruption	(Réthoré et al., 2009)
7	Geographical Barriers (GEB)	GEB1	Conflict with shipping routes	(Biehl & Lehmann, 2006)
		GEB2	Aquatic protected zones	(Qu et al., 2021)
		GEB3	Conflict with fishing zones	(Y. Zhang et al., 2017)
		GEB4	Ocean topography	(Y. H. Kim & Lim, 2017)
		GEB5	Risk of natural disasters	(Rueda-Bayona et al., 2019)

2.2.3 Regulatory and Political

The policies adopted by the government in encouraging OWE development play a crucial role in their initial years of growth. There is a need for political commitment for a long period over the adoption of RE and reaching climate targets (Sunila et al., 2019). The coordination between the ministry and collaboration through public-private partnerships provided long-lasting fruits for RE development (Li & Xu, 2019). However, the institutional barriers have negatively influenced cost-sharing contracts and establishing roles and responsibilities. In Europe, political commitment toward energy technologies is determined by public opinions and a series of protests against the development of power plants. For example, activism in Not In My Backyard (NIMBY) has shaped the political will to permit onshore wind farms (Sunila et al., 2019). In Tamil Nadu, the installation of LiDaR (Light Detection and Ranging) for observing wind speed and consistency has failed due to public opinion (Davidson & Perez-Arriaga, 2018).

Lack of political commitment and support for reorganizing the energy sector to incorporate wind energy can weaken mainly due to political institutions (Lakhanpal, 2019). Delay in bureaucratic permits and approvals in grid infrastructure, space allocation, and distribution have affected the onshore wind sector. A similar trajectory is observed in the initial OWE development; the long approval and clearance procedures daunt its deployments (Satpute & Kumar, 2021).

2.2.4 Social Barriers

Public acceptance has favoured OWE over onshore wind farms in the last decade. Public awareness, the legal system, and environmental concerns are some of the social factors influencing this opinion's tilt (Cairney, 2015; Ubay, 2021). Some recent developments may solve the public issues relating to OWE deployment. Together, the quest for energy security and meeting climate goals has shaped the general acceptance of OWE (Guo et al., 2022).

The cables, piling, platforms, and electromagnetic waves can directly impact the aquatic ecosystem (Kaldellis & Apostolou, 2017). Some studies explored the impact OWE causes visually, especially in locations that attract tourists. The noise impacts are also quoted as an issue by the coastal communities. The same issue was the primary reason for NIMBY movement for onshore wind farms. Ideally, OWE farms should be located beyond the 12 and within 200 nautical miles of EEZ, enabling 1) harnessing consistent wind, 2) away from conflicting stakeholders 3) reducing visual and noise impacts (Thompson et al., 2013).

2.2.5 Supply chain barriers

From a supply chain point of view, the availability of machines and technologies required for installation, operation, and decommissioning is the main barrier to OWE development. Machines such as cranes and vessels should be large and strong enough to hold the turbines at these three stages (Gudmestad, 2020). OWE turbines are large, with a height of 150m and a diameter of 120m may strain the logistics during assembly and installation. Pre-assembly includes sophisticated transportation from the manufacturing unit to the port, handled by dedicated cranes and heavy equipment (Dinh & McKeogh, 2019). The supply chain process must be explicitly designed to match each specific project based on the type of foundation used, the typography involved, and the energy indents to be generated (Hrouga & Bostel, 2021).

The OWE maintenance must be consistent to reduce the risk of fatigue and damage (Li et al., 2020). However, O&M comes out with a number of disadvantages, including poor accessibility, high cost, and lack of skilled workforce (Dinwoodie et al., 2015). In addition, owing to the testing marine conditions conducting regular O&M becomes a tedious process (Beinke et al., 2020). Efforts to simplify the communication process can reduce costs and bring coordination between the producer and the O&M team (Sarker & Faiz, 2017).

2.2.6 Institutional Barriers

Every country has its own domestic rules and regulations, from auctions to installations; even the domestic procurement process has issues in coordination. The lack of coordination between state and national authorities, inspection misinterpretations, and energy and maritime regulations all add up to the challenges faced by OWE sector in its growth (Charles Rajesh Kumar et al., 2021). In developing countries, it is seen that the uneven nature of the institutional framework draws the energy sector from effective policy formulation (Tagotra, 2018). A similar situation is identified in the Indian context; lack of institutional capacity has caused a backlog of infrastructure procurement and restricted outdated and insufficient technology (Dutta et al., 2016). While in Europe, cross-border meshed grid infrastructure is actively pursued to reduce the OWE curtailment (Sunila et al., 2019). For OWE to play an important role in meeting net zero targets, the challenges related to infrastructure need to be fixed at the earliest (Willsteed et al., 2018).

Knowledge and skills in operations and maintenance, turbine foundation construction, turbine designing, and submarine electrical cables are crucial for the smooth functioning of OWE farms (Charles Rajesh Kumar et al., 2021; Dinwoodie et al., 2015). China's BRI has been criticized in recent studies as an act of corrupting developing countries to derail their climate goals towards environmental degradation (Sum, 2019). Such practices may counter the adoption of OWE in developing countries.

2.2.7 Geographical barriers

Geographical barriers such as the existence of fishing zones, marine protected regions, uneven topography, and shipping lines may act as barriers to installing OWE (Lee et al., 2020). An adequate measurement of the condition, proper assessment of wind resources, and keeping the interest of all the stakeholders becomes highly important in OWE's adoption (R. Aswani et al., 2021). Offshore wind farms may negatively influence the risk to marine species during breeding and migration (Thomsen et al., 2006). These negative impacts happen throughout the lifetime of offshore wind farms, at the time of installation, construction, operations, and maintenance (Madsen et al., 2006). During the initial installation stages, marine habitat pollution and disruption are higher. The sound caused due to piling, and operations can cause hearing damage to marine mammals (Pfeiffer et al., 2021). Though some studies identify that the bird collision with turbine blades is higher, they do not come close to the numbers onshore wind suggests (Johnston et al., 2014). More long-term impacts during operations include changes in water quality and ocean dynamics (Farr et al., 2021).

2.3 Hybrid renewable energy solutions (HRES)

2.3.1 Hybrid Energy for rural electrification

Rural electrification lacks consistency and affordability; most importantly, it lacks a combination of the sustainable energy mix. Mokhtara et al., (2021) suggest an optimal Wind-PV-Diesel-battery design for Algerian rural areas, intending to reduce the cost of energy (COE) and maximize system reliability. The study used ArcGIS, a geographic information system tool, to plot potential renewable energy zones. Vendoti et al., (2021) assessed a series of combinations of HRES on technical and financial parameters for ten houses in rural villages in the Moroccan Fez-Meknes region. Results suggest a 100% RE penetration requires a combination of wind at 11%, solar at 41%, and biomass at 48% (Acakpovi et al., 2020).

2.3.2 Hybrid energy for Institutions/universities

In the HRES literature, proper attention was given to the techno-economic viability of academic institutions. In six distinct climatic zones in Morocco, Ladide et al. (2019) gave government institutions an ideal power supply option. A feasibility study of standalone hybrid systems for electrifying educational establishments in Rabat, Morocco, was conducted by Kharrich et al. in 2017. Tazay (2020) examined the best alternative among grid-only, HRES-only, and HRES with the grid in four provinces in Saudi Arabia. The techno-economics of hybrid energy systems with off-grid and grid-connected alternatives were examined by Nesamalar et al. in 2021 for Kamaraj College of Engineering and Technology (KCET) in Tamil Nadu.

2.3.3 Hybrid energy in India

Pal & Bhattacharjee, (2020) proposed an optimal HRES solution for a small rural community at Patharpratima Island, Sundarbans, India. The model ensured zero loss of power supply probability (LPSP) the COE of ₹ 9.22/kWh, which is more economical than similar systems. Murugaperumal et al., (2020) suggest combining wind, solar, and bio generators as the best source for HRES for the rural district of Korkadu, India. Existing studies on the rural village of India on optimal HRES sizing include studies by Murugaperumal & Ajay D Vimal Raj, (2019); Ramezanzade et al., (2020). A combination of floating and rooftop solar energy, wind energy, and ESS were studied with their potential for building a smart city in Vishakhapatnam to comprehensively assessed the optimal sizing of HRES with ESS (Nuvvula et al., 2021).

2.4 Climate Change induced catastrophes

The dynamic relationship between the increase in global temperature because of the greenhouse gas concentration in the atmosphere and the rise in the frequency, intensity, and impact of catastrophes are explored by a wide range of studies in the existing literature (Linnerooth-Bayer & Hochrainer-Stigler, 2015). One strand of studies explored the societal aspects of catastrophic events, such as the impact on the financially vulnerable population and others on the impact of catastrophes on infrastructure (Y. Paudel et al., 2015). Not all countries have the necessary financial and technological resources to tackle the relatively uncertain climate change-induced droughts, storms, fires, and floodings (Alam et al., 2017). Reducing emissions and stabilizing the GHG concentration in the earth's atmosphere is termed 'mitigation.' The 'adaptation' measures are to adjust to the actual or expected future climate scenarios (Seneviratne et al., 2012). Adaptation is getting better at various levels in many countries. The inclusion of climate change into development plans helped in better adaptation practices (Alam et al., 2017). The recent literature has expressed better disaster management strategies, protecting the coastline against sea level and coastal flooding, better management of land and forest, plans for draughts, crop diversification, energy efficiency, and renewable technologies (Zafarullah & Huque, 2018).

Few studies have analyzed the impact of climate change catastrophes on renewable energy technologies. Future technologies should withstand these high-intensity windstorms, flooding, lightning, sea level rise, and droughts (Nerem et al., 2018). Assessing climate change impacts on hydropower is complex due to nonlinear and region-specific changes in precipitation and temperatures (Huangpeng et al., 2021). Most studies focus on streamflow variations due to precipitation and temperature changes. Wind energy generation in 2017 accounted for 539 GW of installed capacity, including almost 20 GW of offshore capacity worldwide (Wilkie & Galasso, 2020). As wind turbines become bigger and taller, they become more vulnerable to damage (Buchana & McSharry, 2019). Therefore, set margins in the design and operation of offshore wind turbines should be increased to adapt to climate change (Wilkie & Galasso, 2020). Wind energy is more sensitive to model formulation than other technologies (D. Zhang et al., 2019). There is also uncertainty surrounding how to separate the climate signal from the climate's inherent variability and regarding long-term records of wind speeds (Baboulet, 2012).

Therefore, for some authors, focusing on projected changes is considered more accurate than relying on absolute predictions (Alharbi & Csala, 2021). It is also key to provide estimates adapted to the height of wind turbines and for the upper percentiles of the wind speed probability distribution, not just the mean speed (Wilkie & Galasso, 2020).

Output is highly dependent on wind speeds, and a small change can substantially impact electricity generation (Wilkie & Galasso, 2020). Therefore, many existing studies focus on wind speed, while only a few estimate wind direction changes. As a result, the statistical significance of the trends is often hard to assess (Ribeiro et al., 2020).

Most studies focus on Europe and North America and changes in mean wind speed. Therefore, further studies should be developed regarding other regions and extreme wind events (Costoya et al., 2021). Furthermore, while most studies focus on onshore production, offshore turbines are more vulnerable to higher wind speeds, and maintenance is usually more expensive (D. Zhang et al., 2019). In addition, technologies based on marine water could potentially be affected by changes in water temperature, temperature gradients, salinity, sea level, and wind patterns (Ribeiro et al., 2020).

Climate change impacts on solar sources have received less attention than wind or hydro (Alharbi & Csala, 2021) due to the high uncertainty of the projections (Sims, 2004) Depending on the model and assumptions, differences in results can be substantial (Costoya et al., 2022). All sources of solar energy are sensitive to climate change. Still, existing literature focuses mainly on photovoltaic generation (PV) and changes in solar irradiation, as it is the most relevant source (Alharbi & Csala, 2021).

2.5 Theoretical Underpinning

All portfolios are affected by macroeconomic factors, and diversification reduces the exposure to risks that are asset specific. Therefore, understanding how risks and uncertainties interact with each asset becomes essential. The critical determinant of risk is the extent to which the return to different assets varies together or in opposite directions. The risk depends on the correlation between returns on assets in portfolios. The measurement for this problem is an analysis of the correlation coefficient and covariance.

Markowitz's modern portfolio theory (MPT) is about maximizing the investor's return considering the risk involved in investment. MPT questions the investor's on how much risk for one investment can impact the entire portfolio. MPT proposes diversifying one investment with a specific and expected rate of return with another investment with the least risk. Markowitz theorized that investors could reduce risk by diversifying their assets quantitatively. The theory is proposed on the assumption that most investors are risk averse, meaning investors' interest in less risk; anxiety and nervousness increase as the risk increases. In other words, investors are better off not losing money than making a profit. Naturally, risk takers view a correlation between higher risks and higher returns.

The theory is criticized for its dependence on projected value and mathematical values on expectation rather than on real or existing phenomena. First, the predictions are based on historical measurements of returns and volatility. However, the variables which did not appear in historical data were not considered at the time of the equation. Second, the investors must estimate the probability of losses without practically examining why the losses could occur. This shows an unstructured risk assessment.

Modern portfolio theory analyses technological alternatives from cost-risk perspectives and return-risk perspectives. MPT also builds a stronger conceptual richness over an individual lower-cost analysis. The essence of MPT is to optimize the relationship between risk and return by creating portfolios based on their covariance or correlation with other assets. The framework established by MPT shows any expected return is composed of various future outcomes and can be risky, and diversification is a tool to optimize the risk-return relationship.

2.5.1 Modern Portfolio Theory in Energy

Diversification is a strategy by large energy investors to minimize losses and profit maximization (Roques et al., 2008). Diversification is a significant component of decision-making under uncertainty based on four principles: correlation, the law of large numbers, the capital-asset pricing model, and risk parity (Koumou, 2020).

Diversification in energy can be analyzed from a financial and strategic point of view, with financial being the price volatility risk associated with the energy industry and strategic being the innovator and expansion into new markets (García Mazo et al., 2020). Energy security is maintained by picking up optimal strategies on diversified portfolio investments in energy technologies and energy prices. Climate change impacts are critical risks that could affect the energy inflow (L. Zhu & Fan, 2010). Diversification can reduce the overall risk exposure while investing in passive energy equity (Galvani & Plourde, 2010). With the role that RE will play in the future, a diversified portfolio strategy of RE investments is becoming even more important to mitigate risks. RE demands technological and geographical diversification, Sinsel et al., (2019) point out that technological diversification is exposed to lesser risks than geographical diversification while increasing the capacity factor of the RE can reduce and mitigate risks.

A diversified portfolio can counter the risk of geographical differences. So based on the locations and the risks, a custom-made RE diversified strategy is to be implemented. Diversifying investments in wind and hydro are common research areas (Suomalainen et al., 2015) Since wind energy can reduce the risk of water inflow leading to hydropower shortages in the dry season and hydro-supporting wind in the rainy season (García Mazo et al., 2020). Pinheiro Neto et al., (2017) point out that reallocation of energy reduced the risks associated with hydroelectric economic risks after studying a diversified strategy from hydro, solar, and wind in Brazil. Other research on the same location with hydro and wind shows strong benefits for some wind products when it is associated with hydro to mitigate risks (Ramos et al., 2013). Sunderkötter & Weber, (2012) studied a diversified portfolio with nuclear, coal, and natural gas in Germany. Roques et al., (2008) used the same variables in the UK; rebalancing power purchase agreements can optimize a diversified portfolio to increase the share of nuclear and coal power plants. For lower-income countries like Jordan, diversifying through conventional energy sources remains the most feasible option for technological and financial benefit (Malkawi et al., 2017). However, diversifying the energy portfolio increases the emission of GHGs (Hasan et al., 2012). Policies and schemes which could encourage investments in renewable energy and diversified portfolios are considered by high-income countries, and studies focusing on these policies are in plenty. Policy measures beyond feed-in tariffs are required for generation practices on a larger scale and ownership (Nolden, 2013). A high negative correlation among the selected sources increases investor payoff and favours diversification (García Mazo et al., 2020). A complementarity between the sources helps to reduce the economic risks; however, the initial correlation between the sources is altered by debt, which reduces the risk and return (Pinheiro Neto et al., 2017).

2.5.2 Geographical Diversification

Geographical diversification can smooth out the generation-related uncertainty associated with wind energy. Roques et al., (2010) studied the diversification in terms of wind's geographical location to meet the EU's energy demand. Onshore and offshore wind in Europe has limitations on risk mitigation strategies, policy, and regulatory risks that appear to be the primary barrier to wind energy investments. Such risks are challenging to mitigate through insurance and diversified portfolios (Gatzert & Kosub, 2016). An optimum allocation of wind energy resources helps save up to 2 GW of required firm capacity in Germany (Bucksteeg, 2019). Spatial diversification positively impacts the RE's market value in Chile with active transmission and storage limitations for hydro (Odeh & Watts, 2019). Wind turbine films have diversified over the years and added width to the global market, with Vestas and Siemens Gamesa leading the market (Yusta & Lacal-Arántegui, 2020).

The location selection for an onshore wind farm is subject to local conflict. The visual effects (Gamboa & Munda, 2007), land availability, NIMBY protests, and noise pollution (Han et al., 2009) are some challenges wind farm developers faces. A social multi-criterion is posed by Gamboa & Munda, (2007) to integrate social, economic, and technological dimensions into one framework. Safety quality and environment-ecology are the two main factors influencing the location decision

(Yeh & Huang, 2014). Wind energy quality is measured by speed and trajectory, turbulence intensity, aerodynamic noise (Ledo et al., 2011), and air density through different seasons (Villacreses et al., 2017). The intergovernmental panel for climate change (IPCC) reports that 80% of the electricity could come from RE by 2050, and wind will play a critical role in that. The low-capacity factor of onshore wind farms and scarcity of lands (Breton & Moe, 2009) brings offshore wind to an advantageous position. The advancement of technology adds to the feasibility of offshore wind erected deeper in the ocean and far from the coast (X. Sun et al., 2012). The study on wind speed and wind farm designs forming a strategic echelon for choosing the best location for wind farm development is frequently visited by researchers. However, very little research has been carried out on the operational echelon, such as maintenance tasks, and tactical echelon, such as inventory management (Shafiee, 2015).

2.5.3 Optimal Energy Solutions

The use of game theory in energy consumption and production is common. Mohsenian-Rad et al., (2010) studied the global optimum usage scheduling game and minimizing cost; the strategies for the consumers are the daily scheduling of a load of household appliances. Aplak & Sogut, (2013) employs an optimum strategy for bidding in the price-competitive energy market. Srinivasan et al., (2017) used dynamic pricing strategies to encourage customers in peak load reduction and obtain incentives in return. Paudel et al., (2019) developed a novel game-thematic model for peer-to-peer energy trading considering price and quality.

Many researchers analyzed the optimum strategy for selecting subsidies. Yang et al., (2018) studied RE investments in neighbouring countries and proposed an optimum subsidy game. The decision depends on social capital, pollution levels, and the production efficiency of RE. Nguyen et al., (2015) identified an optimum storage strategy and improved the power grid's reliability and efficiency. Yi et al., (2019) used the system Dynamic Model to determine a strategy best for the electricity producer in incentive scheme contexts. A further contribution to the literature on the system dynamic model was analyzed by Zhu et al., (2020), investigating the impact of significant parameters concerning Renewable Portfolio Standards (RPS) schemes on stakeholders' optimum strategy. The evolution of RPS and electricity producer's techniques was studied by Xin-gang et al., (2018), who discussed the key parameters that affect the dynamic evolution process of electric producers. Proposes an optimum strategy in determining the best bidding value to maximize total profit in a monthly context (Lasemi & Arabkoohsar, 2020). Hauer et al., (2020) propose a methodology to size a battery energy storage system for self-consumption in a windless period.

2.5.4 Prospect Theory

Prospect theory applies to uncertain and risky prospects with any number of outcomes and allows different weighting functions for gains and losses (Tversky & Kahneman, 1992) (Fig.2.1). Choices among risky prospects exhibit several pervasive effects inconsistent with the basic tenets of utility theory. In particular, underweight outcomes are merely probable compared to results obtained with certainty. This tendency, called the certainty effect, contributes to risk aversion in choices involving sure gains and to risk seeking in options involving certain losses (Kahneman & Tversky, 2018). Probabilistic insurance is an insurance policy involving a small probability that the consumer will not be reimbursed. Under highly plausible assumptions about the utility function, willingness to pay for probabilistic insurance should be very close to a desire to pay for standard insurance less the default risk. However, the weighting function of prospect theory predicts the reluctance to buy probabilistic insurance (Wakker et al., 1997).

Risk theory deals with stochastic insurance models and is a classical probability theory presentation. The fundamental problem in risk theory is examining the risk of a business's ruin and possibility. Traditionally the occurrence of the claims is labelled by a Poisson process, and the cost of the claims by a series of random variables ("Aspects of Risk Theory.," 1994). It discusses collective risk modelling, individual claim size modelling, approximations for compound distributions, ruin theory, premium calculation principles, tariffs with generalized linear models, credibility theory, claims reserving and solvency (Wuthrich, 2013).

Utility theory and prospect theory treat multiple goals and suggest several ways context can affect choice. Among other anomalies, people insure against non-catastrophic events, underinsure against catastrophic risks, and allow extraneous factors to influence insurance purchases and other protective decisions. ("Goals and Plans in Decision Making," 2007). The empirical results from the study conducted by Hansen et al., (2016) provided evidence that the insured's willingness to pay is marginally more substantial than the actual actuarial value under the expected utility theory and 600% higher under the rank-dependent utility theory.

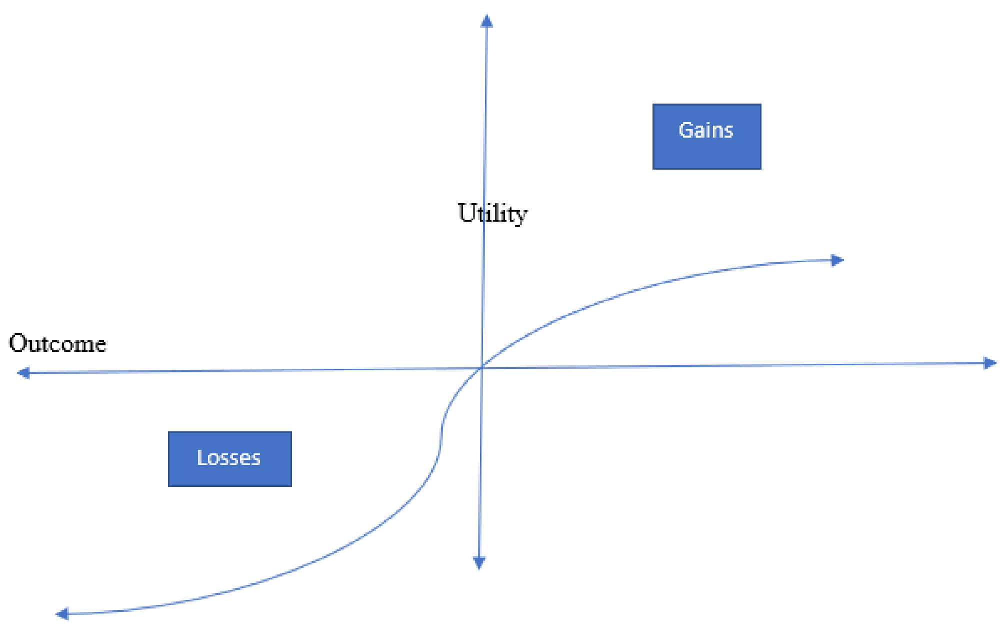

Fig. 2.1 Risk aversion according to prospect theory

Utility Theory under the willingness of the energy producers to pay more in terms of the insurance premium for OWE considering the capacity factor of OWE compared to other RE, making it the best bet for the producer to meet the demand. The 'unfriend coal' campaign will keep the producers conservative on future investments, and nuclear phase policies raise the expectation of energy generation from new RE sources. High risk in the OWE segment creates the utility function from the producer's point of view. It would be willing to pay for the extra premium, which acts as a cushion for the insurance company venturing into a new energy sector with limited experience. Prospect theory is more refined for the study of insurance and decision-making on risk assessment.

The catastrophic risks associated with OWE have more probability of occurrence than other renewable energy (solar, onshore wind, and hydropower) (Esteban et al., 2011) (Shafiee, 2015) The marginal utility of gain diminishes while the pain from the losses is more given the same value as stated in the prospect theory. The losses from offshore wind need to be mitigated through insurance and diversification. The utility function for the producer is energy security. To maintain energy security, the producer would extend their willingness to pay a higher premium leaving the insurance company with a choice of mitigating the possible losses by limiting the insured value, higher deductibles, co-insurance, and reinsurance.

2.5.5 Themes identified and reviewed articles

The literature is classified into six themes and review is performed (Table 2.3). A total of 155 papers are reviewed.

Table 2.3 Thematic classification of the reviewed studies and number of articles under each theme

Themes	**Total Reviewed paper under the themes**
Portfolio Diversification theory- Energy management	20
Utility Theory and Prospect Theory	27
Environmental Kuznets Curve	29
Energy Optimization	31
Climate Change, CO_2, RE Nexus	22
Offshore wind energy- Location, Technology, Policies	26

2.6 Theoretical Justification

We understand how investors behave in various risky circumstances through utility, prospect, and risk theories of profit. But none of these theories explicitly views how the investments must be made by a risk element, in this case, weather-related climate change risk. The Modern Portfolio Theory to diversify renewable energy investment is helpful for this study. The decision to diversify the portfolio is based on a) the strong correlation between wind and solar energy that might solve the variability issue b) the cost of investments, i.e., OWE has a higher cost of investment than solar PV and other energy sources in the system c) the possibility of losses and mitigating risks, i.e., the higher chance of damage to solar PV plates on an event of the cyclone to wind blades. In all these three cases, energy security is maintained, and risk is reduced by optimal diversification of energy sources.

2.6.1 Insurance and Climate Change

Munich Re adopted a specific serial loss insurance cover scheme to mitigate the loss arising from the early application of new technology. OWE is a relatively new technology exposed to high risks at sea. Such schemes can help bring more market investments (Gatzert & Kosub, 2016). Catastrophes can harm insurance, potentially slowing the industry down and shifting the burden to individuals and the government. Insurance companies are well-positioned to predict and model the losses caused by catastrophes and find strategies to mitigate them (Mills, 2005). Climate change often exposes the insured to novel risks that are often outside the experience range of catastrophe modeling. These new impacts relate to the increased intensity of hurricanes, droughts, heat waves, and accelerated glacier retreats (Agrawala et al., 2007). It is argued that social welfare improves as insurance companies step in to cover up part of the losses caused by climate change (Botzen & van den Bergh, 2008). IPCC called for a new balance between reducing the risk and transferring it through insurance as a practical step in dealing with climate change. A risk management approach that could set a risk reduction and financing target at various layers during an unpredictable changing climate could support the insurance industry. Risk financing can complement and stimulate mitigation (Linnerooth-Bayer & Hochrainer-Stigler, 2015). With a well-aligned private-public partnership, climate change adaptation can bring new business opportunities for insurance companies (Botzen et al., 2010). Developments in the reinsurance industry could maintain the affordability and availability of insurance to face the new era of catastrophic risk (Kunreuther et al., 2013).

Insurance companies must diversify their portfolio investments based on technology, energy output, cost, geography, peril, and damage exposure. Compared to traditional insurance coverage for energy companies, which is limited to property damage, new-age technologies face multiple risks from construction to decommissioning and insurance companies are becoming flexible in addressing these risks. Catastrophe modelling and risk profiling have come of age to provide data-backed risk analysis.

2.6.1.1 Technology

Some technologies are more exposed to perils than others. For example, nuclear energy is less risky than solar panels to tropical cyclones. The cost involved in building both technologies also varies. The frequency of risk is another factor to be considered by insurance companies, along with the possibility of losses. Nuclear power plants face fewer losses than solar panels, while the frequency of peril, such as cyclones, stays the same for both energy systems. However, if there is a loss run for nuclear power plants, the cost of claims will be much higher than solar panels. Here, insurance companies can adopt strategies of co-insuring and re-insuring. Underwriters must decide based on the possibility of losses that may be faced by each of the catastrophes on the energy technologies.

2.6.1.2 Energy output

Renewable energy output is highly vulnerable to variability in weather conditions and intermittent. The low wind and solar days reduce the farm's output, affecting the energy company's profitability. Insurance companies can step in to provide coverage for business interruptions. From the Insurance company's point of view, the mitigation of losses can be done effectively by providing coverages to complementary sources such as wind and solar or solar-wind and hydro. Moreover, the geographical differences can be considered for selecting an optimal portfolio, solar energy produced from two or more different solar states may complement each other to generate enough energy required to meet the demand; in such a way, insurance companies can maintain the energy output.

2.6.1.3 Cost

The cost varies among the energy sources for the same energy output produced. Thus, insurance companies must set specific limits and deductibles for each energy source to optimize the risk profile. The insurance companies could prioritize each energy source based on techno-economic and environmental considerations. The deductibles, limits, co-insurance and reinsurance strategies shall be assigned to each portfolio based on the priority and rank given to the energy sources involved.

2.6.1.4 Peril

The type of peril dictates insurance companies' decision to underwrite the risk. The location plays a crucial role in risk modelling. Historical data is considered in analyzing the probability of the occurrence of a peril. The underwriter takes a call on providing coverage for the portfolio; for a high-risk exposure, premiums can be set high along with higher deductibles and reduced limits, thereby reducing the loss against high-risk perils.

2.6.2 Unfriend Coal

The 'Insure Our Future' campaign aims to make coal and other fossil fuels uninsurable, slowing the growth of carbon emitting sector and focusing towards cleaner and greener energy sector. Without insurance, few new coal mines, oil pipelines, and thermal power plants can be built, and existing projects must be phased out. Coal is identified as the most significant single contributor to human-made climate change (Unfriend Coal, 2018) The world's first three insurers adopted rudimentary coal exit policies in 2017. Four followed in 2018, and 10 more this year. As a result, 17 insurance and reinsurance companies have ended or limited their cover for coal projects. They control 9.5% of the primary insurance market and 46.4% of the reinsurance market (Katz-Kimchi & Manosevitch, 2019). This action has a tangible impact; insurance brokers consistently report that the insurance market for the coal sector is shrinking and that rates are increasing (Unfriend Coal, 2018).

2.6.3 Nuclear Phase-Out

The nuclear meltdown in Fukushima resulted in diverging energy policy decisions worldwide (Rehner & McCauley, 2016 andconcerns over nuclear waste disposal (Vinet & Zhedanov, 2011). Germany is now embarking on what is known as the Energiewende, a plan to turn the entire economy into a low-carbon energy structure that does not make use of nuclear energy (Schreurs, 2012). However, results suggest significant long-term consequences (Rehner & McCauley, 2016), with more coal and lignite-based generation and a decrease in German electricity exports (Bruninx et al., 2013). Germany's nuclear phase-out policy has positively impacted the expansion of new RE sources by innovation (Rogge & Johnstone, 2017). Nuclear Free policy in Sweden would constitute a retrograde step toward economic protection (van der Zwaan, 2002), health and climate goals (Qvist & Brook, 2015). The social cost of this shift from nuclear to coal is estimated to be 12 billion dollars annually. Nuclear phase-out by Germany motivated many countries in the global north to follow the path; however, China and Russia continue to increase their presence in the nuclear power sector with new modular reactors, which are much smaller in capacity. The public opposition to nuclear energy has increased after the Fukushima nuclear meltdown, which has prompted many countries to intensify their regulations and safety measures. Thus, increasing the cost and time needed to get approvals for large nuclear power plants. The levelized cost of energy for nuclear energy has increased in the last decade compared to wind and solar; their cost has taken a downward trajectory.

2.6.4 Geopolitical Risks

Geopolitical risks, such as the war in Ukraine, have strained the relationship between Russia and the West. Due to the sanctions, the low gas imports from Russia to Germany have caused energy insecurity and blackouts. The disruptions in gas pipelines have prompted Germany and other western European countries to look for LNG imports from Qatar, USA, and Australia to fill up their reservoir to meet the demand in the winter season. Opening a new market in Europe has urged the

LNG exporters to look away from Pakistan, Bangladesh, and Sri Lanka, throwing them into energy insecurity and forced to face long blackouts. Geopolitical risk has triggered Germany and Western European countries to speed up their investments in OWE in the Baltic and the North Sea. Offshore wind energy provides diversity to energy supplies and may solve the excess dependence on one source affected by geopolitical sanctions.

On the other hand, China's potential invasion of Taiwan can cause massive risks to the OWE. The Taiwan Strait is identified as having excellent wind resources most suitable for OWE deployment. China's tensions with Taiwan may demand military operations back and forth in Taiwan Strait and cause energy supply intervention. Similar patterns are observed in India. Rameswaram (one location identified by NMRE for OWE generation) is close to Sri Lanka, and considering the Island's current financial crisis, a security threat is inevitable. China's increased presence in the Indian Ocean Region (IOR) can also be framed as a potential risk for energy infrastructure in IOR. The above factors make future energy investments in the future diverse. Therefore, to meet the growing energy need and the Paris Agreement target by 2050, countries should align their energy policies towards diversifying their energy mix that may have lesser dependence on fossil fuels.

2.7 Research Gap

The extant literature shows that a few studies expressed interest in examining why OWE did not take off even after formulating the National Offshore Wind Energy Policy (NOWE policy) in 2015. There is an absence of literature addressing the barrier that offshore wind energy faces from policy formulation to installation. Moreover, few studies categorize the barriers into categories and again sub-divided into sub-categories. The prioritization of barriers is also limited, especially after policy formulation.

Similarly, few studies compared the OWE conditions in UK and Germany. Still, these studies appeared to be old, and lessons learned in 2013 cannot be replicated in the current situation in India (Mani & Dhingra, 2013). Thus, there is a need to explore the development of OWE further, compare policy mechanisms adopted, and wisely suggest which policies are best suited to the current OWE environment.

There are studies on assessing India's offshore wind resources using a geographical information system, cost optimization model, factor analysis, and high-resolution global reanalysis data (Chakraborty et al., 2021; Lu et al., 2020; Nagababu, Kachhwaha, et al., 2017; Satyanarayana Gubbala et al., 2021). On the other hand, studies explored the fiscal incentives and development schemes available in the Indian wind energy market (Sharma & Sinha, 2019; Thapar et al., 2018), but these studies majorly address the onshore wind segment. Furthermore, the NOWE policy was screened and analyzed from political (R. Aswani et al., 2021), technical (J. Hossain et al., 2016), and environmental (Charles Rajesh Kumar et al., 2021) aspects. However, these studies did not provide a critical analysis of the effectiveness of the policy. This thesis intends to fill the gap by carefully examining and analyzing the policy mechanisms and approaches used in NOWE policy and drawing parallels to UK, Germany, and China policy schemes. The study will also provide policy suggestions based on the lessons learned from the three leaders in the global OWE race.

Though some studies explored the need to diversify the energy mix by optimal sizing by considering the cost and energy output, only a few studies have suggested a solution regarding the techno-economic and environmental factors for an optimal Hybrid Renewable Energy Solution (HRES). None of the studies optimized an HRES consisting of Offshore Wind Turbines. Markowitz's Modern Portfolio Theory is relatively untouched in creating and suggesting an HRES on techno-economic and environmental aspects, though most studies revolve around risks and cost. Moreover, the selection of an optimal energy mix that drew a comparison between a 100% renewable energy solution, an optimal standalone solution, a grid-connected option, and a diversified portfolio solution is yet to be explored.

The looming energy crisis has prompted many countries to switch to renewables. Offshore Wind Energy (OWE) is one of the most promising energy sources that can meet energy needs with clean, affordable, and accessible energy and provides a solution for energy security (Kumar et al., 2021). Meanwhile, the growth of OWE is formidable, and the barriers to its deployment have increased manyfold. The National Offshore Wind Energy Policy (NOWE policy) was drafted in 2015 for safe, effective deployment but failed to provide fruitful results. The initial aim of reaching 5 GW of OWE by 2022 looks meek (Charles Rajesh Kumar et al., 2021).

The low investment in OWE is due primarily to the existence of barriers. To solve these barriers, India must learn the best practices and successful business models from the countries that have excelled in OWE deployments, such as China, the UK, and Germany. Moreover, future risks, such as climate change, can cause severe operational risks to wind turbines and their energy generation. The absence of these risk transfer tools keeps investors sceptical about participation.

The study on a diversified portfolio for insurance companies becomes significant for reducing risk exposure and maintaining energy security. Literature on using a diversified portfolio to mitigate climate change risks and create energy security is absent. The simulation that could explore both grid-connected and off-grid options needs further analysis and recommend the best hybrid renewable energy system (HRES) for investors based on its techno-economic and environmental characteristics from an insurance company's point of view. A diversified portfolio may provide a solution to mitigate the risk, here, in this case, reduce the loss for one climate change-induced catastrophe (windstorm) due to the negative correlation between energy sources (especially wind and solar energy) in cost, risk, and variability aspects.

2.8 Research problem

Preliminary assessments have indicated prospects of the development of OWE in the Gulf of Khambhat, Kanyakumari, and Rameswaram. Previous studies show a constant and strong challenge for OWE deployment in India (Kota et al., 2015; Mani & Dhingra, 2013, 2013; Nagababu, Kachhwaha, et al., 2017; Nagababu, Naidu, et al., 2017). But these studies are concentrated on a single or a few phenomena, ignoring the overall picture (Aswani et al., 2021; Charles Rajesh Kumar et al., 2021; Kota et al., 2015; Kumar et al., 2021). One study by Govindan & Shankar, (2016), examined the existing barriers in the Indian OWE sector; however, it was carried out at the onset of the NOWE policy and had a study over 12 barriers. This study, on the other hand, covers 46 sub-barriers spread across seven global barriers.

Results from the analysis of the barriers that affect OWE deployment in India showed that financial and technological barriers need the utmost attention. These barriers took the top spots in the ranking of the barriers. There is a further need to analyze the financial and technological barriers and see if NOWE policy employs them effectively. The need for research arises from a comparative study on countries that have successfully installed OWE, showing fast growth and drawing parallels to NOWE policy. Germany's recent OWE auction was on a subsidy-free basis, and it is vital to know the policy changes that led to highly competitive bidding. The lessons learned from China, the UK, and Germany need an examination, and best practices must be suggested to Indian OWE policies and practices.

The variability of renewable energy prompts energy providers to diversify their energy mix. Studies previously have shown that there is a negative correlation between wind and solar energy. This may form the basis for building energy security and risk mitigation. A diversified energy system that considers technological, environmental, and economic aspects needs to explore by investors. The diversity in the energy mix may help the insurance companies to curb losses on a climate change-induced windstorm.

2.8.1 Research Problem Statement

The vast coastline, favourable wind conditions, and NOWE policy have not contributed to the successful deployment of OWE in India. The barriers in the Indian OWE sector are significant and need to be addressed instantly. An analysis of NOWE policy with policies and schemes adopted to enable OWE in other countries needs to be studied. Suggesting an optimal energy mix for the investors to beat climate risks and build energy security.

2.9 Research Questions

- What are the different barriers in the Indian OWE sector, and how is it categorized and prioritized?
- What are the outcomes of the National Offshore Wind Energy Policy, and how did it perform in Infrastructural, Financial, and environmental aspects? What are the lessons learned from UK, Germany, and China?
- What is the optimal energy mix based on the cost for investors? What diversified options can reduce the climate change-induced catastrophic risk and build energy security from an insurance perspective?

2.10 Research objective

The research objectives of this study are.

1. Identify the main barrier that hindered the growth of OWE and prioritize these barriers with their degree of importance using multi-criteria decision-making tools.
2. To analyze the NOWE policy and compare schemes adopted in Germany, China, and the UK on financial, infrastructural, and environmental aspects.
3. To provide the Insurance companies with options on a diversified energy mix that would reduce the losses caused by climate change-induced catastrophes for insurance investments.

This section reviews the existing literature thematically on OWE sector. Further, the barriers to OWE deployment was explored, and finally, the existing literature which explored the possibility of hybrid renewable energy system were identified, leading to gap identification.

CHAPTER 3

METHODOLOGY

The first objective of this study is to explore the barriers that hinder the initialization and growth of OWE in India. Here a Multi-Criteria Decision Making (MCDM) method is proposed. Fig. 3.1 presents the research methodology used for this study to identify and rank the essential obstacles to OWE.

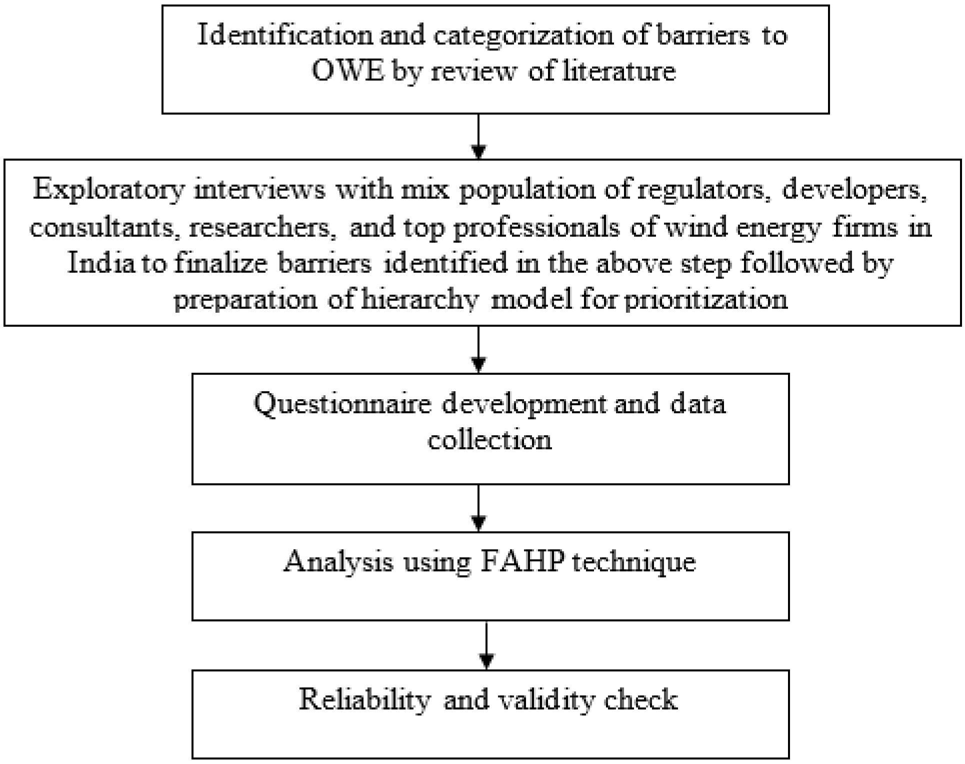

Fig. 3.1. Research Methodology in Phases

Phase 1: From the extant literature, the barrier in OWE is identified, and a review is conducted.

Phase 2: The wind energy experts in India are identified, and exploratory interviews are conducted to finalize the barriers. The expert panel includes a mix of wind energy developers, consultants, regulators, and academicians. This panel helped in reframing the barriers in the Indian context, and suggestions led to identifying more barriers, and subsequent literature was identified through the second review process. These interviews and literature review assisted in categorizing the 46 barriers into seven categories.

Phase 3: Development of surveys and data gathering: A questionnaire is developed with pairwise comparison applying fuzzy triangular numbers followed by identifying experts from whom the data is collected.

Phase 4: Analysis using the Fuzzy AHP technique

The Fuzzy-AHP, an MCDM method, lowers the fuzziness of the data in classifying the key barriers.

Phase 5: Reliability and Validity

The triangulation approach and peer briefing method will improve the validity and reliability of this research.

3.1 Multi-Criteria Decision-Making Using Fuzzy Analytical Hierarchy Process

3.1.1 Fuzzy AHP methodology

The Analytical Hierarchy Process (AHP) is an MCDM tool used for decision-making quantitatively and qualitatively. AHP reduces subjectivity in research. The complex problems are broken down into sub-problems, and comparison is made on a one-to-one basis enabling prioritization and arriving at the optimal decision.

A fuzzy number is shown as seen in Fig. 3.2 if (a, b, c) represents a triangular fuzzy number M and (m (w)) indicates the membership function.

$$\mu_m(w) = \begin{cases} \frac{w-a}{b-a} & a \le w \le b \\ \frac{c-w}{c-b} & b \le w \le c \\ 0 & \text{Otherwise} \end{cases}$$

with $-\infty < a \le b \le c \le \infty$. (1)

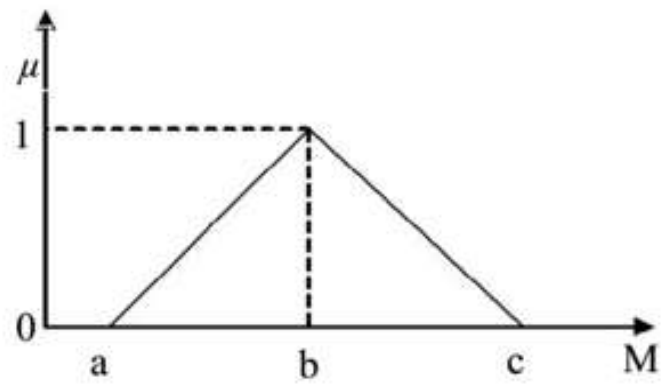

Fig. 3.2. Triangular fuzzy number

1. Fuzzy synthetic extent value calculation

$$\text{FNi} = \sum_{j=i}^{m} P_{gi}^{j} \otimes \left(\sum_{i=1}^{n} \sum_{j=1}^{m} P_{gi}^{j} \right)^{-1}, \qquad i = 1,2, \ldots \ldots n \tag{2}$$

$$\textstyle\sum_{j=i}^{m} P_{gi}^{j} = \left(\sum_{j=i}^{m} P_{ij}^{-}, \sum_{j=i}^{m} P_{ij}, \sum_{j=i}^{m} P_{ij}^{+}\right) \qquad i = 1,2, \ldots \ldots n \tag{3}$$

$$\left(\textstyle\sum_{i=1}^{n} \sum_{j=1}^{m} P_{gi}^{j}\right)^{-1} = \left[\frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{m} P_{ij}^{+}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{m} P_{ij}}, \frac{1}{\sum_{i=1}^{n} \sum_{j=1}^{m} P_{ij}^{-}}\right] \tag{4}$$

2. Calculation of the likelihood

If $P_2 = (p_2^-, p_2, p_2^+) \geq P_1 = (p_1^-, p_1, p_1^+)$ then $(P2 \geq P1 = \sup_{y \geq x} [\min(\mu_{P1}(x), \mu_{P2}(y))]$

where the membership values x and y are shown.

3. Determining the weight vector.

The definition of a convex fuzzy number is as follows:

$$V(FN \geq FN_1, FN_2 \ldots FN_K) = \min V(FN \geq FN_i), \quad i = 1, 2, \ldots\ldots k \tag{5}$$

$$d(FN_i) = \min V(FN \geq FN_k) = WB_i' \; k = 1, 2, \ldots\ldots, n \text{ and } k \neq I \tag{6}$$

Weights, WB_i' of the factors are

$$WB' = (WB_1', WB_2', \ldots\ldots, WB_n')^{T} \tag{7}$$

4. Priority weightage.

$$WB' = (WB_1, WB_2, \ldots\ldots, WB_n)^{T} \tag{8}$$

3.2 Weighting all obstacles according to their respective barrier types

The experts conducted paired comparisons across 46 subcategories and seven barrier categories. Table 6 depicts the allotted fuzzy triangular numbers, and Table 6 shows the comparison matrix of the barrier.

Table 3.1 Assessment scale.

Semantic attributes	Triangular fuzzy number
Absolute	(4, 5, 6)
Very Strong	(3, 4, 5)
Fairly Strong	(2, 3, 4)
Weak	(1, 2, 3)
Just equal	(1, 1, 1)

Table 3.2 Comparison matrix of barrier categories

	TB	FB	RPB	SB	SCB	IB	GB
TB	(1, 1 ,1)	(1, 1 ,1)	(0.25, 0.33, 0.5)	(1, 1 ,1)	(0.25, 0.33, 0.5)	(0.33, 0.5, 1)	(1, 2, 3)
FB	(1, 1 ,1)	(1, 1, 1)	(0.25, 0.33, 0.5)	(1, 2, 3)	(0.25, 0.33, 0.5)	(0.33, 0.5, 1)	(1, 2, 3)
RPB	(2, 3, 4)	(2, 3, 4)	(1, 1, 1)	(2, 3, 4)	(2, 3, 4)	(0.33, 0.5, 1)	(0.33, 0.5, 1)
SB	(1, 1 ,1)	(0.33, 0.5, 1)	(0.25, 0.33, 0.5)	(1, 1, 1)	(1, 2, 3)	(1, 2, 3)	(0.25, 0.33, 0.5)
SCB	(2, 3, 4)	(2, 3, 4)	(0.25, 0.33, 0.5)	(0.33, 0.5, 1)	(1, 1, 1)	(2, 3, 4)	(1, 1 ,1)
IB	(1, 2, 3)	(1, 2, 3)	(1, 2, 3)	(0.33, 0.5, 1)	(0.25, 0.33, 0.5)	(1, 1, 1)	(1, 2, 3)
GB	(0.33, 0.5, 1)	(0.33, 0.5, 1)	(1, 2, 3)	(2, 3, 4)	(1, 1 ,1)	(0.33, 0.5, 1)	(1, 1, 1)

3.2 Comparative Analysis Using Systematic Literature Review

Research objective two can be fulfilled by applying a systematic literature review (SLR) to identify and analyze the published Offshore Wind Energy

Policy studies. This method appeared in various studies in recent years (Mukoro et al., 2022). Some studies similar to this study used the PRISMA approach having stages of Identification, Screening, Eligibility, and Included (Turschwell et al., 2022). This study identifies (identification stage) the existing literature from the Scopus database. A step-by-step process is carried out to exclude the paper and identify the most relevant literature (Fig. 3.3). The keyword "offshore wind energy policy" is used to find the literature. The results show 711 documents at the first stage after excluding documents published before 2011. At the second stage (screening stage), books, book chapters, conference papers, and non-English articles were excluded, bringing the total count to 512 journal articles. In the third stage, the researcher read the title and abstract of the papers selected in the next step and excluded 295 papers.

Further, the authors read the introduction and conclusion in the next stage, and 102 papers that did not fall into the discussion were excluded. In the last few stages (eligibility stage), 115 full articles were read, and 23 were rejected. However, after checking their indexing in the Scopus database, 15 additional papers were identified through references and added to the list (after checking their indexing in the Scopus database). The review was carried out on a list of 107 papers (included).

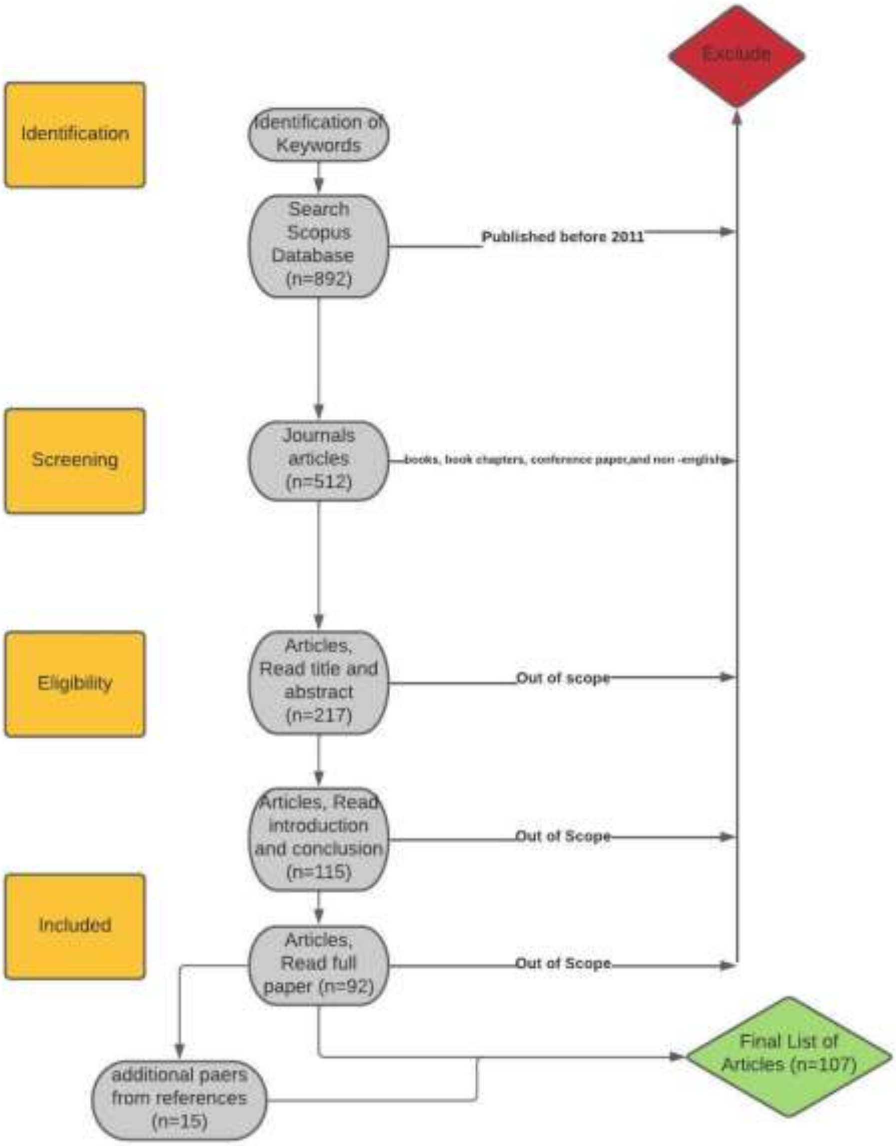

Fig 3.3 Research procedure

3.2.1 Justification of comparison of policies of China, the UK, and Germany with India

China, Germany, and the United Kingdom have significantly increased OWE in the last five years. Together they formed 82.46% of global OWE power capacity in 2021 (Table 3.3). Globally 10.5 GW of OWE power capacity was added in 2021, of which 8 GW was from China. The OWE capacity in the UK is 11 GW, and Germany stands at 7.5 GW (Fig. 3.4). The prediction of OWE installation is expected to reach 28.5 GW by 2030. The predictions show that the United States will increase its capacity installation by 2030 with France, Taiwan, India, and South Korea. The challenges these countries face must be studied from the lessons learned and successful policies adopted by Germany, China, and the United Kingdom.

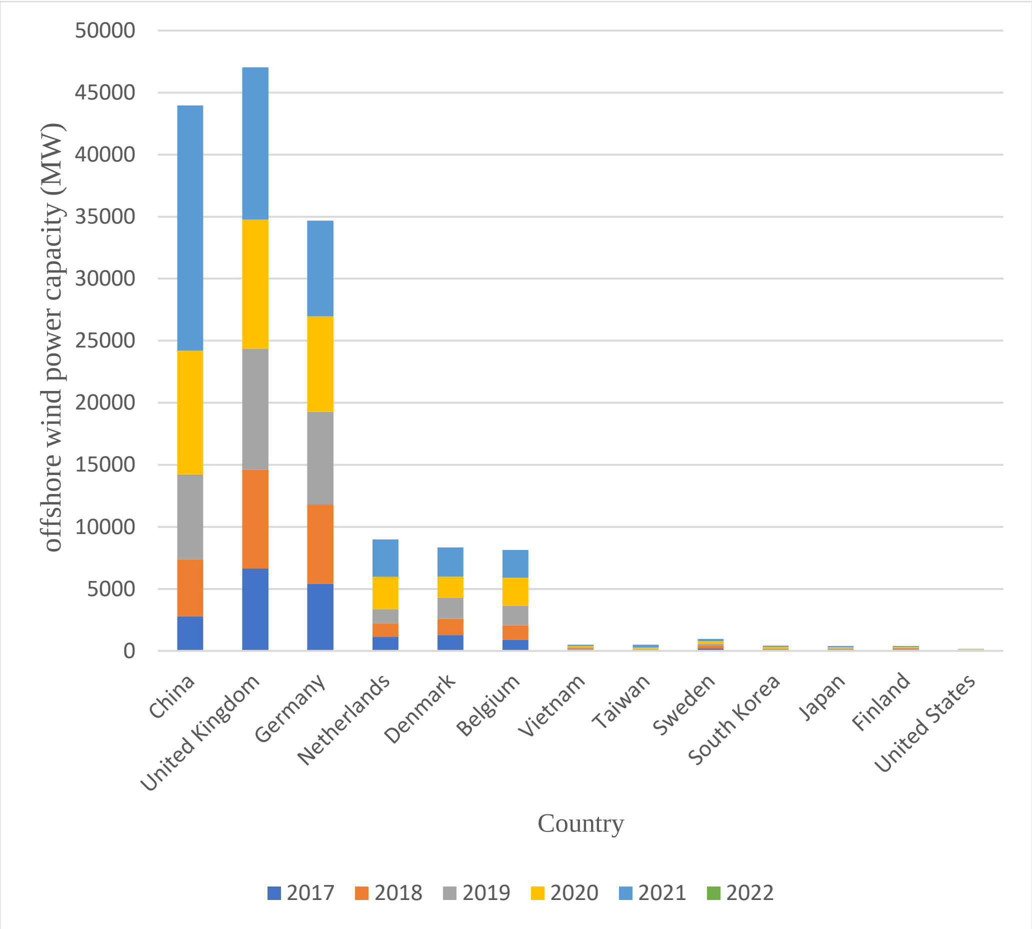

Fig. 3.4 Annual offshore wind installations (BloombergNEF, 2020)

Table 3.3 List of countries with cumulative installed capacity in MW

Rank	Country	2016	2017	2018	2019	2020	2021
1	China	1627	2788	4588	6838	9996	19747
2	United Kingdom	5156	6651	7963	9723	10428	12281
3	Germany	4108	5411	6380	7493	7689	7701
4	Netherlands	1118	1118	1118	1118	2611	3010
5	Denmark	1271	1268	1329	1703	1703	2343
6	Belgium	712	877	1186	1556	2261	2263
7	Taiwan	0	8	8	128	128	237
8	Sweden	202	202	192	191	192	191
9	South Korea	35	38	73	73	136	104
10	Vietnam	99	99	99	99	99	99
11	Japan	60	65	65	85	85	85
12	Finland	32	92	87	71	71	71
13	United States	30	30	30	30	42	42
14	Ireland	25	25	25	25	25	25
15	Portugal					25	25
16	Norway	2	2	2	2	2	6
17	Spain	5	5	5	5	5	5
18	France	0	2	2	2	2	2
	World total	**14482**	**18658**	**23140**	**29142**	**35500**	**48176**
	Increase	**-**	**0.288**	**0.24**	**0.259**	**0.218**	**0.357**

3.3 Simulations using HOMER

The next method adopted in this thesis is the Hybrid Optimization Model for Electric Renewables (HOMER). HOMER is a tool used for optimizing mini/macro grids based on techno-economic and environmental parameters (Rozlan et al., 2011; G. Zhang et al., 2020). The software is suitable for optimization, feasibility, and sensitivity analysis in several possible system configurations (Afif et al., 2017). The National Renewable Energy Laboratory (NREL) developed the HOMER software for both off-grid systems and on-grid. It uses Windows as a computer platform, with C++ as a programming language. HOMER uses inputs like resource availability, various technology options, manufacturer's data, component costs, etc., to simulate different system configurations and produces results as a list of feasible configurations organized by Net Present Cost (NPC). HOMER can simulate a system for 8760 h in a year. The results are simulated in various graphs and tables, which support comparison among configurations and evaluate them based on their economic and technical values. It can determine load-serve policies with the lowest cost source to meet the load. In the literature for the optimization of hybrid renewable energy systems and several case studies, HOMER recommends the design of a variety of systems based on economic criteria (El-houari et al., 2020; Katsivelakis et al., 2021; Mazzeo et al., 2021). After the optimization process, the software provides the results of optimized system configurations based on NPC. HOMER has limitations; it does not consider the depth of discharge (DOD) of the battery bank, which plays a significant role in optimizing the hybrid system, as both life and size of the battery bank decrease with the increase in DOD. Therefore, the DOD should be optimized or included in the software's sensory inputs. HOMER does not consider intra-hour variability variations in bus voltage (Kharrich et al., 2019). A schematic representation of the research design is shown in Fig. 3.5.

3.3.1 Location of study

3.3.1.1 Site Overview

Willingdon Island is in the heart of Kochi, Kerala. Willingdon Island is the largest artificial Island in India (Fig. 3.6), a hub for commercial shipping and cruise liners. The Island is home to 17,226 residents spanning out to 8.21 square kms. Customs house Cochin, Port of Kochi, Kochi Naval Base, and the southern naval command of the Indian Navy are in Willingdon Island. The Island is vulnerable to cyclones, flooding, and sea level rise (Hunt & Menon, 2020; Lal et al., 2020).

The offshore wind energy exploration is projected on India's three locations: Gulf of Khambhat (Gujarat), Rameswaram and Kanyakumari (Tamil Nadu). But here in this study, we are using Willingdon Island as a suitable location for HRES for a) Willingdon Island is in the heart of densely populated Kochi; the energy demand is high b) this location is highly vulnerable to climate change (flooding in 2018 and increase in cyclones) c) involvement of other stakeholders such as fishing zones, shipping lines and port security concerns d) availability of supply chain facilities and shallow depth of the sea. Willingdon Island's vulnerability to climate change-induced catastrophes like cyclones makes it a suitable case study for investment in OWE technologies and the insurance industry's mitigation strategies. The frequency of cyclones in the Arabian Sea is rising by 52% in the last two decades (Shanas et al., 2021).

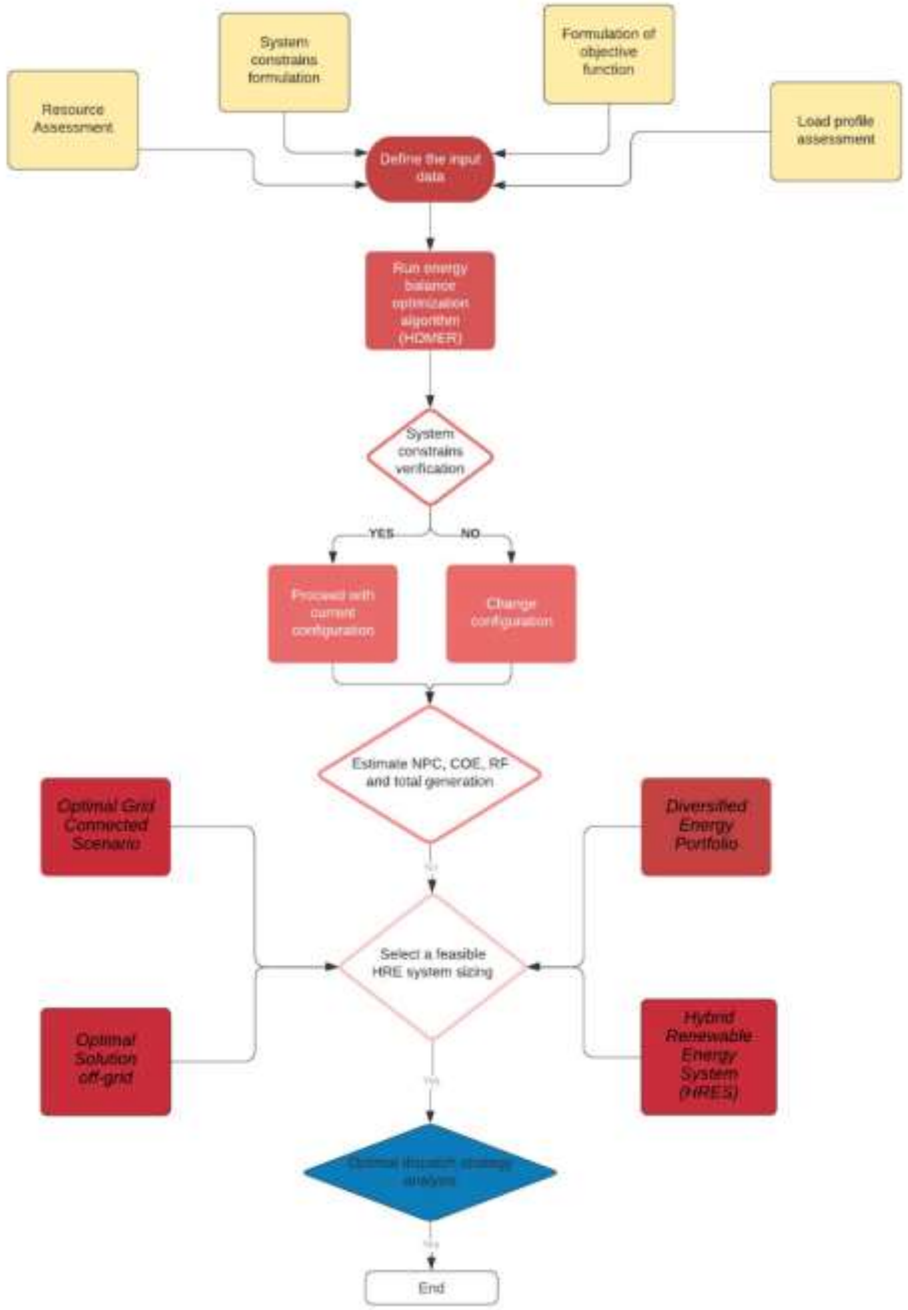

Fig. 3.5. An illustration of the research design

Fig. 3.6. Map of Willingdon Island (Source: ArcGIS)

3.3.1.2 The energy scenario in Willington Island

Kerala's installed capacity is 2,880 MW, with 4.5% (134.6 MW) coming from RE sources. Wind energy contributed 59.2 MW and solar energy created 75.4 MW. To meet the growing demand in Willingdon Island, Cochin Port Trust (CPT) had to install two solar power plants of 150 kW and 100 kW in 2017. Fig. 3.7, 3.8 & 3.9 show daily, seasonal, and yearly energy profiles, respectively.

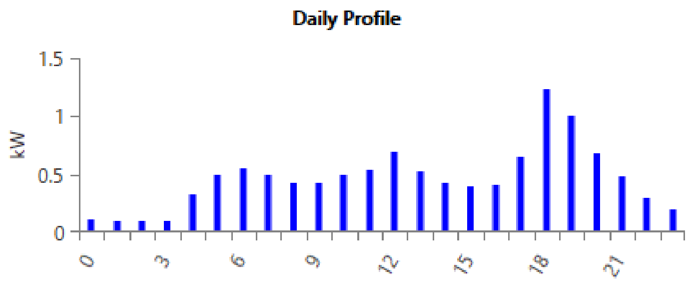

Fig. 3.7 The daily profile of energy

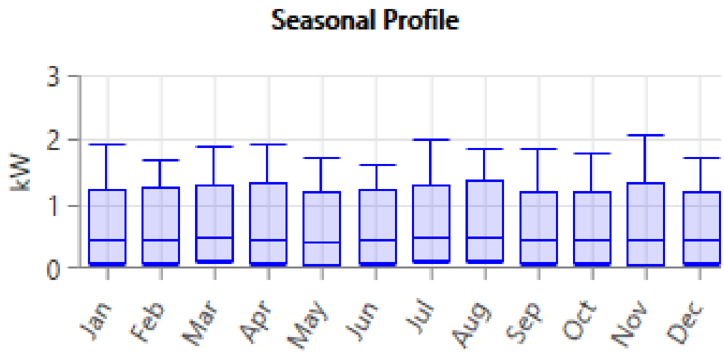

Fig. 3.8. Seasonal profile of energy

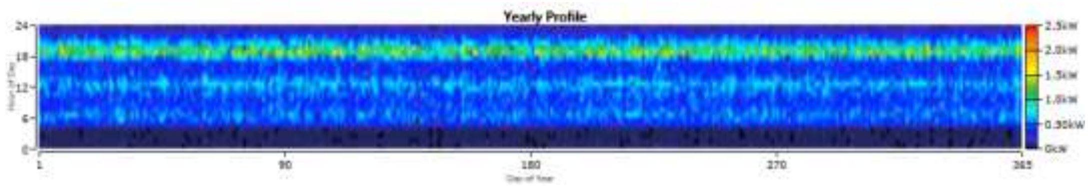

Fig. 3.9. Yearly profile

3.3.2 Design

Fig. 3.10 shows a schematic representation of the proposed system, including its PV module, wind turbine (WT), battery, and diesel generator (DG) components. In this configuration, the WT and DG are linked to the AC. The load demand is connected to the AC bus, and the PV module and battery are connected to the DC bus. A bi-directional converter transfers energy from the DC bus to the AC bus to satisfy load demand or from the AC bus to the DC bus to keep the battery charged. The energy from the RE sources (PV/Wind) is discharged after meeting the electrical requirement and recharging the battery.

The grid-connected solution's configuration is shown in Fig. 3.10, and an autonomous solution's layout for WTs, PV plates, and batteries is shown in Fig. 3.11. Here, a grid that is connected to an AC bus takes the role of the diesel generator.

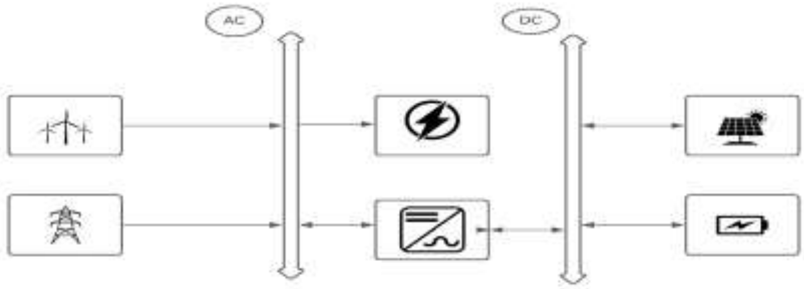

Fig. 3.10. The schematic layout of the proposed standalone system

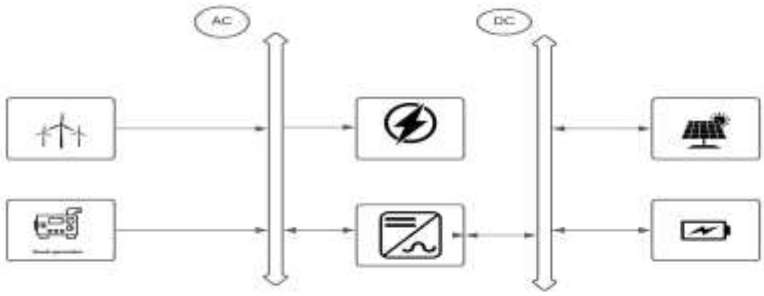

Fig. 3.11. The schematic layout of the proposed grid-connected system

3.3.2.1 Wind Turbines

Vestas's entire market share in India is just 15%, and Siemens Gamesa Renewable Energy (SGRE) makes up 30%. However, in the worldwide context, Vestas makes up 18% of the market share, while SGRE captured 20% (Fig. 3.12). Yusta & Lacal-Arántegui, (2020) point out the significant growth of Vestas in global markets, with predictions looking strong, which prompted this study to adopt Vestas wind turbines over other players. Using the technology of one WT supplier will help in standardization, and future studies can include optimization using SGRE, Inox Wind, and Suzlon.

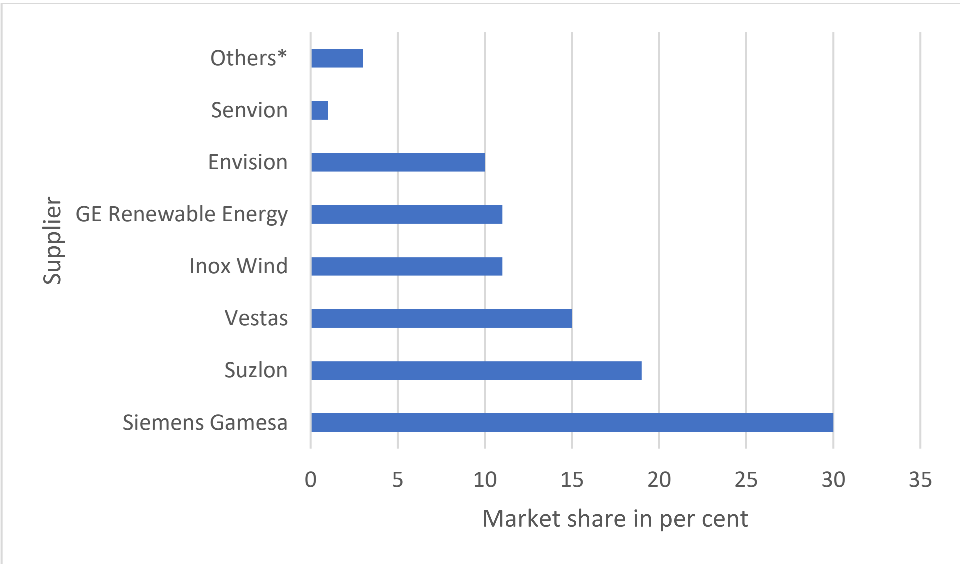

Fig. 3.12. 2019 market share for Indian suppliers of wind turbines (Statista, 2021)

We utilize Vestas V82 with a rated capacity of 1.65 MW for the grid-connected system in the scenario and Vestas V47 with a rated capacity of 660 kW for the off-grid system. Using a WT with a greater capacity factor reduces the amount of power used from the grid. Table 3.4 (Vestas V47) and Table 3.5 show both turbines' capital, operation and maintenance, and replacement expenses (Vestas V82). The highest power out is reached at a wind speed of 15 m/s for Vestas V47 (Fig. 3.13), while the maximum capacity for Vestas V82 is reached at a wind speed of 12.5 m/s (Fig. 3.14), signifying its efficiency. Thus the latter is best suited for grid-connected scenarios.

There are two main analytical models to calculate the wind speed at the hub height of the WT in HOMER: the logarithmic law and the power law (G. Zhang et al., 2020). The logarithmic law is defined as

$$u_{2} = u_{1}\left(\frac{In\ (\frac{z2}{z0})}{In\ (\frac{z1}{z0})}\right)$$

where z2 is the hub height of the WT (m), z1 is the anemometer height (m), u 2 is the wind speed at the hub height of the WT (m/s), u 1 is the wind speed at the anemometer height (m/s), and z0 is the surface roughness of the surrounding landscape (m). Seasonal changes influence the calculation of z0 in the local terrain features.

The power law is defined as

$$u_{2} = u_{1}\ \left(\frac{Z_2}{Z_1}\right)^2$$

Once the hub height wind speed has been determined, the WT power output is calculated from the WT's power curve. The WT's power curve is developed at wind speed under STP (standard temperature and pressure conditions). According to the following equation, HOMER multiplies the power value predicted by the power curve by the air density ratio to adjust to actual conditions.

$$P_W = \left(\frac{\rho}{\rho 0}\right) P_{W,STP}$$

where PW is the actual WT power output (kW), PW, STP is the WT power output at standard temperature and pressure, r is the actual air density, and r0 is the air density at standard pressure (1.225 kg/m3) and temperature. The air density ratio can also be calculated as a function of the altitude as follows:

$$\left(\frac{\rho}{\rho 0}\right) = \left(1 - \frac{B_z}{T_0}\right)^{\frac{g}{RB}} \left(\frac{T_0}{T_0 - B_z}\right)$$

Where B is the lapse rate (0.0065 K/m), g is the gravitational acceleration (9.81 m/s2), z is the altitude (m), T0 is the standard temperature (288.16 K), and R is the gas constant (287 J/ kg K).

Table 3.4. Vestas V47 specification used for simulation

Specification	Unit
Capacity	660 Kw
Hub Height	50m

Capital	$10,000
Replacement	$10,000
O & M	$200
Lifetime	20 years

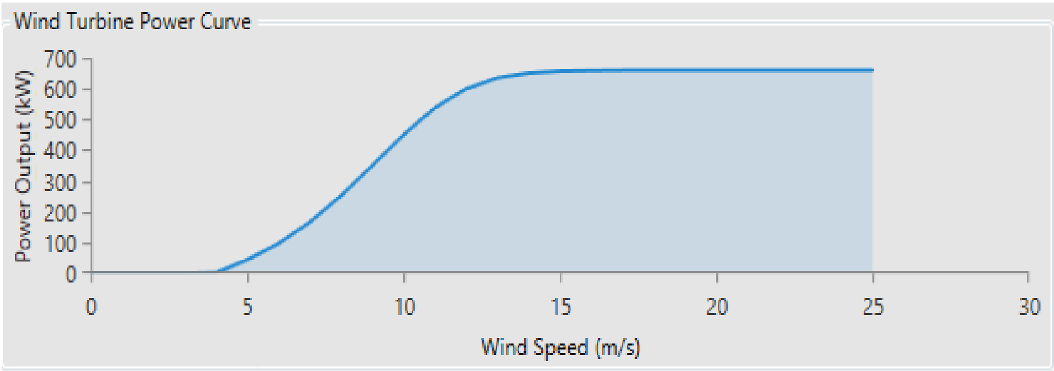

Fig. 3.13 Wind turbine power curve (Vestas V47)

Table 3.5. Vestas V82 specifications used for simulation

Specification	Unit
Capacity	1650 kWh
Hub Height	70
Capital	10,000
Replacement	10,000
O & M	200
Lifetime	20

3.3.2.2 Solar PV

To find the best option amongst the two scenarios (grid-connected and off-grid systems), generic flat-plate PV is employed with a 1 kW rated capacity, with a lifespan of 25 years. The capacity factor for the flat plate panel type is 18.3%. Table 3.6 provides the techno-economic details of the Generic Solar PV plate utilized in the simulation.

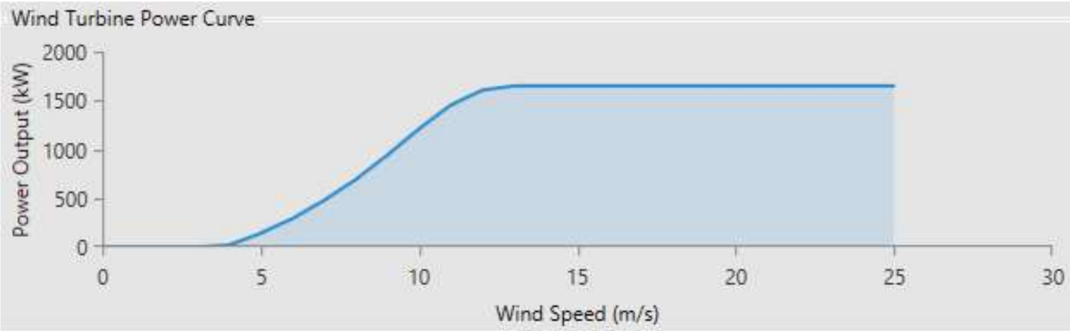

Fig. 3.14. Vestas V82 Power Curve

PV array power output is stated as

$$P_{PV=}P_{PV,STC} \int PV \int temp\left(\frac{l_T}{l_{T,STC}}\right)$$

Where l (T,STC) is the incoming radiation during standard test circumstances (1 kW/m2), temp is the temperature derating factor, PV is the PV derating factor (%), and P (PV,STC) is the rated capacity of the Solar-Flat PV array under standard test conditions (kW). Derating factors include everything that would cause the PV array output to differ from what would be expected under ideal circumstances, such as dust on the surface of the panels, wiring losses, shade, age, high temperatures, or other factors.

The temperature derating factor is calculated as follows.

$$\int temp = [1 + \alpha_\rho(T_c - T_{C,STC})]$$

where α_ρ is the power temperature coefficient (%/°C), Tc is the PV cell temperature in each time step (°C), and $T_{C,STC}$ is the PV cell temperature at STC (standard test conditions) (25° C)

Table 3.6. Specifications for Generic Flat PV

Specification	Unit
Type	Flat Plate
Capacity (kW)	1
Capital ($)	3,000
Replacement ($)	3,000
O&M (per year in $)	10
Lifetime (years)	25
Derating Factor (%)	80
Ground Reflectance (%)	20

3.3.2.3 Converter

The power generated by solar PV and WTs is DC in nature. The DC power is converted to AC using power inverters at the desired frequency. To meet the load demand (Table 3.7). The efficiency of the converter (η_{cnv}) can be approximated in the function of the input power (P_{input}) and output power (P_{output}) by equation

$$\eta_{cnv} = \frac{Poutput}{Pinpu}$$

Table 3.7. Techno-economic specification of the Converter used in the simulation

Specification	Unit
Capacity (kW)	1kW
Capital ($)	$300
Replacement ($)	$300
O & M (per year in $)	$0
Lifetime (years)	15
Efficiency (inverter output in %)	95%
Relative capacity (inverter output in %)	100%
Efficiency (Rectifier Input in %)	90%
Relative capacity (%)	100%

3.3.2.4 Generic 100kWh – Li-Ion

Batteries are the most commonly used storage devices, more than supercapacitors, flywheel storage, and pumped hydro storage. Batteries form a significant portion of the COE primarily due to their regular replacement, usually every 6-8 years. The batteries' lifetime depends on the manner they operate and external conditions such as temperature and dirt. We have considered Generic 100 kWh – Lithium-Ion batteries for this study (Table 3.8) due to their better performance, high depth of discharge, and extended operating lifetime over the lead acid battery (Come Zebra et al., 2021). Another study found that Li-ion-based systems operate 30%-35% lower cost than lead-acid battery-based PV/Hydro systems (Carroquino et al., 2021).

The surplus energy from the RE sources is stored in the battery. When the total generated energy ET is greater than the load demand EL, the battery is charged, and the available battery bank capacity at any time (t) during this process can be described by the following equation.

$$E_{Batt\ (t)} = E_{Batt\ (t-1)} \times (1-\sigma) + \left(E_T(t) - \left(\frac{E_{L(t)}}{n_{inv}}\right) \times n_{bat}\right)$$

When the load requirement is larger than the energy generation from the RE, the battery serves the load requirement. Eq defines the battery bank capacity at any time (t) in discharging.

$$E_{Batt\ (t)} = E_{Batt\ (t-1)} \times (1-\sigma) - \left(\left(\frac{E_{L(t)}}{n_{inv}}\right) - E_T(t)\right)$$

whereby $E_{Batt\ (t)}$ and $E_{Batt\ (t-1)}$ are the available energy quantities (kWh) at time *t* and *t-1*, respectively, σ refers to the battery self-discharge rate, n_{bat} is the efficiency of the battery bank, n_{inv} is the inverter efficiency.

3.3.2.5 Diesel Generator

Diesel generators (DG) are usually employed to meet the peak demand, mainly when the wind and solar output is low. The capital and replacement costs are 500 $/kW each, where the maintenance cost was 0.030 $/h for simulation (Table 3.9). The efficiency of the DG reaches 40% and gains its consistency after 1000 kW of power output. The fuel consumption undergoes a steady increase against power output; at 1500 kW of output power, DG consumes 400 litres/hour of fuel (Fig 3.15).

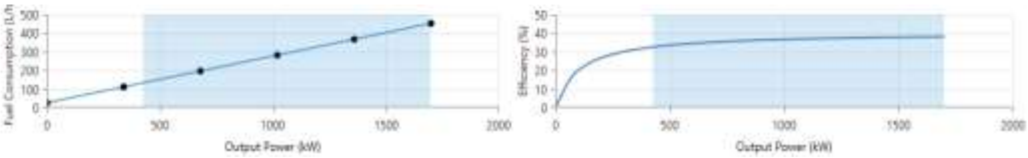

Fig. 3.15 Fuel consumption on output power and efficiency as against output power (DG)

Table 3.8 Specifications of Generic 100kWh – Li-Ion used in the simulation

Specification	Unit
Nominal Voltage (V)	600
Nominal Capacity (kWh)	100
Nominal capacity (Ah)	167
Round trip efficiency (%)	90
Maximum charge current (A)	167
Maximum discharge current (A)	500
Capital ($)	70,000
Replacement ($)	56,000
O&M (per year in $)	10
Time (years)	10
Throughput (kWh)	300,000
Minimum state of charge (%)	20

3.3.2.6 Grid

Excess electricity is the difference between the power generated from renewable sources and the demand to be met. When this difference is positive in the grid-connected mode with fully charged batteries, the energy is supplied back to the grid. Net metering is not applied to this study; HOMER calculates the total annual energy charge using the below equation.

$$C_{grid,energy}= \sum_{i}^{rates} \sum_{j}^{12} E_{grid\ purchases,i,j}.C_{power,i}$$

$$- \sum_{i}^{rates} \sum_{j}^{12} E_{gridsales,i,j}.\ C_{sellback,i}$$

Where $E_{grid\ purchases,i,j}$ is the amount of energy purchased from the grid in month *j* during the time that rate *i* applies in kWh, $C_{power,i}$ is the grid power price for rate i ($/kWh). $E_{grid-sales,i,j}$ is the amount of energy sold to the grid in month *j* during the time the rate *i* applied in kWh. $C_{sellback,i}$ is the sellback rate for rate *I* in kWh. The grid emits 632 g/kWh of carbon dioxide and 1.34 g/kWh of nitrogen dioxide (Table 3.10).

Table 3.9. Techno-economic and emissions specification of DG

Specification	Unit
Name	Autosize Genset
Fuel	Diesel
Fuel Curve intercept	25.8 L/hr
Fuel curve slope	0.251 L/hr/kW
Initial Capital	$500
Replacement	$500
O&M (per operation hour)	$0.030
Minimum Load Ratio	25%
Lifetime hours	15,000
CO (g/L fuel)	16.5
Unburned HC (g/L Fuel)	0.72

Particulates (g/L fuel)	0.1
Fuel Sulfur to PM	2.2%
NOx (g/L fuel)	15.5
Lowest heating value (MJ/kg)	43.2
Density (kg/m3)	820
Carbon Content	88%
Sulfur content	0.4%

1.3.3 Economic and Environmental Parameters

In accordance with the supplied parameters, the HOMER simulates several system setups and selects the best option among possible pairings using the total net present cost (TNPC). The total present value of all expenditures incurred during the system's lifespan, less the current value of all money generated, is calculated as the TNPC. The following equation is used to get the total net current cost:

$$C_{NPC} = \frac{C_{ann}, tot}{CRF(i, N)}$$

where C_{ann}, tot is the total annualized cost, and CRF indicates the capital recovery factor; it is calculated as

$$CRF(i, N) = \frac{i(1 + i)^N}{(1 + i)^N - 1}$$

where, N = project lifetime in years, *i* = interest rate in %

The following equation calculates the cost of energy (COE)

$$COE = \frac{C_{ann}, tot}{Eprim, AC}$$

where $Eprim, AC$ is the AC primary load served (kWh/yr).

The COE disregards the effects on the environment, taxes and subsidies, and daily variations in supply and demand. These elements have an impact on how flexible various energy-producing systems are.

Table 3.10. Economic and Emission specification of the grid in the simulation

Specification	Unit
Grid Power Price ($/kWh)	0.100
Grid Sellback price ($/kWh)	0.050
Carbon Dioxide (g/kWh)	632
Carbon Monoxide (g/kWh)	0.00
Unburned hydrocarbons (g/kWh)	0.00
Particulate Matter (g/kWh)	0.00
Sulfur Dioxide (g/kWh)	2.74
Nitrogen Dioxide (g/kWh)	1.34

3.3.4 CO_2 Emission

The emitted CO_2 by the system can be calculated as follows.

$$Totalemmision = \sum t \in T \sum n \in N\, E_n gn_{nt}$$

E_n is the emitted CO_2 of the nth unit in period t (ton/MWh), and gn_{nt} denotes total power generation of non-renewable in period t (MWh).

3.3.5 Renewable fraction

The following equation is used to calculate the total amount of power produced by RE sources in HRES.

$$RF(\%) = (1 - \frac{\sum P\ DG}{\sum P\ renew}) * 100$$

3.3.6 Objective function and control strategy

A load-following strategy is adopted due to the stochastic nature of the RE and demand load. The energy generated from renewables is the first choice, followed by the batteries. The diesel generators and the grid are called upon to meet the energy load demand to provide energy security. The variability of RE may occur for a longer duration which may not provide enough time for the Li-ion batteries to charge. The system is designed so that batteries won't get charged by the energy provided by the grid or the diesel generator but rather only by the renewables.

This section explains the methodology adopted for the study. Firstly, the barriers to OWE in India are identified through an extensive literature review followed by ranking these barriers using Fuzzy Analytical Hierarchy Process. Secondly, a Systematic Literature Review (SLR) is adopted to compare the policies and schemes of the National Offshore Wind Energy Policy with the successful policies and schemes embraced by China, the UK and Germany. Finally, HOMER simulation is employed to identify the optimal energy solution for the selected region, i.e. Willingdon Island, to implement OWE complemented by other energy sources to meet energy security.

CHAPTER 4

RESULTS AND DISCUSSION

From the literature review, it is observed that OWE in India faces multiple barriers. The barriers are categorized into seven headings, namely, financial barriers, technical barriers, political barriers, social barriers, supply chain barriers, geographical barriers, and institutional barriers. The seven broad barriers have 46 sub-barriers. The results through fuzzy AHP, which ranked and prioritized these barriers, show that technical barriers are the highest-ranked barrier, followed by financial barriers. Regulatory and Political barriers take the third position, Social barriers stand fourth, and Supply chain barriers take the fifth. Institutional and geographical barriers are ranked sixth and seventh, respectively (Table 4.1).

4.1 Identifying, Analyzing and Prioritization of Barriers to OWE

Table 4.1 OWE Barriers and Rankings

Barriers		Relative weight	Rank of main barrier	Local weights	Ranking within main barrier	Global weights	Global Ranking
1	THB	0.2538	1				
	THB1			0.09960	7	0.02529	17
	THB2			0.13520	5	0.03432	12
	THB3			0.16550	1	0.04199	8

THB4			0.13990	4	0.03552	11
THB5			0.04010	8	0.01019	32
THB6			0.10020	6	0.02542	16
THB7			0.16160	2	0.04102	9
THB8			0.15790	3	0.04007	10
2 FIB						
FIB1			0.34270	1	0.06673	1
FIB2			0.02300	8	0.00447	42
FIB3			0.10280	4	0.02001	21
FIB4	0.1947	2	0.08040	5	0.01565	27
FIB5			0.23050	2	0.04488	4
FIB6			0.06950	6	0.01353	30
FIB7			0.03870	7	0.00753	38
FIB8			0.11250	3	0.0219	20
3 R&PB						
R&PB1			0.12230	5	0.0065	40
R&PB2			0.10870	6	0.0058	41
R&PB3			0.02730	9	0.0015	46
R&PB4			0.22170	1	0.0118	31
R&PB5	0.05330	7	0.15630	3	0.0083	37
R&PB6			0.04130	7	0.0022	43
R&PB7			0.04020	8	0.0021	44
R&PB8			0.12410	4	0.0066	39
R&PB9			0.15813	2	0.0084	36
4 SOB						
SOB1			0.22610	3	0.0422	6
SOB2			0.29390	1	0.0548	2
SOB3	0.18640	3	0.24330	2	0.0454	3
SOB4			0.01060	4	0.0020	45
SOB5			0.22610	3	0.0422	7
5 SUCB						
SUCB1			0.11510	5	0.0088	34
SUCB2			0.11510	5	0.0088	35
SUCB3	0.07600	6	0.11730	4	0.0089	33
SUCB4			0.20960	2	0.0159	26
SUCB5			0.19860	3	0.0151	28

	SUCB6			0.24440	1	0.0186	22
6	INB						
	INB1			0.34950	1	0.0448	5
	INB2			0.13250	4	0.0170	25
	INB3	0.12820	4	0.19830	3	0.0254	15
	INB4			0.21200	2	0.0272	13
	INB5			0.10760	5	0.0138	29
7	GEB						
	GEB1			0.16120	5	0.0173	24
	GEB2			0.16390	4	0.0176	23
	GEB3	0.10750	5	0.21750	2	0.0234	18
	GEB4			0.20960	3	0.0225	19
	GEB5			0.24780	1	0.0266	14

4.1.1 Technical Barriers

Technical barriers are ranked highest among the seven barriers. Lack of maintenance activities and uncertainties on foundation technologies occupied the first two spots, and the lack of offshore wind zones is ranked third. Lack of maintenance activities occupied eight global barriers. Unlike European offshore leaders, India does not have expertise in offshore technology. The increase in project cost during its operation is largely due to inadequate testing, technological failure, and a lack of supporting industries and infrastructure (Shafiee & Kolios, 2015). Lack of energy storage occupied a higher rank among the list of sub-barriers. The scale of energy production is larger in OWE, and without an adequate energy storage system, the risk of curtailment is inevitable (Guo et al., 2022; Wilkie & Galasso, 2020). The future scope of OWE is its collaboration with green hydrogen technologies, which may provide a solution for the user without energy curtailment (Wu et al., 2019)

The cable and grid connection barriers cause significant hindrances to OWE deployment (Roetert et al., 2017). Cabling also poses a threat to the marine environment. But cable installation is ranked lower in the results. Sub-barriers in technical barriers did not occupy the top five global rankings, but their position overall has signified technical barriers as the most important barrier among the seven barriers in this study.

4.1.2 Financial barriers

The analysis puts financial barriers in the second position on overall barriers categorization. High capital occupied the first rank, followed by the high cost of engineering facilities. The cost involved in OWE is 2.5 times more than onshore wind (Sun et al., 2017). This increases the need for financial incentives by the government to cover the burden incurred by the OWE producer (Nguyen & Chou, 2019). Not surprisingly, the high levelized cost of electricity and inadequate subsidies and incentives occupied the next two ranks in financial barriers. The NOWE policy proposes incentives and subsidies as a tool to increase investments. However, the lack of it is still lingering in the industry, and this study provides evidence of the same. Insurance is crucial to covering the cost of natural catastrophes because of their rising frequency (Kim & Manuel, 2016). Finances availability and lack of consistency of feed-in tariffs are the least ranked sub-barriers under the financial barrier.

The NOWE policy states the extension of fiscal incentives for onshore wind to OWE deployment. However, findings from this study point out that these incentives are not enough to effectively deploy OWE. The applicability of onshore incentives to OWE is under question. There is a need for OWE-specific policies, considering the specific risks associated with the offshore condition.

4.1.3 Social barriers

Thirdly, social hurdles, which primarily involve the human and environmental aspects of the OWE project acceptability, are a hindrance to the expansion of OWE. Any new technology-based project's development is critically dependent on public acceptability, the availability of expertise and practice, and the project's environmental effect (Staid et al., 2015). Social acceptability ranks top among the five social sub-barriers, followed by noise and visual effects. The fact that these two are ranked second and third globally highlights the crucial role that societal approval, including voice and noise, may play in a project's success (Thomsen et al., 2006).

Another noteworthy point is that the third-ranked social barrier, lack of expertise and practice, is equal in importance to public awareness. OWE in social barriers is somewhat influenced by environmental preservation. These two are ranked sixth and seventh globally, respectively, making social barriers the factor that contributes the most to rankings. Five sub-barriers, with the exception of one, are in the top 10 globally, indicating the growing importance of societal approval of the project in recent years. The NOWE strategy, however, gave social obstacles just a little amount of precedence. The state governments may keep an eye on coastal growth and are urged to include grid infrastructure and logistics planning in their State Action Plans (NMRE, 2015). The uncertainty surrounding OWE operations in India would decrease with the addition of strategies to address social barriers.

4.1.4 Institutional Barriers

Institutional barriers that compiled the fourth rank consist of the accessibility of organizations offering a smooth flow of human resources, infrastructural facilities, capacity, collaboration, and corruption-free project clearance and implementation (Hamilton, 2012; Wüstemeyer et al., 2015). The top two factors causing institutional hurdles are a lack of infrastructure and a shortage of competent human resources. One of the key goals of NOWE strategy is to create skilled labour and jobs in the OWE industry (NMRE, 2015). Our findings indicate the necessity to focus additional efforts on developing trained labour for India's OWE sector. The function of institutional linkage and capability for the efficient execution of OWE business is ranked third and fourth due to a lack of institutional capacity and coordination. The least significant sub-barriers to OWE initiatives are governmental inefficiency and corruption, which can stifle innovation, ardour, and funding.

4.1.5 Geographical Barriers

Geographical obstacles are placed sixth in terms of their impact on OWE, with natural disasters being the top barrier. Due to its geographic position, OWE is substantially more vulnerable to natural disasters and extreme climatic occurrences like cyclones and earthquakes. It makes OWF developers' evaluation of windstorm risk worse and draws emphasis to insurance as a risk-reduction measure (Liao et al., 2021). Natural catastrophe is ranked second, followed by fishing lines, ocean depth, and uneven geography. The NOWE policy considers how the project may affect the way of life of fishing villages, and precautions are taken to avoid entering the fishing areas (NMRE, 2015). Because policies supporting one cause the loss of others, the fisheries industry and OWE have traded off ties with one another. The ocean's depth determines the choice of the turbine foundation and its uneven terrain, much as the sea's depth, seabed surface, and topography affect the offshore wind turbine structure. A protected marine area is the other geographical barrier that comes second in this category. Due to sound and electromagnetic waves, OWE substantially impacts marine ecosystems and puts marine animals in danger when migrating and mating. Concern over OWE's potential impact on marine ecology has grown recently (Deveci et al., 2020).

4.1.6 Supply chain barriers

The next priorities for OWE generation are the lack of alignment of tooling facilities, lack of port facilities, facilities for assembly and maintenance, unreliable turbine vessel carriers, and a lack of heavy-duty supply chain machinery and technology. Large monopile and jacket foundation manufacturing is not matched with tooling and facilities at the yards, which are at local rank one. This issue is crucial since floating turbines are now an option (Keivanpour et al., 2020). The next two local rankings are for lack of port facilities and a lack of assembly facilities.

Marine conditions that are dynamic and turbulent have an impact on the logistical process of component assembly. Pre-assembling turbine parts can cut costs and time, but a lack of facilities makes it difficult. The cost, accessibility, and dependability of OWE systems are primarily determined by field assembly, maintenance, and operations vendors, who rank fourth locally. These factors also depend on the availability of qualified labour and technicians. Unreliable transportation infrastructure and the absence of heavy-duty supply chain technologies, which rank fifth locally, are last in the category. Large wind turbines provide supply chain issues since they need specialized care throughout manufacturing and installation. As the most advanced technology, heavy-duty supply chain technology is an expensive endeavour. Interestingly, none of the supply chain's six sub-barriers fit under the top 20.

4.1.7 Regulatory and Political Barriers

Political and regulatory constraints are in the seventh position and barely affect OWE's expansion. If entry barriers are lowered, this might be a major factor in encouraging increased involvement from local manufacturers (Jadali et al., 2021). The most significant barrier to entry has been found to be technology. The second item in this category is how well electricity suppliers adhere to the applicable poor standards and the renewable cost. The lack of Renewable

Obligation Certificates is debatable since OWE in India hasn't really taken off yet.

The lack of required standards hampers the OWE since it is a significant technological barrier. The next local level is reserved for the institutional regulatory framework and enabling business models. Although it is mainly missing in the case of OWE, the Power Purchase Agreement (PPA) between generators and state governments emerged as a significant milestone for the growth of renewable energy in India. Players and reverse auction participation had led to a scenario where the state government had to cancel the PPA because of the ongoing decline in renewable energy costs brought on by technological advancement.

A lack of coordination and inter-ministerial cooperation amongst relevant entities hampers the development of OWE. Integration of wind energy into the energy mix necessitates political commitment and broad support for revamping the power industry. Given that the current Modi administration has undertaken ambitious initiatives, it gets ranked lower as a result (sixth). Next are weak financial policy backing and wind-targeted initiatives. Finding the lowest tariff has been emphasized by the e-reverse auction mechanism since it impacts the project's financial feasibility. Investment attraction is hampered by inadequately tailored policies relating to various OWE technologies. The OWE in this category is least affected by bureaucratic permission procedures. This category is made up of all sub-barriers with the lowest global rank.

4.1.8 Barriers from an Insurance Perspective

India's lack of experience tapping offshore energy resources and technical barriers dictates insurance companies' investment decisions in the Indian OWE sector. The technical issues of low-quality turbines and lack of maintenance activities increase the risk of damage arising from climate change-induced cyclones. The turbine's life span will be significantly lowered when the turbines do not meet the required quality in harsh ocean conditions. The high initial cost of OWE deployment will factor developers into looking for insurance support for risk transfer. The premium set by the insurance companies will also be on the higher side.

During construction, wind energy projects are generally covered against accidents, physical damage, business interruptions, and natural disasters. Some of the insurance coverage provided by insurance companies for offshore wind developers are offshore logistical cover, operations and maintenance cover, serial loss cover, Engineering, Construction, and Procurement (EPC) cover, and lack of wind cover. In addition, the catastrophic modelling tools employed by insurance companies can mitigate the loss arising out of weather-related disasters and help insurance companies diversify their investment portfolio limiting the losses caused by a single event of a catastrophe.

4.2 Comparison of NOWE policy with the schemes adopted by China, the UK, and Germany

The initial analysis of the barriers hindering OWE's progress in India provides empirical evidence that financial and technological barriers formed the backbone of barriers. The NOWE policy drafted in 2015 has given due importance to solving these issues, but the results did not prove its effectiveness. India has yet to see an OWE farm with abundant wind resources on its coasts. Thus, the policy needs to be compared and analyzed with successful lessons learned from the UK, China, and Germany. The review is on three broad parameters: Financial concerns, Infrastructural Concerns, and Environmental Concerns.

4.2.1 Financial Concerns

This section compares NOWE policy with the policies adopted by major OWE countries in financial aspects. The National Offshore Wind Energy Policy may support the development of OWE projects through international collaborations, allowing Foreign Direct Investments and Public-Private Partnerships. The OWE projects are made available with all the fiscal incentives provided to onshore wind energy. The policy also intends to promote power generated from OWE over conventional power subject to the availability of unallocated conventional power to lower costs and improve accessibility (NMRE, 2015). The NOWE policy did not provide offshore wind-specific incentives and support schemes, which may have affected the investor's interest. The technology and risks differ in OWE compared to onshore wind. Thus, the need to provide more investment-friendly subsidies and incentives becomes essential at the initial stages of development.

China introduced Feed-in-Tariff (FIT), which is applied to the entire wind energy generation operational period. This scheme sent a powerful message to investors on price stability. China adopted four different tariff strategies ranging from 0.08 $/kWh to 0.10 $/kWh, depending on the area's wind resources. Under the FIT system, the developer wins the project by competition after meeting the techno-environmental requirements and criteria (Liu et al., 2021). The Chinese FIT scheme provided OWE installed capacity to jump from 450 MW in 2013 to 4445 MW in 2018. However, because of the falling cost of OWE generation, the FIT system was amended for new projects to be determined by market competition. A dynamic FIT may track the changes in technology and avoid the inefficiencies of fixed FIT (L. Li et al., 2020). Renewable Portfolio Standard (RPS) was launched in 2019 along with Tradable Green Certificate (TGC) to force the price drop, increase the demand for RE, and reduce the deficit of the National Renewable Energy Fund (NREF).

The United Kingdom implemented the Contracts of Difference (CfD) scheme, creating a competitive platform to drive down costs and attract investments. Subsidies in the first 15 years of development of OWE projects show that the price per unit of OWE has fallen by 65% between the first allocation (2015) and the third (2019) (Welisch & Poudineh, 2020). The recent OWE auctions in

Netherlands and Germany have been subsidy-free, but having two bidders in the Dutch leasing rounds hints at investor sentiment towards the model. However, subsidy-free auctions are criticized heavily from the UK perspective, as they could jeopardize the 40 GW OWE target (Jansen et al., 2020).

In Germany, FITs have been available since 1991, and with subsequent revisions, it has brought long-term certainty to investors and developers. At the onset of wind energy development, FITs were set at 90% of the average electric utility rate per kWh (Papież et al., 2019). In 2017, Germany shifted to a reverse auction method, where the lowest offer would be chosen rather than the government setting the premium, and the developers may seek the required amount. The average bid for the first system was 0.44 cents per kWh. All three OWE farms chosen through the auction made no requests for financial assistance in 2021, and the sector can survive without aid from the government. However, because of insufficient development space provided by the government, Germany's addition of OWE in 2020 was just 219 MW. Since then, the German government has increased expansion objectives in the hopes that new development areas would be possible (Girard et al., 2020).

A preliminary analysis of OWE deployment on Malaysian coasts shows that 67% of the project's total cost was incurred by capital expenditure and 26% by operation and maintenance costs, and decommissioning of wind turbines covered 7% (Alsubal et al., 2021). The cost reduction may depend on the capacity factor effect, learning effect, and installed cost effect (Y. Yao et al., 2021). While other studies proved to 'learning by deployment' was the most critical innovation driver responsible for half of the cost reduction (Elia et al., 2020). Previous studies which analyzed the LCOE of various locations for OWE in India found that Tamil Nadu coasts have the lowest LCOE of €106.8/MWh, implying an optimal site for OWE development (Arun Kumar et al., 2020).

4.2.2 Infrastructure Concerns

In this section, we compare approaches by NOWE policy in infrastructural development with the leaders in OWE deployment. Many countries that adopted OWE followed the roadmap published by their government. It was observed that significant delays in investments because of a lack of improvement in specialized skills and barriers to addressing external factors such as regulatory approvals (Bento & Fontes, 2019). The OWE infrastructure needs to withstand natural events such as cyclones. Therefore, it is vital to comprehensively analyze cyclone patterns and design the infrastructure suited to the environment (Hong & Möller, 2011). Energy security may be ensured by designing wind turbines for higher wind speeds, making sure turbine nacelles can follow the wind direction, and finding areas with reduced cyclone risk (Rose et al., 2013). To reduce the risks associated with OWE, Shafiee, (2015) suggested four potential solutions: improvement in maintenance services, variation of OWE site layout, modification in the design of OWE turbines, and upgrading the monitory systems. The optimization of maintenance activities varies according to the changes in government subsidies under the influence of the time value of money (Nguyen & Chou, 2019). In the Indian context, technical barriers appeared to be the most impactful in the progress of OWE. The technical barriers are grid link challenges, inadequate technologies, and a lack of maintenance services that require immediate attention to streamline the progress (Dhingra et al., 2022).

The NOWE policy suggested the Ministry of Shipping will provide major port-like facilities to enable heavy construction, fabrication, and O&M activities at the seashore from where it will be moved to OWE farm site. The State Government or State Maritime Board handles delivery for minor port facilities. A specific charge may be made payable to the respective State Government or Central Government Agencies for enlisting their services. Central Transmission Unit or State Transmission Unit may direct the grid connectivity and onshore evacuation (NMRE, 2015). The MNRE established NIWE as an autonomous research and development institution. NIWE tests Wind Turbine Generator systems (WTGs) and Offshore Wind Turbine Models according to international standards.

In 2010, China invested $1.3 billion in clean energy R&D; this fund was directed towards innovation, energy conservation, industrial restructuring, and ecological improvements during the 11th Five-Year Plan. Chinese policies on grid connection are precise. The developers of OWE should have grid connection approval before proceeding with construction. The grid operators have a legal requirement to source a portion of energy from RE sources, which should be from licensed companies (R. Zhang et al., 2019).

A vast majority of German OWE turbines are in the North Sea, comprising 6.7 GW compared to 1.1 GW in the Baltic Sea. The cluster of turbines in one region created challenges in transmission and a lack of connection between grids. In the Baltic Sea, meshed grids can improve grid development. However, this potential solution has significant barriers to legal and regulatory frameworks (Sunila et al., 2019). The joint North Seas Countries Offshore Grid Initiative integrates International Law, National Law, and European Law for shared OWE infrastructure (Roeben, 2013).

The UK Government started an Offshore Wind Investment Programme to support the delivery of investments in OWE supply. Siemens Gamesa will benefit from £186 million to make next-generation turbines, Smulders will expand the existing Wallsend port facility with a grand of £70 million. In addition, SeaH will manufacture monopiles for OWE projects with £250 million over three years, and GRI will produce towers for OWE projects suitable for the deep water port site (Bahaj et al., 2020). The UK's trade and investment body, the Offshore Wind Investment Organization, is a section that focuses on developing the supply chain by assisting businesses with a high potential for employment growth. Sustained political will, consistent subsidy schemes, and regular seabed leasing through Crown Estate back UK's success in the offshore wind sector (Durning & Broderick, 2019).

The NOWE policy is silent on creating long-term international collaboration or ties for improving technology, supply chain growth, testing, and demonstration. For example, the lack of facilities in Indian ports may be a barrier to deploying new technology. In addition, the NOWE policy did not consider conditions for a demonstration project, which would have given crucial data and knowledge on technology optimization, initial cost, subsidies, incentives required, and capacity factors.

4.2.3 Environmental Concerns

This section analyzes the environmental concerns, strategies that NOWE policy adopted, and other countries' measures. Significant environmental problems are associated with OWE deployments, such as noise effects on marine mammals, chances of a collision, changes to benthic and pelagic habitats, pollution by increased traffic, and changes to food webs. The OWE projects in Germany faced environmental opposition from German nature protection organizations regarding construction, installation, and operations-related effects on habitats, marine protected regions, biotopes, and marine species (Kannen et al., 2013). The developer shall consider EIA, Federal Maritime and Hydrographic Agency, Federal Agency for Environmental Protection, and the public shall review and decide the project's compatibility by protecting the marine environment. The most recent leasing process in the UK includes a detailed assessment of economic, engineering, and environmental factors (Glasson et al., 2022). The National Infrastructure Directorate (NID) will be subject to an environmental impact assessment. The Department of Energy and Climate Change, which makes the ultimate choice, will get a recommendation from the NID after balancing the farm's advantages and environmental effects. A disjoint consenting process was observed in England and Scotland for a full assessment of the environmental impact of OWE as required by the European Union (Caine, 2020).

MNRE should consider a written policy on OWE's environmental impact and safety. Wind turbines should be meticulously designed to mitigate bird collisions, and measures should be taken to avoid maintenance activities during breeding seasons. Moreover, building standards on cable laying, turbine characteristics, construction, and maintenance activities must be considered. The multipurpose nature of wind turbines is given limited attention in the policy. At the same time, previous studies have identified the possibility of the co-existence of energy and aquaculture using planning and shared infrastructure (Abhinav et al., 2020).

The locations suitable for OWE development were demarcated after conducting an Environmental Impact Assessment (EIA), environmental audit, oceanographic surveys, etc. These surveys were conducted by entities with expertise and a proven track record under the guidelines issued by NIWE. The developers will require clearance from the Ministry of Environment, Forests, and Climate Change. A proper decommissioning and site restoration program before the construction is necessary for approval. NOWE policy takes the project's impact on the livelihood of the fishing communities, and efforts are made to keep out of the fishing zones. Several studies used the GIS method to develop maps for wind farms with careful exclusion of marine protected regions, fishing lines, migratory bird movement zones, and shipping transportation (Nagababu, Naidu, et al., 2017; Patel et al., 2018). Careful consideration of maritime safety may follow the submarine cable route. The policy also stressed the developers' role in ensuring the OWE project's security. The policy is silent on the method adopted by the developer to maintain the safety of the OWE farm.

Previous studies have pointed out the environmental risk of OWE farms in the Gulf of Mannar (Kiran et al., 2017). The region is home to pearl oyster rocks and is rich in biodiversity with swallow water depths. The farm's location close to Sri Lanka is a threat to reckon with (R. Aswani et al., 2021). China's presence in the IOR increases geopolitical uncertainties. Energy security needs risk assessment from environmental, social, technological, and geopolitical aspects and the risk of catastrophes. The NOWE policy states that the developer must conduct the risk assessment, and risks should be mitigated by insurance. The State Governments are encouraged to include OWE policy in their State Action Plan for effective promotion and monitoring.

The comparative analysis from China, UK and Germany gave lessons for the Indian OWE sector and what all measures need to be taken to see growth in the sector. It is to be pointed out that India's target of 30 GW by 2030 and 5 GW by the end of 2022 was too ambitious. Europe and China implemented a robust plan that has considered economic, environmental, and infrastructural aspects. China's 14th Five-Year Plan (2021-2025) ensures a growing market for all OWE turbine manufacturers, where Western companies are leading the market share. The plan also committed to building OWE 'bases' in five regions, increasing OWE presence to more than 60% by 2020 levels.

The UK, Germany and China faced challenges in the initial years of OWE deployment due to a lack of infrastructure and support facilities. The gestation period of the first few OWE projects is expected to be longer. India should make room for facing these challenges with updated infrastructure and manufacturing capacity in time to avoid delays. Further, the subsidies and schemes should focus on OWE solely than one scheme for all wind products. The DISCOMs' aptitude for OWE is low without subsidies. The government should encourage the OWE in the initial years with schemes that have been proven successful in Europe and China, such as Contract for Difference (CfD).

Initial years saw challenges faced by the UK, Germany, and China; however, they followed the step-by-step process of developing OWE, which reaped dividends. There was consistency, openness, and transparency in the countries' approach towards the development of OWE, which India can learn and adopt in NOWE policy. The OWE foundations and technology keep on improving, and lessons from established countries prove that long-term renewable energy targets, subsidies and strategies will not be effective. There must be efforts to strengthen the supply chain through local and international partnerships; NOWE policy should include a framework for practice that could streamline the process and encourage supporting sectors. The government can promote these sectors and industries through low-interest loans, public guarantees, grants, and incentives for developing research and development. Moreover, Indian ports need to modify to meet the requirements for handling OWE turbines, equipment, large vessels, and cranes. With their experience in developing offshore oil exploration, European ports came in handy when the need was to develop OWE. India's efforts towards its target of OWE must follow China's footsteps by exploring opportunities to build exclusive offshore wind ports, like how China built Nantong Port in Jiangsu Province. The environmental aspects of OWE are a high priority for European countries; an Environmental Impact Assessment followed by close monitoring of the project with adequate follow-up programs makes OWE industry a sustainable venture for all the stakeholders using the space. Concerns by fishing communities in India have delayed OWE development, particularly in Tamil Nadu. The government should provide measures to resolve conflicts about sea use along with follow-programs to keep the sustainability of the ecosystem, fishing communities and tourism sector in check.

India's growth of OWE will encounter multiple challenges and barriers. The lessons learned from other countries which successfully employed offshore wind energy needs to be revisited and applied to the Indian context. Some of the policy mechanisms adopted in India are outdated and used in the onshore wind sector. Identifying and prioritizing the barriers suggest that Indian policies need to be regenerated to meet requirements and terminate the barriers.

Offshore wind investments face major issues with uncertainty and probable risk exposures. The risk of natural disasters is ranked as India's fifth most important barrier in offshore wind energy. The turbines are exposed to hostile sea conditions, such as storms and liquefaction resulting from earthquakes and tsunamis. All these events can cause damage to the wind turbine and disrupt the energy supply. Some of the new technologies developed are designed to mitigate the strong impact of windstorms. In contrast, the impact of liquefaction is applicable mostly to surface-mounted foundations. Very few studies have modelled the devastating effect of the tsunami on the turbines. Floating turbines are designed to withstand waves above the hub height and mitigate liquefaction. However, the potential damage caused by windstorms (cyclones) on turbines forms a bigger risk largely due to its higher probability. However, a recent study proved that there were 13% fewer storms in the 2010s than two years ago (Mohanty et al., 2020). Data showing fewer storms does not encourage OWE investments because there is a spike in intensity, making storms even more unpredictable in risk modelling.

4.2.4 Climate change-induced catastrophes and their relationship with offshore wind

The concentration of offshore wind zones in three locations in India may not be an ideal solution for insurance companies since modelling a risk (in this case, cyclone) is focused on two locations in Tamil Nadu, and the distance separating them is only 310 km. This accounts for a higher risk for one energy source. This thesis proposes a diversified energy portfolio that includes offshore wind energy, solar PVs, thermal energy plants, batteries, diesel generators, and converters to neutralize the risk. The complementing nature of the energy sources used can mitigate the risk of variability and catastrophe impacting one of the energy sources.

4.2.5 Opportunities for Insurance Companies in the Indian OWE Sector

Apart from UK, Germany, and China, all other countries perusing OWE face tough challenges from policy, technical, environmental, and economic factors. The OWE in developing countries comes with the risk of losses due to climate change impacts and catastrophes. The review provided evidence of a lesser risk of natural disasters on turbines in European countries. However, China is at risk of natural disasters, particularly typhoons, from May to November. Insurers can play a crucial role in mitigating risk in OWE growth in the Asian market. The offshore wind resources are significant in Asia, with increasing energy demand and a large population making a favourable OWE market.

The cyclones originating from the Indian Ocean moving northwest of the Indian subcontinent is of higher threat to cause landfall and damage to offshore structures and turbines. The insurance companies get an opportunity to provide insurance coverage to three broad categories.

1. Natural Disaster/Catastrophes – Catastrophic risk coverage provide comprehensive coverage for regions exposed to cyclones and tsunamis. The coverage may include coverage against business interruptions caused by the damage and time needed for repair and reconstruction.
2. Start-up Delay- This review provided evidence of the infrastructural, financial, and environmental factors that could relay the OWE deployment. Such uncertainties can be mitigated through insurance coverage. The underdeveloped Indian OWE sector will be exposed to relays from regulatory clearances during the initial construction phase.
3. Contractor's error – The risk of a lack of skilled workforce may cause technical errors. The cost reduction pressure can deviate the contractors and subcontractors into applying low-quality parts. In both cases, there is an elevated risk of catastrophes that may damage the structure and turbine, which otherwise would not have happened.

Indian power companies face multiple risks from the inception to decommission phase of OWE projects. Since Indian energy companies and DISCOMs have limited experience dealing with offshore and open sea risks, mitigation through insurance becomes vital. Generation and transmission companies face similar risks; lighting strikes, theft, piracy, espionage, and collision accidents are some of the risks that can be mitigated through risk transfer in the form of insurance.

However, other insurance coverage schemes should be part of utility sector plans, such as

Liability Insurance (Public entity liability coverage): These cover losses brought by accidents, loss or damage of life or property, and misconduct of duties that causes damages. Since energy companies work with multiple partners and some of their work is subcontracted to local players, the possibility of supervision towards smooth operations is reduced. The presence of multiple stakeholders in the system, with civilians, public and private property involved, makes liability insurance a must-have in the portfolio.

Pollution Liability Coverage: The risk of pollution during the construction and operation of OWE is inevitable. Insurance companies provide risk coverage on pollution to energy firms to cover damage caused to the marine environment. The subsea cable may disrupt the marine floor and habitat. The risk of protest or strikes by environmentalists on energy companies may force the companies to face charges or payment for damages which may affect the company's economic output. Hence the need to cover pollution liability becomes highly necessary.

Equipment breakdown coverage: The OWE operations need the support of specialized heavy cranes, vessels, and equipment. Due to the limited availability and high rent put forward by equipment and machines, energy companies face the risk of business interruption, which in turn leads to losses. Business interruption due to equipment failure can be mitigated by insurance coverage.

Supply Chain Risk Insurance Coverage: The dependence on other partners for supply chain and logistics puts the energy companies at risk of possible loss of reputation and damage. Insurance coverage during the transit of equipment, people, and energy covers the whole operations at a limited control of the energy utility companies.

Start-up delays, contractor errors and third-party liability are operational risks, whilst natural catastrophes in the form of climate change-induced cyclones can cause unpredictable losses to wind turbine structures. In addition, the frequency, intensity, and impact of these catastrophes may challenge insurance companies in providing coverage at the expense of profit. Thus, it is important to diversify the energy mix so that the balance between energy security and risk mitigation is met.

4.3 Results and Discussion of Diversification of Energy Mix

Insurance companies benefit from diversifying the investment, limiting the cover, availing re-insurance, and setting deductibles and co-insurance. These strategies help reduce the losses for each probability of loss occurrence. Diversification in the context of insurance companies is a risk management strategy wherein loss exposure is spread across a variety of products, markets, and areas. This strategy lowers risks for different types of portfolios.

The event of climate change-induced cyclones will be limited to a particular geographical location. Further, storms affect different technologies/properties to varying degrees. Therefore, the losses are inconsistent with other RE technologies for the same event. Thus, the insurance companies can reduce their risks and mitigate losses by diversifying their investments in a combination of RE technologies such as offshore wind turbines, solar panels, battery storage systems, and diesel generators.

A diversified energy mix will reduce the risk of losses because of catastrophes and maintain the energy supply without disruption. For this objective to reach, the insurance companies would prefer a portfolio of energy sources that includes solar PV, wind turbines, Energy Storage Systems (ESS), diesel generators, and grid options if necessary to meet the energy demand. A total of 24 results are selected, including ten from the standalone option (Table 4.2), and 14 from the grid-connected option (Table 4.3). These solutions are further examined and ranked based on economic, technological, and environmental factors. The findings are further broken down based on the best choice for HRES with zero emissions, the best option for independent (off-grid) solutions, and a diversified portfolio with all the systems, assuring energy security. The COE for grid-connected alternatives ranged from \$0.04 (Rs. 3.65) to \$0.12 (Rs. 9.89), while the COE for off-grid options ranged from \$0.28 (Rs (Rs. 45.53).

However, the results are converted to INR for practicality in Tables 4.2 & 4.3. In comparison, in a study by Pal & Mukherjee, (2021) on solar PV and hydrogen fuel cells for an optimal techno-economic solution for rural India, a COE appeared between $ 0.50 and $ 0.68. Similar studies pointed out COE for grid-connected options is lower than off-grid connected options (Nesamalar et al., 2021).

Table 4.2 Grid-connected options

Design	COE (Rs.)	NPC (Rs.)	Operating cost (Rs./yr)	Initial capital (RS.)	System/Ren Frac (%)
PV-Wind/Grid	3.65	136321444.00	9294639.04	17504786.00	62.54
PV/Wind/Grid/Battery/Conv.	3.85	143669095.00	9418194.04	23272960.00	62.54
PV/Grid	4.48	167251544.00	12124946.37	12254070.00	49.76
PV/Grid/Battery/Conv.	4.68	174675058.00	12225940.23	18386508.00	49.86
PV/Wind/DG/Grid	5.10	190430462.00	8050405.59	87519278.00	62.54
PV/Wind/DG/Grid/Battery/Conv.	5.30	197813450.00	8266957.97	92133975.00	62.04
Wind/Grid	5.69	212451175.00	15137349.06	18945100.00	39.48
Wind/Grid/Battery/Conv.	5.89	219928312.00	15396353.29	23111235.00	38.71
Wind/DG/Grid	5.93	221360479.00	10883177.44	82236882.00	49.75
PV/DG/Grid/Battery/Conv.	6.13	228784075.00	10981708.43	88401049.00	49.86
Wind/DG/Grid	7.14	266560275.00	13893117.26	88959600.00	39.48
Wind/DG/Grid/Battery/Conv.	7.35	274177853.00	13840960.58	97243963.00	40.53
DG/Grid	9.69	361574894.00	22807808.20	70014500.00	0.00
Grid/DG/Battery/Conv.	9.89	369301859.00	22938792.98	76067155.00	0.00

Table 4.3 Standalone options

Design	COE (Rs.)	NPC (Rs.)	Operating cost (Rs./yr)	Initial capital (Rs.)	System/Ren Frac (%)
PV/Wind/DG/Battery/Conv.	23.64	882461111.00	39870984.30	372775978.00	45.88
Wind/DG/Battery/Conv.	25.66	957927681.00	58156218.30	214496093.00	24.82
PV/DG/Battery/Conv.	28.13	1050068410.00	53212000.20	369840229.00	27.46
PV/Wind/Battery/Conv.	31.25	1128178234.00	12352172.30	971966000.00	100.00
DG/Battery/Conv.	33.56	1252635185.00	82616780.50	196515793.00	0.00
Wind/DG	38.14	1423785219.00	101197311.00	130144600.00	0.00
PV/Wind/DG	38.40	1433246237.00	101196240.00	139618468.00	0.00
PV/Battery/Conv.	42.99	1547661462.00	13760320.40	1375579000.00	100.00
DG	45.52	1699257681.00	127450360.00	70014500.00	0.00
PV/DG	45.53	1699522912.00	127445912.00	70336303.10	0.00

4.3.1 Optimal Solution Grid-Connected Scenario (henceforth OSG)

The findings reveal that using PV-Wind-Grid is the best option for lowering COE to Rs. 3.65. The NPC for this option amounts to Rs.136.32 M, and the grid contributes 84 % of the total NPC. The contribution of wind turbines (V82) and PV are 8.4% and 7 %, respectively. The total energy production from PV is 50.2%, the wind turbine is 40.7%, and the rest, 9.12%, is by the grid. June to August are the months with high wind penetration in the seasonal profile (Fig. 4.1).

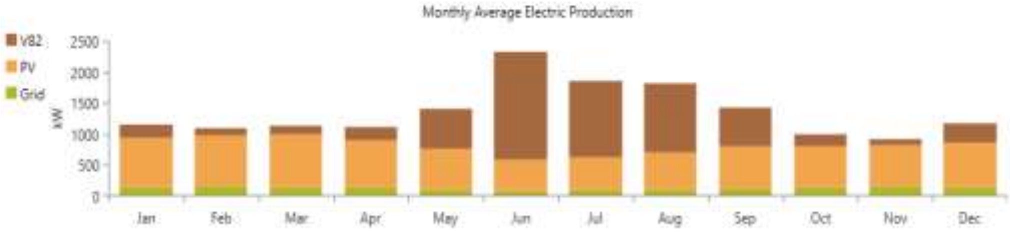

Fig 4.1. Average monthly electric production - optimal solution with grid

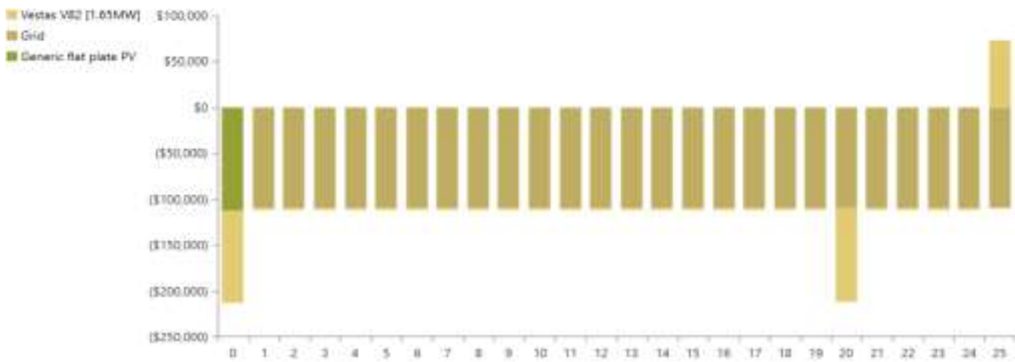

Fig 4.2. Component vise cash flow in the project lifetime (vertical axis denotes the cost in US$, the horizontal axis denotes the years).

4.3.2 Diversified Portfolio with Grid (hence forth DPG)

Diversifying the energy mix will reduce the dependence on one single energy source. To diversify the electricity mix of Wind-PV-DG-Battery-Grid-Converter is used. The COE of this option is Rs. 5.30, and the NPC of Rs. 197.81 M (Table 18). The grid contributes 59% of the NPC, and diesel generators contribute 27.35%. Wind and Solar cover 5.21% and 4.70 %, respectively to NPC (Fig. 4.3). This option's initial capital reported Rs. 92.13 M, and O&M cost Rs 82,66,957.97 per year for 25 years (Fig. 4.3, 4.4 & 4.5).

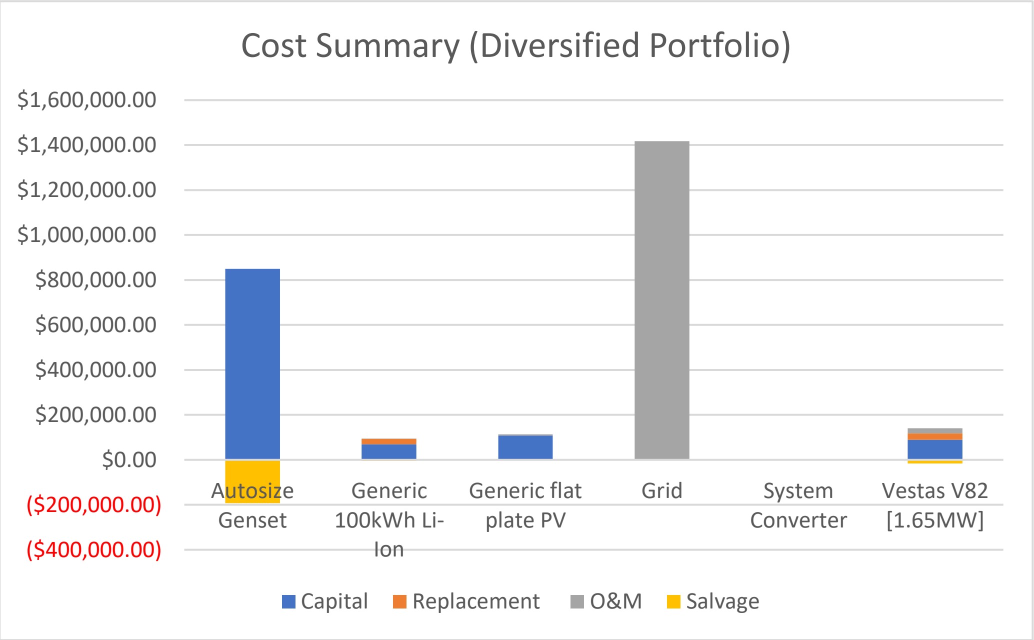

Fig. 4.3 Cost Summary of Diversified Energy Portfolio

This system uses nine wind turbines (V82) and 3,615kW of PV. Solar PV produces 51.41%, and grid purchases meet wind with 38.82% rest of the demand.

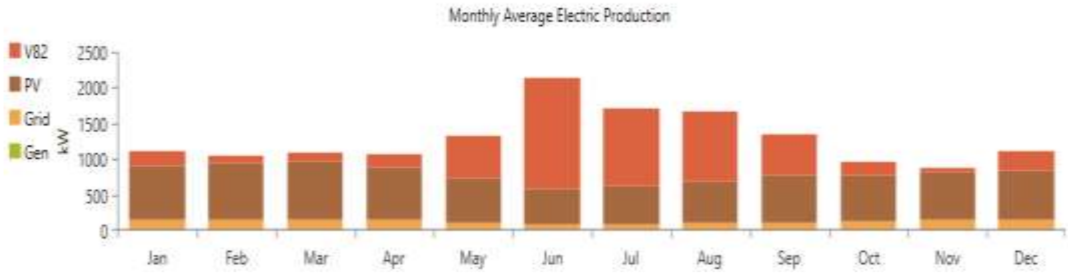

Fig. 4.4 Monthly average electricity generation for Diversified Portfolio

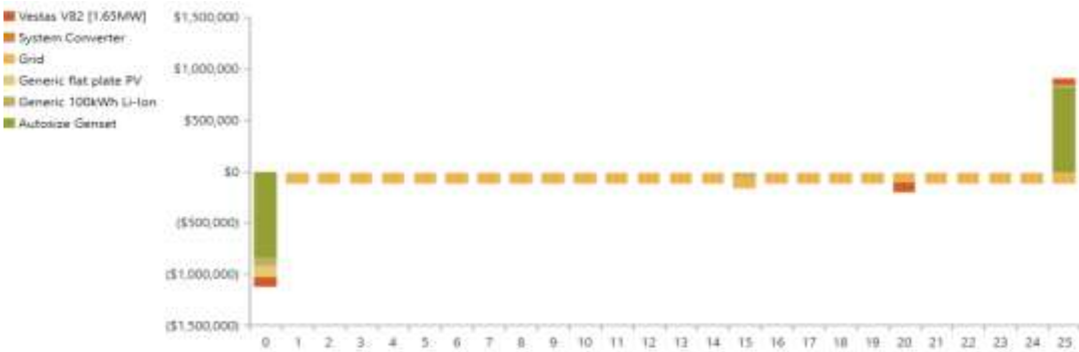

Fig. 4.5 Component vise cash flow in the project lifetime for a diversified portfolio. (Vertical axis denotes the cost in US$, and the horizontal axis represents the years)

4.3.3 Optimal Solution off-grid (henceforth OSOG)

An off-grid or standalone option will allow the energy providers to generate energy largely from RE sources. The excess energy generated through renewables is stored in batteries. Diesel generators provide the last resort to meet the energy security when the batteries run out of charge. The combination of PV-Wind-DG- Converter-Battery is an optimal solution among the off-grid options. The COE is Rs. 23.64 ($ 0.2870), which is 8.5 % lower than the next best scenario. The NPC is Rs. 882. 46 M ($10.7 M), consumed primarily by generators to cover the intermittency of solar and wind energy. Diesel generators consume 44.6 % of the total cost, PV panels take 18.2 %, and lithium-ion batteries burn up 29.3 %. Convertor and OWE make up 3.9 % and 3.7 % of cost (Fig. 4.6 & 4.7).

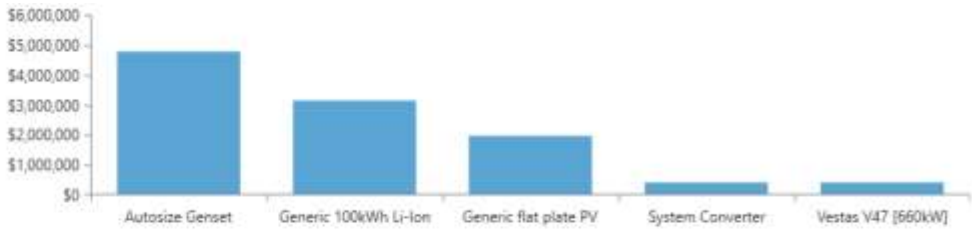

Fig 4.6. optimal solution off-grid - cost outline

The investment cost encountered in this case is Rs. 37,27,75,978.00 ($ 4,525,627.78). The fuel cost largely covers the operations and maintenance cost (Fig. 4.7). The seasonal change in the wind resources, from June to September, is considerable in producing wind energy in the system. A dip in wind energy generation can be observed in the rest of the months (Fig. 4.8). Diesel generators add to the energy mix, complementing the intermittent renewables. Diesel generators add to the harmful greenhouse gas emissions. However, the CO2 emission in this scenario is 28.8 % lower than the next best option. This option utilizes 29 Vestas V47, seven 100 kWh lithium-ion batteries, 626 kW of Solar

PV (Generic flat-plate PV), and a diesel generator (Autosize Genset) of 1700 kW. The Vestas V47 turbine produces 660 kW, the highest load with 60.40 % of the total; the diesel generator produces 24.20 %, and PV panels produce 15.40 %. Thus, in terms of optimal COE and NPC, the combination of PV-Wind-Diesel generator-Battery-Converter is the best solution for off-grid scenarios. In a similar study by Elmaadawy et al., (2020), the same configuration PV-Wind-generator-Battery-Converter is considered as the most profitable option having a COE of Rs. 13.19/kWh and NPC of Rs. 257.24 M.

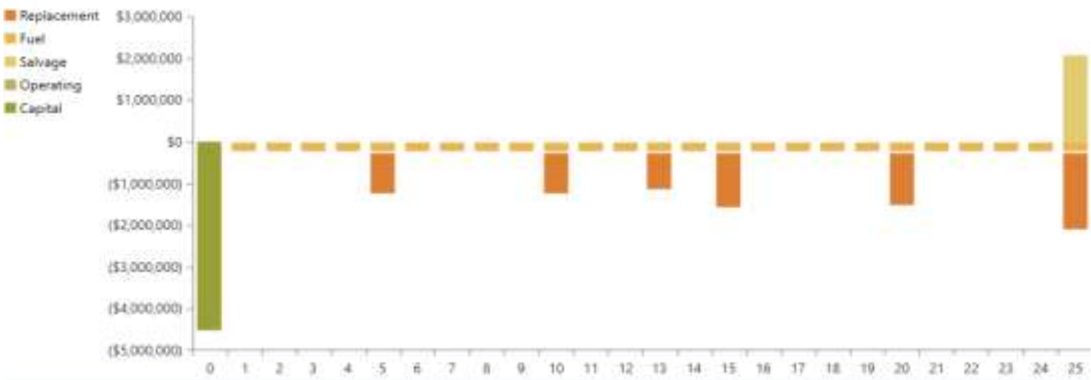

Fig. 4.7 Component vise cash flow in the project lifetime for optimal off-grid option. (Vertical axis denotes the cost in US$, the horizontal axis denotes the years)

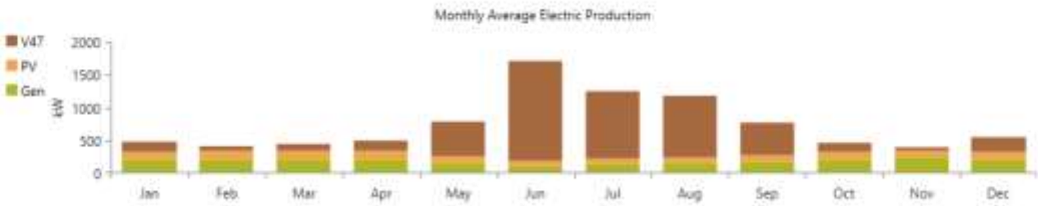

Fig. 4.8 Monthly average electric production for optimal off-grid

4.3.4 Hybrid Renewable Energy System (henceforth HRES)

The grid should be redesigned for a cleaner planet to facilitate more renewable intake. A combination of PV-Wind- Converter-Battery is used to meet the carbon-free demand. HRES is ranked fourth amongst off-grid scenarios. The high COE and NPC push this option economically unattractive, the high initial capital for renewables explains the cost. HRES used 26 Vestas V47 make and 1,980 kW of PV panels, 72 lithium-ion batteries of 100 kWh each. This option has a COE of (Rs. 31.25) $0.379 and NPC of Rs. 1128.17 M ($13.7M). The cost of operation of HRES is (Rs. 1,23,52,172.30) $149,959. Lithium-ion batteries formed 46.8 % of total cost followed by solar PV panels with 45.2 % (Fig. 4.9). Vestas V47 has the smallest amount cost contribution with 2.6%, while it has an energy production of 52.7% in the system, June to September are wind-dominated months. Solar PV forms 47.30 % of the production. The supply of electricity is balanced with more lithium-ion batteries addressing the intermittency of wind and solar. HRES generates low operating costs through its 25 years of lifetime, and nearly all costs incurred are in the early stage of construction and installation (Fig. 4.10 & Fig. 4.11).

4.3.5 Rankings Based on Economic Factors

Here, we evaluate and rank the four alternatives based on their NPC and COE. OSG has the lowest COE with Rs. 3.65 ($0.0443), followed by DPG of Rs. 5.30 ($0.064), the OSOG in third place with a COE of Rs. 23.64 ($0.287), and the HRES with 100% renewable energy generation in fourth place with a COE of

Rs. 31.25 ($0.379). The NPC also had comparable rankings to COE, with OSG taking the top spot with Rs. 13,63,21,444.00 ($1.65 M), DPG coming in second with Rs. 197813450.00 ($2.40 M), OSOG and HRES coming in third and fourth, respectively, with Rs. 88,24,61,111.00 ($10.71 M) and Rs. 1,12,81,78,234.00 ($13.69 M).

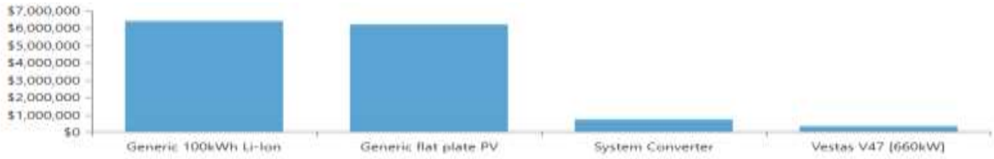

Fig. 4.9. Cost Summary of HRES

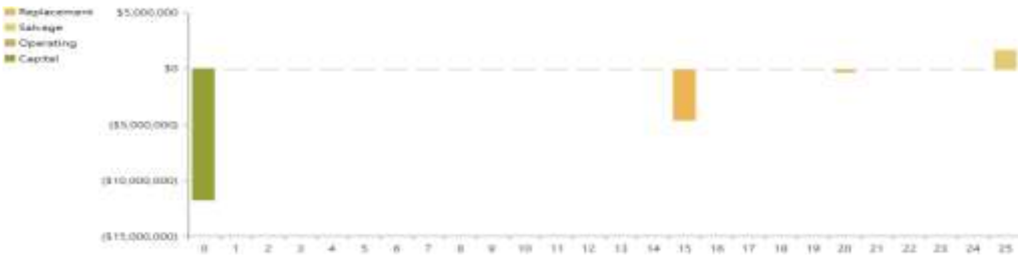

Fig 4.10. Component vise cash flow in the project lifetime for HRES (Vertical axis denotes the cost in US$, the horizontal axis denotes the years)

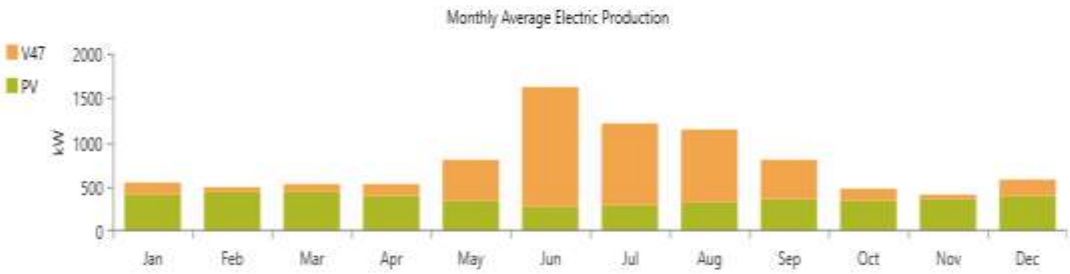

Fig. 4.11. Monthly average electric production for HRES

4.3.5.1 Renewable Penetration

This subsection seeks to identify the scenario with the highest penetration of RE among the four possibilities. The HRES uses 100% RE, compared to 90.9 % and 90.2 %, respectively, in the DPG and OSG scenarios. The higher DG share is for OSOG options resulting in a 75.8% penetration of RE. Total renewable production by generation and total non-renewable production split by load is much lower for the OSOG than for the alternatives. It is a symbol of OSOG's incapability to produce clean energy. In other words, Willingdon Island's use of off-grid hybrid energy incorporating Diesel Generators is not sustainable (Table 4.4).

Compared to OSG and DPG choices, the overall renewable energy generation by load was for OSOG at 54.42% and 51.28% lower. OSOG has the lowest total renewable production per generation, but DPG and OSG are 90.2% and 90.9%, respectively. Due to low RP and high COE, "Diesel-wind" mode is not advised when the battery is being used.

4.3.5.2 Capacity-Based Metrics

Table 4.5 shows the capacity-based metrics for all four scenarios. For the system to serve as a sustainable model, the OSOG must create the renewable energy needed. The combined usage of OSG and HRES results in a nominal RE capacity of 92.10% and a usable RE capacity of 40.60%. The DPG scenario has a lower nominal RE capacity and usable RE capacity, which reduces its viability for OSG and HRES, which RE dominates.

Table 4.4 Renewable energy penetration for optimized options

Energy-Based Metrics	Diversified Portfolio with Grid (DPG)	Optimal Solution with Grid (OSG)	Optimal Solution Off-grid (OSOG)	Hybrid Renewable Energy Solution (HRES)
Total renewable production divided by load	349	373	170	238
Total renewable production divided by generation	90.2	90.9	75.8	100
One minus total non-renewable production divided by the load	100	100	45.9	100

Table 4.5 Capacity Based Metric of optimized options Solar PV output

Capacity Based Metrics	Diversified Portfolio with Grid (DPG)	Optimal Solution with Grid (OSG)	Optimal Solution Off-grid (OSOG)	Hybrid Renewable Energy Solution (HRES)
Nominal renewable capacity divided by total nominal capacity	91.6	100	92.1	100
Usable renewable capacity divided by total capacity	72.8	100	40.6	100

The option OSOG has the lowest solar penetration of 34.4%, OSG 206%, HRES 109%, and DPG 199% (Table 4.6). Results by Pal & Mukherjee, (2021) revealed that North-East Indian states have a capacity factor of 38.3% for PV penetration. Its rated capacity of 626 kW has reduced the optimal off-grid option's ability to generate solar energy; in contrast, OSG, DPG, and HRES have capacities of 3750 kW, 3615 kW, and 1980 kW, respectively.

Table 4.6 Techno-economic simulated results for Solar Flat PV in all four optimized options

Quantity	**Units**	**DPG**	**OSG**	**OSOG**	**HRES**
Minimum Output	kW	0	0	0	0
Maximum Output	kW	3,539	3,672	613	1939
PV Penetration	%	199	206	34.4	109
Hours of Operation	hrs/yr	4,462	4,462	4,462	4462
Levelized Cost	$/kWh	0.00152	0.00152	0.152	0.152
Total Rated Capacity	kW	3,615	3,750	626	1980
Mean Output	kW	663	688	115	363
Capacity Factor	%	18.3	18.3	18.3	18.3
Total Production	kWh/yr	5,806,152	6,024,350	1,005,023	3,180,292

All four solutions under consideration for the research result in considerable modifications to wind production. The OSOG option, which has the highest display, is followed by the OSG option, which has a 7.03% lower output. In contrast, the OSG option's wind penetration was more significant, and OSOG, ranked third among the four alternatives, had a wind penetration of 135%. The primary reason the COE for OSOG is greater than the OSG option is that V82 is used in off-grid settings (Table 4.7). It shows that even if the production is somewhat excellent for OSOG, the OSOG is less desirable for investment in Willingdon Island due to the increased COE. It can also be supported by the fact that OSOG's overall production is 19.08% lower than OSG's overall production. Therefore, Willingdon Island has a lower capacity factor for wind energy than the study by Cozzolino et al., (2016) on four man-made islands that connect Italy and Tunisia, with 3.3% for DPG and OSG, 2.3% OSG and HRES, and 10.2% for wind turbines, respectively.

Table 4.7. Techno-economic simulated results for Wind Turbines in all four optimized options

Quantity	Units	DPG	OSG	OSOG	HRES
Minimum Output	kW	0	0	0	0
Maximum Output	kW	14,725	16,362	17,599	15,778
Wind Penetration	%	150	167	135	121
Hours of Operation	hrs/yr	4,129	4,129	3,878	3878
Levelized Cost	$/kWh	0.00223	0.00223	0.00801	0.00801
Total Rated Capacity	kW	14,850	16,500	19,140	17,160
Mean Output	kW	501	557	451	404
Capacity Factor	%	3.37	3.37	2.35	2.35
Total Production	kWh/yr	4,389,715	4,877,461	3,946,790	3,538,501

4.3.5.3 Technological Rankings

Here, we contrast and order the four choices according to their technical strength. The largest combined output from wind turbines and solar PV is for OSG, which ranks top. Wind and solar together account for 90.9% of the load in this option, making it appealing for adoption on Willingdon Island. With a somewhat lower total output from solar and wind providing 90.2% of total production, DPG holds the second position among the technical elements. Despite producing less overall power from wind turbines than OSOG, HRES holds down the third spot because of the latter's substantially greater solar energy output. For HRES and OSOG, respectively, all the energy produced by renewable sources is at 100% and 75.8%.

4.3.5.4 Emissions

The NPC and COE will decrease if the thermal to-electric load is increased but at the price of higher CO_2 emissions and lower renewable energy percentages (Das & Hasan, 2021). Maintaining an equilibrium between cost and emission is crucial. Due to the high percentage of Diesel Generators (DG) used in OSOG, carbon emissions are 61% and 62.5% higher than OSG and DPG, respectively. While all other choices stayed at zero, OSOG had significant emissions of additional dangerous gases. Compared to OSG and DPG, Nitrogen Dioxide emissions in OSOG increased by 22.09% and 22.38%, respectively (Table 4.8).

According to Das & Hasan, (2021), a hybridized strategy for satisfying energy demand results in a 40% decrease in CO_2 emissions from thermal loads.

According to research by Elmaadawy et al., (2020), the penetration of renewable energy decreased carbon emissions to 81.5% from 73.74%. However, according to Jahangir and Cheraghi (2020), CO2 emissions from HRES in a remote community close to the Indo-Pak border are insignificant compared to the grid. Therefore, as preventing climate change is of the utmost importance, HRES will be ranked as the choice with the lowest emission, and OSOG will be ranked as the option with the highest emission. With somewhat greater emissions than the former, the OSG and DPG are both placed third.

Table 4.8 Emission results

Gases	**Diversified portfolio with Grid (DPG)**	**Optimal Solution with Grid (OSG)**	**Optimal Solution Off-grid (OSOG)**	**Hybrid Renewable Energy Solution (HRES)**
Carbon Dioxide	700,524	691,363	691,363	0
Carbon Monoxide	0	0	0	0
Unburned Hydrocarbons	0	0	0	0
Particulate Matter	0	0	0	0
$S0_2$	3,037	2,997	2,997	0
N_2o	1,485	1,466	1,466	0

4.5 Validity and Reliability

4.5.1 Content Validity

The barriers identified through extant literature are further verified through exploratory interviews and adapted for the Indian Context. The exploratory discussions were with wind energy experts, consultants, developers, regulators, professionals dealing with the wind power sector, and academicians experienced in the wind sector and their challenges. Fuzzy- AHP is validated through the triangulation method and peer briefing. The results from Fuzzy-AHP and HOMER methodology are further validated through sensitivity analysis (Section 4.5)

4.4.2 Internal Validity

Hybrid optimization of multiple energy resources (HOMER) is designed to navigate complexities in suggesting cost-effective and reliable HRES. HOMER is the market leader in optimization and feasibility study and has over 250,000 registered users across 193 countries (G. Zhang et al., 2020). The literature which compares HOMER with similar platforms like iHOGA, pvPlanner, PV-F-Chart, RETscreen, and solar pro points out that HOMER's flexibility, user-friendliness, and generic control strategies stand out from the rest (Mokheimer et al., 2015). The software also has the advantage of using 100% population, which is not the case of iHOGA (al Garni et al., 2018). These findings prove that most of the HOMER simulations are valid, and the data used are based on the current market situations that undergo constant updating (Ekren et al., 2021).

4.4.3 External Validity

Previous studies that adopted the use of various MCDM tools to find the barriers to adopting renewable energy found similar results to this study, proving the generalizability of the study. For example, Asante et al., (2022) used Fuzzy TOPSIS to identify and prioritize the barriers of RE adoption in Ghana, and the results suggest substantial similarity to ours. Similar to this research, technical and financial barriers occupy the first two ranks. Another study validating this study's generalizability is by Sadat et. al., (2021). This study used fuzzy TOPSIS to identify the barriers to solar PV in Iran, and economic and financial barriers appeared to be the most noticeable.

The HOMER simulations' results are generalizable to other regions, locations, or countries. HOMER uses wind speed data obtained from monthly average wind speeds and solar radiation data from time series data provided by US National Renewable Energy Laboratory. The technological specifications are based on the global average, presenting a relatable comparison to regions with similar topography and conditions. Among the previous studies similar to this research, a survey by Ramesh & Saini (2020) on a group of unconnected villages in Karnataka produced a COE and NPC of Rs 8.74/kWh ($0.106/kWh) and Rs. 3,84,03,943 ($4,65,790). Using COE and NPC data at Rs. 23.75/kWh ($ 0.288/kWh) and Rs. 1,88,27,487.91 ($228,353), respectively, Krishan and Suhag (2019) investigated the Yamunanagar district in Haryana. Pujari & Rudramoorthy, (2021) analyzed Kanakadri palle village, Andhra Pradesh, India, and the optimal COE is at Rs. 17.8 ($0.217), and NPC of Rs. 2,81,38,211 ($ 341 280), Hossain et al., (2017) studied the tourist sectors in the South China Sea, Malaysia, and the NPC was at Rs. 1,414 M ($17.15 M) while the COE is Rs. 23/kWh ($ 0.279/kWh). The study by Rezk et al., (2019) on Minya city, Egypt, has a similar COE to this study at Rs. 5.11/kWh ($ 0.062), and NPC was at Rs. 9,53,51,50 ($115,649). These studies show the similarity of results which can be generalized to other regions and locations.

4.5.4 Reliability

4.5.4.1 Sensitivity analysis on results from Fuzzy AHP

This study uses sensitivity analysis to confirm the robustness of the approach and the suggested framework. According to Table 4.9, the technical barrier has the most excellent rating and weight among all the barrier categories. Any modification to the technical barrier may also affect how other obstacles are ranked. Technical obstacles' impacts on other barrier categories and the barriers stated in those categories are assessed using sensitivity analysis. As shown in Table 4.10, the weight of the technical barrier varied from 85% to 115%. The impact was also seen in other barrier categories. A lack of maintenance services is one of the most sensitive barriers among the 46 barriers. As the weight of the technical barriers increased to 115%, the rank of lack of maintenance services increased to three and technical barriers decreased to 85%, which saw a drop in ranking to eight (Fig.4.12).

Regulatory and political barriers and social barriers maintained the last and second last barrier ranks, respectively, owing to the changes made to technical barriers. Of all seven barriers, technical barriers appeared to be the most impactful, and an active policy intervention can eliminate this by the government. The policies should emphasize building active collaboration with Dutch, English, German, or Chinese technical experts in facilitating OWE deployment. The technical barriers cannot be solved through self-reliance, and India's expertise in the onshore wind may not be the solution for offshore wind. Moreover, technical barriers revolve around grid connection, O&M facilities, and offshore wind zones, which are subsidiary producers' industries. Policies should focus on building facilities for such industries and encourage investments following practices from the West and China.

The insurance industry may facilitate OWE's growth by emphasizing the need to deploy better quality technologies and meet international standards. This may reduce the risks arising from climate change catastrophes and other operational risks that may cause energy supply interruptions. The results from sensitivity analysis suggest the need for strengthening maintenance activities. Most wind turbines have an average lifespan of 25 years and active maintenance will ensure lifetime completion with limited energy supply interruptions. The developers, operators, policymakers, and insurance sector need to extend their efforts to provide maintenance activities of global standard.

Table 4.9 Technical barriers' effects on other barriers

Groupings	Weights									
FIB	0.195	0.235	0.209	0.183	0.157	0.130	0.104	0.078	0.052	0.026
R&PB	0.053	0.064	0.057	0.050	0.043	0.036	0.029	0.021	0.014	0.007
SOB	0.186	0.225	0.200	0.175	0.150	0.125	0.100	0.075	0.050	0.025
THB	0.254	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900
SUCB	0.076	0.092	0.082	0.071	0.061	0.051	0.041	0.031	0.020	0.010
INB	0.128	0.155	0.137	0.120	0.103	0.086	0.069	0.052	0.034	0.017
GEB	0.107	0.130	0.115	0.101	0.086	0.072	0.058	0.043	0.029	0.014
Overall	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

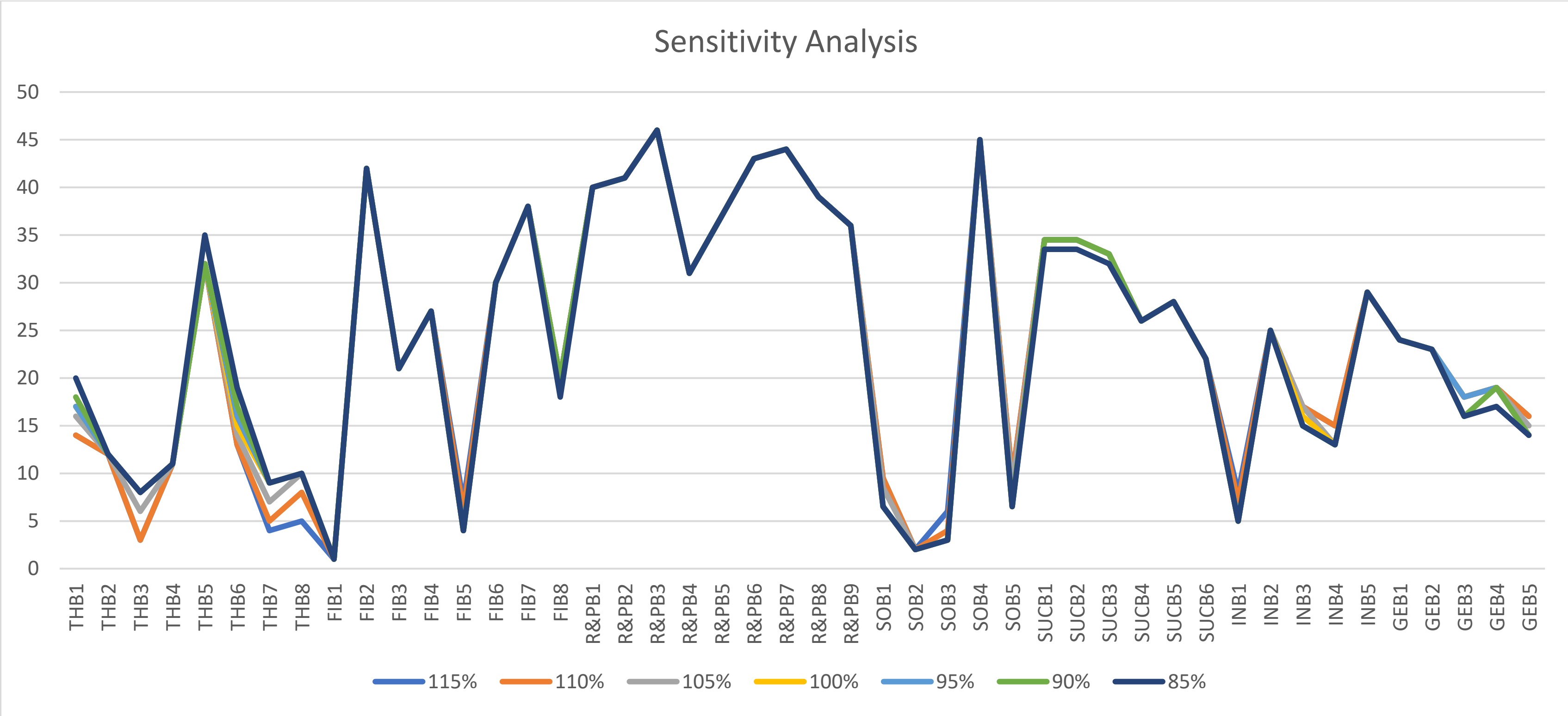

Fig. 4.12 Sensitivity analysis on the barriers of OWE

Table 4.10 Using sensitivity analysis to rank barriers when the value of a technical barrier changes

	115%	**110%**	**105%**	**100%**	**95%**	**90%**	**85%**
THB1	14	14	16	17	17	18	20
THB2	12	12	12	12	12	12	12
THB3	3	3	6	8	8	8	8
THB4	11	11	11	11	11	11	11
THB5	32	32	32	32	32	32	35
THB6	13	13	14	15	16	17	19
THB7	4	5	7	9	9	9	9
THB8	5	8	10	10	10	10	10
FIB1	1	1	1	1	1	1	1
FIB2	42	42	42	42	42	42	42
FIB3	21	21	21	21	21	21	21
FIB4	27	27	27	27	27	27	27
FIB5	7	6	4	4	4	4	4
FIB6	30	30	30	30	30	30	30
FIB7	38	38	38	38	38	38	38
FIB8	20	20	20	20	20	20	18
R&PB1	40	40	40	40	40	40	40
R&PB2	41	41	41	41	41	41	41
R&PB3	46	46	46	46	46	46	46
R&PB4	31	31	31	31	31	31	31
R&PB5	37	37	37	37	37	37	37
R&PB6	43	43	43	43	43	43	43
R&PB7	44	44	44	44	44	44	44
R&PB8	39	39	39	39	39	39	39

R&PB9	36	36	36	36	36	36	36
SOB1	10	10	9	7	7	7	7
SOB2	2	2	2	2	2	2	2
SOB3	6	4	3	3	3	3	3
SOB4	45	45	45	45	45	45	45
SOB5	10	10	9	7	7	7	7
SUCB1	35	35	35	35	35	35	34
SUCB2	35	35	35	35	35	35	34
SUCB3	33	33	33	33	33	33	32
SUCB4	26	26	26	26	26	26	26
SUCB5	28	28	28	28	28	28	28
SUCB6	22	22	22	22	22	22	22
INB1	8	7	5	5	5	5	5
INB2	25	25	25	25	25	25	25
INB3	17	17	17	16	15	15	15
INB4	15	15	13	13	13	13	13
INB5	29	29	29	29	29	29	29
GEB1	24	24	24	24	24	24	24
GEB2	23	23	23	23	23	23	23
GEB3	18	18	18	18	18	16	16
GEB4	19	19	19	19	19	19	17
GEB5	16	16	15	14	14	14	14

4.5.2 Sensitivity analysis on results from HOMER simulations

A sensitivity analysis is performed for fuel prices within $0.50 and $2.00 and wind speed variations between 3 m/s and 8 m/s. For the PV-Wind-Battery-Converter 100% RE solution, the wind speed should not be more than 6.84 m/s, and the gasoline price shouldn't be lower than $0.84. Beyond 6.84 m/s, the gasoline expense should increase as the wind speed lowers, and after $1.45, even 3m/s wind speed will be the best option. Each alternative that uses DG should be less expensive than $1.15 in terms of fuel costs. The DG, Wind, and Battery are successful (Fig. 4.13), but from an environmental standpoint, gasoline prices ought to be higher to promote energy from RE sources.

Fossil fuel consumption has to be lowered to reach climate goals and meet energy security. However, diesel prices in the future will likely increase due to government policies, geopolitical uncertainties, and emissions reduction measures. Moreover, the advancement of technologies may enable the cost of RE technologies to be lower in the future, ensuring the deployment of more wind turbines and solar panels. The results show diesel generators are cost-saving only below $1.45; breaching this threshold may be highly unlikely. Thus, demanding wind and solar energy to contribute more to the energy mix, lowering the emissions.

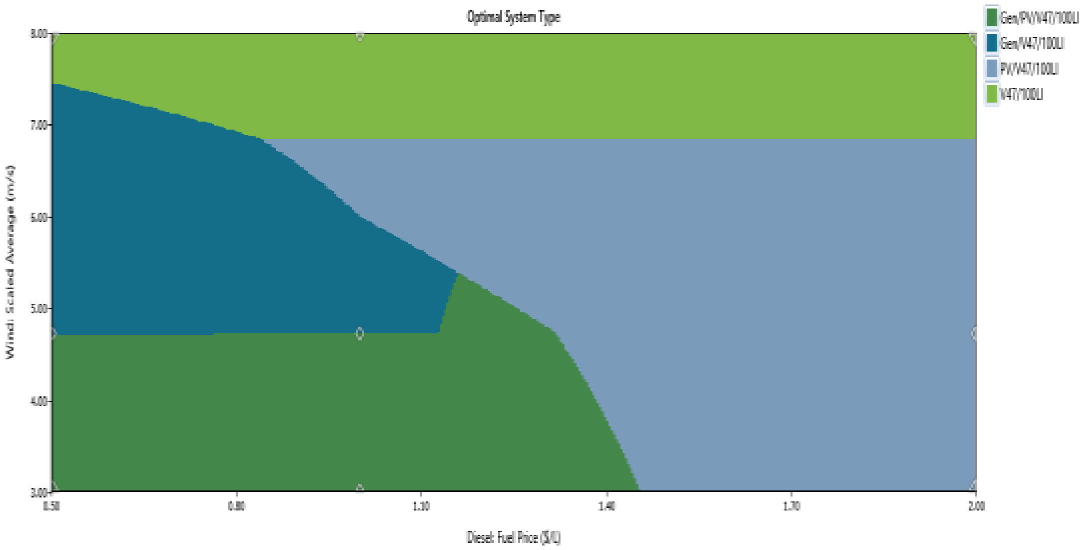

Fig. 4. 13. Sensitivity result for stand-alone options

4.6 The Scope for Energy Zones

Developing a hybrid renewable energy system that may generate electricity for the needs of a specific community or a location is not new. This system is more suitable for a place distant from a populous town/city or an island. However, creating an energy zone that may involve a combination of renewable energy sources connected to the grid may solve rising energy costs and dependence on fossil fuel imports. Energy zones can boost interconnection with landlocked states and depend heavily on non-renewables. The lengthy approval procedure under regulatory barriers can be relaxed since the effort for a combination of RE sources is lower than a single technology.

There is a need to alter the regulatory framework to encourage investments in energy zones since the availability of resources, reliability, and security are significant issues to be managed. The financial incentives to boost the investor's participation are vital in building an energy zone. Solar energy is cheaper than any other energy source currently. Mixing solar energy with costly OWE and storage systems may bring the incentives down compared to a standalone OWE farm. The National Wind-Solar Hybrid Policy in 2018 aimed to provide a framework for the promotion of large grid-connected solar-wind systems for optimal use of land, and transmission resources, achieving grid stability and reducing the variability of the RE sources. However, this policy has no attention to smaller HRES and offshore wind as an option to build on diversity.

The HRES system has the potential to be competitive with 30-40% of existing coal power plants in India. Even at today's rates of roughly INR 6-7/kWh, an ideal mix of solar, wind, and storage can provide consistent round-the-clock electricity. HRES can become a feasible alternative for fulfilling future baseload power demand with zero carbon emissions and no future cost inflation. The decline in cost encourages more HRES to be deployed in India's solar and wind-rich locations.

4.7 Contribution to the theory

The Modern Portfolio Theory considers risk and returns to suggest a diversified portfolio. Moreover, the calculation is based on historical data. But a variable that has not appeared in the historical data is not considered in MPT. This fall is a significant limitation. This thesis projects the rising threat of windstorms because of changes in global temperature to cause business interruptions and cause energy security. Storm intensity, frequency, and impact increase as the global temperature increases. They cause damage to energy technologies and, subsequently, the energy supply. This thesis contributes to the theory by identifying a futuristic potential risk that must be added to the variable's segments in calculating risk factors. The mere dependence on historical data may divert the optimal results. Certain risks which can be futuristic can cause a threat to the portfolio and need to be considered for effective risk mitigation.

There are different viewpoints on handling the economic risk associated with renewable energy sources (RES). The RES technologies are known to be risk-free, according to prior studies. Since they don't have any fuel expenses (apart from biomass), which are prone to significant price volatility, they would incorporate them into the behaviour of risk-free assets in modern portfolio theory. RES technologies often employ freely accessible natural resources and have no availability costs (wind, sea currents, precipitation, or solar radiation). Additionally, because they are not sources of emissions, they do not suffer expenses associated with CO2 emissions, except for biomass technologies, which only have investment and O&M costs.

For this reason, it is believed that there is no link between fuel prices and fuel CO2 emissions. This supports the beneficial function of RES in the portfolio by lowering the risk associated with fossil fuel technologies. Our research examines an alternative school of thinking, which holds that the relationship between renewables serves as the best countermeasure to the problems associated with variability. There is a relationship between regional disaster risks, their impact and cost, and renewable energy sources (installation and re-installation due to catastrophes).

In this case of energy diversification, the cost and risk form the primary reason to diversify the investments. Systematic risks include catastrophes, changes in weather patterns, market and policy changes, foreign investment policies, competition with clean coal and shale gas production, geopolitical uncertainty, and innovation. Unsystematic risks include operational errors, supply chain and installation risks, environmental impacts, and technological flaws. According to MPT, unsystematic risks are diversifiable risks. However, results from our study claim systematic risks can also be mitigated by a diversified energy portfolio since the impact and damage caused by each catastrophic event on the different energy sources are different.

4.8 Contribution to practice

This thesis comprehensively explains the OWE sector, from its planning to potential policy interventions and insurance strategies for its growth. The first contribution is to identify, categorize, and prioritize barriers that hinder the deployment of OWE in Indian waters. This exercise provided an understanding of financial and technical barriers that formed the most significant barriers to consider in policy making. The second contribution compares the NOWE policy, 2015 with policies and schemes adopted by the leaders in the global OWE sector; China, Germany, and the UK. The findings from this examination lead to the solution to diversify the energy portfolio. The third contribution is to select a diversified portfolio that includes wind-solar-energy storage systems and a grid. The simulation results gave 24 options, categorized into grid-connected and standalone options. Out of 24 options, the study is conducted on four solutions based on their techno-economic and environmental attributes. These four options are an optimal grid-connected option, a diversified energy solution, an optimal off-grid solution, and an HRES using 100% RE. The simulation results will help the investors select a system most suited for a particular location/region.

The contribution of this thesis

- The variability of RE can be diminished by adopting a mixed RE approach. The simulations help the investor(s) identify and select an optimal solution based on its technological, economic, and environmental characteristics.
- A mixed approach may help the investors get clearance from various government bodies since regulatory roadblocks can be removed with the support of the NOWE policy and the national wind-solar hybrid policy, 2018.
- Recommending a dedicated infrastructure facility for consistent service and maintenance can solve the issue of fewer maintenance activities. Lack of maintenance activities appeared at global rank 11 in the

examination of barriers, and it is one of the main issues to be delt with during the operations stage.

- A hybrid energy mix can improve energy output, and the availability of energy storage systems can reduce curtailment risks.
- A diversified energy mix has the advantage of cost differences among the sources, solar panels are cheaper than wind turbines, and their installation process may be higher on the cost ladder. This study's initial capital is ranked at the top of global rankings. The high initial capital can be managed with more options on credit access with a mix of energy sources.
- An investor in a diversified energy portfolio can assign a dedicated team of skilled workforce.
- A diversified portfolio will benefit the insurance company by reducing the risk. The negative correlation between the risk of a wind catastrophe and solar provides an optimal investment scenario.

CHAPTER 5

CONCLUSION, POLICY SUGGESTIONS, AND FUTURE SCOPE OF STUDY

Global warming has a dangerous effect on weather events. The climate depends on the earth's temperature; a few degrees increase can intensify weather-related disasters to raise their frequency, intensity, and impact. Tackling climate change and keeping the global temperature within 1.5°C above the pre-industrial revolution requires a massive energy transition from fossil fuel to renewable energy deployment. However, climate change-induced catastrophes are causing damage and interruptions to renewable energy (RE) technologies and which in turn causes energy insecurity. Countries may go back to fossil fuel consumption to meet the energy demand for every unit of energy RE lost. This thesis is the first attempt to comprehensively study the impact of climate change-induced catastrophes on renewable energy technology, i.e., offshore wind energy, from an insurance perspective. Global offshore wind energy (OWE) generation is only 30 GW, led by China, the United Kingdom, and Germany. India is yet to have energy generation from OWE even after the notification of the National Offshore Wind Energy Policy in 2015, signifying the existence of substantial barriers in the sector. Understanding these barriers will help insurance companies set strategies for limits, premiums, deductibles, co-insurance, and re-insurance decisions. China, the UK, and Germany have excelled in OWE deployment; lessons learned from these countries add to the knowledge of a booming OWE sector. However, the weather conditions are not the same in all three countries. Chinese OWE sector is exposed to climate change-induced typhoons. UK and Germany have lesser exposure while the risk of winter storms looms. Cyclones originating from Indian Ocean Region may cause damage to OWE structures and foundations, leading to energy supply interruptions. Insurance can mitigate these risks; however, insurance companies need to reduce their losses through diversification. A single weather event impacts RE technologies in varying differences. Wind turbines and solar panels complement each other in terms of cost, energy generation pattern, and risk of catastrophes. Thus, having wind and solar in a portfolio will reduce the risk of one single hazard (reducing the probable losses from an insurance perspective) and keeps the energy supply secure. This thesis attempts to suggest an optimal energy mix for creating energy security and mitigating insurance losses with the combination of OWE, solar panels, Li-ion batteries, grid, and diesel generators by assessing its techno-economic and environmental aspects.

India has set a lofty goal for RE: 450 gigawatts of installed capacity by 2030. Despite having a long coastline and legislation in place to support it, it has failed to install OWE. The primary goal of this thesis is to evaluate, classify, and rank the obstacles found in the existing literature. Forty-six barriers are found in the extant literature and grouped into seven general groups. Expert interviews were performed to verify the accuracy of the noted impediments.

Additionally, it attempted to make an effort to organize the dispersed literature. These impediments are categorized and given priority using a multi-criteria decision-making process. These barriers were systematically categorized and prioritized using fuzzy AHP, going from more to least affecting.

This thesis offered insights into seven kinds of obstacles that India's OWE expansion has been facing. These include Regulatory & Political hurdles, Financial & Economic, Social & Institutional, Geographical & Supply Chain, and Technical & Financial Barriers. Data gathered from experts through a survey was used to account for data uncertainties and determine the weighting of the criterion. Fuzzy triangular numbers were then used to calculate the criteria value. The most critical impediments to OWE growth in India are technical and financial, with supply chain, regulatory, and political constraints emerging as the least important.

The top four hurdles worldwide are the upfront cost need, lack of societal acceptability & visual & noise issues, and an underdeveloped offshore engineering industry. Governmental permit requirements are a major hurdle globally (regulatory & political barriers). Lack of servicing and maintenance facilities in the technological category, initial capital in the financial category, lack of social acceptability in the social category, and lack of skilled personnel in the institutional category are the top hurdles in the individual relative ranking.

High individual barriers include natural disasters in the category of geographic barriers, misalignment between manufacturing equipment and facilities at the yards, serial production of large monopiles & jacket foundations in the category of supply chains, and entry barriers in the category of regulatory & political barriers. These findings contribute to the creation of a sound policy mix by highlighting the need for financial incentives to lower initial capital, the creation of a comprehensive guideline for the planning and delivery of grid infrastructure, the allocation of resources to the development of a skilled OWE workforce, and the inclusion of social considerations in the National Offshore Wind Energy Policy.

From an insurer's perspective, natural disasters have highlighted offshore wind generation risks. The risk of cyclones in the Indian Ocean Region can cause losses, and proper modelling of these risks based on their risk exposure needs to be carried out. Most leading insurance companies employ catastrophic modelling tools to mitigate these risks. This study's dominance of technical barriers is a worrying sign for insurance companies since the chances of damage to wind turbines, and structures are higher for low-quality turbines. The lack of a skilled workforce again adds more risk to the OWE insurance. The high initial capital will increase the premium. Deductibles and limits should be set optimally to minimize the risk when exposed to peril.

By highlighting the significance of technological and financial constraints and the need to decrease their existence, this study adds to the body of knowledge in the field. Investors must update technology with appropriate support and upkeep, and they should gain from subsidies and other cost-saving measures. OWE progress is slow globally; identifying and assessing OWE hurdles in India will help other nations identify their weaknesses and implement the necessary legislative adjustments. In order to provide a clean and sustainable earth, the RE industry must generally overcome obstacles. Since India experiences strong barriers to OWE deployment, it is necessary to study how other countries excelled in OWE deployment and identify their successful strategies. These strategies can limit the barriers and reduce the risk of climate change catastrophic events and establish mitigation and adaptation measures. When compared with schemes adopted by leading OWE-generating countries, the insurance industry will benefit from analyzing the policy instruments and efforts or lack thereof in the National Offshore Wind Energy Policy, 2015.

In the existing literature, few studies have analyzed the NOWE policy and proposed changes for overcoming the obstacles and improving investment opportunities. This thesis also aims to compare the NOWE policy with the policy instruments and strategies adopted by the top three leaders in OWE sector: the UK, China, and Germany. The lessons learned from each OWE leader are viewed from an Indian perspective, and practices well suited to the Indian context are suggested.

This study segments the policy into financial, infrastructure, and environmental aspects. The NOWE policy omitted offshore wind-specific subsidies and incentive schemes to build confidence among the investors. Since OWE development and operations are subject to risks such as climate change-induced catastrophes, the policy should adopt schemes that may address these risks. China adopted four different Feed-in Tariffs (FIT) strategies, the UK's Contract of Difference, and Germany's reverse auction system contributed to their success in OWE sector. Although these tools fall into different timelines of OWE growth, India can improve its advent's timing to enable OWE's growth.

China plans to invest heavily in R&D. Germany's attempt to integrate OWE infrastructure interconnecting several countries and the UK's efforts to facilitate investments in wind turbine manufacturers have created a favourable environment for the growth of OWE infrastructure. The NOWE policy did not recommend conditions for demonstration projects that could provide vital information regarding capacity factors, cost, and government support needed. The NOWE policy has under-explored the support that a long-term international collaboration brings to supply chain growth, technology up-gradation, and standardization. The NOWE policy considers the environmental impact caused by OWE development. However, the method to maintain the safety of the OWE farms is absent. The marine ecosystem in Tamil Nadu differs from Gujarat, and measures should be taken to ensure the interest of all the stakeholders. Moreover, the policy failed to address the uncertainties of OWE, and there is no attention given to climate change-induced windstorms and methods to mitigate them. India should promote engagement among decision-makers from the local to the central government to support OWE development strategies.

Insurance companies must diversify their portfolio to limit the loss from climate change-induced catastrophic events. A diversified RE portfolio consisting of OWE turbines, solar panels, li-ion batteries, diesel generators, and grid connections may reduce the risk of climate change-induced catastrophes. Grid-connected and standalone settings are the focus of this investigation. It offers four options—an optimal grid solution, an optimal off-grid solution, a diversified energy mix, and a solution with 100% RE to satisfy the island's energy needs to minimize the amount of electricity purchased from the grid.

This study chose four ideal solutions for the alternatives out of the 24 shortlisted simulation outcomes produced by the Hybrid Optimization of Multiple Energy Resources (HOMER). According to the results, a PV-Wind-Grid combination with Rs. 3.65 of COE and NPC of Rs. 13,63,21,444 is the best solution in terms of COE and NPC. The second-best choice is a diversified energy portfolio. The COE is Rs. 5.30, and the NPC is Rs. 19,78,13,450, with the PV and wind providing most of the energy generated at 51.4% and 38.8%, respectively. Diesel generators supply electricity when the demand is not fulfilled since RE sources are variable, assuring energy security. However, the options with diesel generators in the energy mix are found to be unattractive due to their role in environmental degradation. Even still, economic considerations put this alternative in third place, with an NPC of Rs. 23.64 and an NPC of Rs.

88,24,61,111. However, the HRES, which has 100% renewable energy, keeps the planet clean with zero emissions. As a result, this alternative doesn't provide enough energy to fulfil the demand, which threatens energy security. With an NPC of Rs. 31.25 and a COE of Rs. 1,12,81,78,234, this option is ranked fourth in terms of economic aspects. The solar and wind energy produced by HRES is 47.20% and 27.45% less than what would be produced if the grid were the best option.

Our findings indicate other options for addressing the energy dilemma on artificial islands. Even so, it integrates PV, wind, and grid to deliver electricity continuously until battery prices drop significantly. The variety of renewable energy penetration for this choice is 90.9%. These results deduced from the analysis that more PV contribution encourages lower COE and emissions while complementing OWE in cost, energy output, and exposure to extreme weather events. In addition, we have found that India gains more from grid-connected hybrid energy systems than standalone ones, which have greater COE and NPC compared to earlier research.

To summarize, there are 46 barriers in the Indian OWE sector, and they can be categorized into seven categories. From the barriers analysis, financial and technological barriers appeared to be the most impactful in the Indian OWE sector, which needs utmost attention. On the other hand, countries like the United Kingdom, Germany, and China have successfully deployed OWE on their coasts with active policies and schemes, which are lessons India can adopt in its quest for OWE generation. Therefore, the NOWE policy should include offshore wind-specific policies, demonstration projects, and scope for mitigating climate change-induced catastrophes. The Indian OWE sector is exposed to a wide range of risks; diversifying the energy mix would reduce the risk exposure to a specific peril, cost, and variability in generation. A portfolio that combines PV-OWE-Grid is identified as an optimal cost solution among the 24 shortlisted options from the simulation results. However, mitigating climate change-induced catastrophe and building energy security require an option that utilizes all energy sources in a diversified energy mix.

5.2 Policy Suggestions

- The policy should suggest prolonged political will and commitment to the development of OWE. Countries such as Germany and the UK prioritize climate goals and net-zero targets. Hence, adopting renewables comes with public acceptance, and companies must invest in sustainable energy and technologies. China introduced the Renewable Energy Law in 2006 to bring transparency to the administrative and permitting process. Political support and certainty may foster confidence across the industry to invest in research and development of technologies, supply chains, and skill development.
- The national offshore wind energy policy should align with the national wind-solar hybrid policy 2018 to effectively deploy RE. In addition, the

growth of OWE will need a diversified mix of energy sources to cover variability in generation, cost, and risk of catastrophes.

- The cost of capital is one of the significant barriers to investment in OWE in India (Govindan & Shankar, 2016b). The burden from the investors through policy mechanisms can deliver a reduction between 10 % and 21 % in overall costs. Further amendments to the NOWE policy may consider tools to reduce the initial capital and facilitate investments.
- The policies from China, the UK, and Germany show that the FITs, RPO, or CfD support benefitted the OWE sector at the right time. As a result, the OWE technologies are improving in quality, and the cost is reduced. Therefore, MNRE should consider the technology change and suggest a policy mechanism best suited for the technology.
- Germany and the UK provided a regular timeline for auctions and reliable revenue streams. This created investor interest in the renewable market and resulted in intense competition between the developers on cost.
- The lessons from the Chinese market show that differentiated tariffs for each region were lengthy and required a well-researched use of concession tenders (Wei et al., 2021). Applying state-wise tariffs on the Indian OWE sector can also follow similar patterns. However, the benefits of a differentiated tariff policy cannot be ruled out considering the difference in supply chain availability, port facilities, wind

speed/consistency, state's will for green transformation, and availability of O&M facilities.

- The Chinese OWE sector has made significant progress in recent years. However, the barriers it faces must be analyzed from an Indian perspective to streamline OWE development. Some of the improvements for OWE sector in China include the need for R&D institutions dedicated to OWE, reducing the transmission issues of wind energy, conducting detailed resource assessments, continued policy development and adjustments, ensuring the availability of a skilled workforce, and standardization and testing of new wind turbines.
- It is evident from the lessons learned from Germany and the UK that it is vital to promote a collective understanding of OWE's socioeconomic benefits for its initial success. India can promote engagement among decision-makers in national, state, and local governments to align OWE development strategies.
- The government should provide allocation for special energy zones where the use of both wind and solar is put into use. The intermittent nature of these renewables complements each other, providing energy security.
- MNRE is targeting green hydrogen, offshore wind, and battery storage systems as critical technologies in the energy transition. However, the feasibility of generating green hydrogen from offshore wind needs to be analyzed from the risk perspective for effective policymaking.

5.3 Limitations and Future Scope of Work

The scope and methodology employed in this study may be expanded in subsequent investigations. Future studies could employ quantitative and qualitative data using ANP and TOPSIS to rate and prioritize the barriers to offshore wind generation. The study may potentially be repeated in nations where OWE has distinct political, social, institutional, technological, and economic obstacles. Financial, environmental, and infrastructural factors are used to compare the policies. Future research can consider institutional, political, social, and regulatory factors.

Any artificial island created in the world closer to the mainland and connected to the grid may use this study as a reference. Willingdon Island in India, near the mainland, is the only place this research is focused on. Future research, however, can examine the energy requirements of artificial islands that are not connected to the mainland and find hybrid energy solutions to meet those demands. In addition, the analysis of this study makes the 25-year lifespan assumption for changeable RE technologies and recommends that analyses in the future take RE technology into account within 20 years or less.

The climate change-induced catastrophes in Indian Ocean Region are mostly restricted to cyclones. Studying other locations may include sea ice, winter storms, lightning, and hailstorms as climate change-induced catastrophes. These catastrophes are options for insurance companies to diversify on peril. This thesis explores the offshore wind industry; onshore counterparts face climate change catastrophe risks such as heatwaves, wildfires, dust storms, and extreme fog. Future studies may explore optimal hybrid energy solutions using onshore wind energy.

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APPENDIX 1

A.1 Questionnaire

Dear Sir/Ma'am,

This questionnaire is designed to gain your insights on importance of various barriers to Offshore Wind Energy. We have identified seven main barrier categories listed (Table 1) below:

C1. Technical barriers
C2. Financial barriers
C3. Regulatory and Political barriers
C4. Social barriers
C5. Supply chain barriers
C6. Institutional Barriers
C7. Geographical barriers

There are several other barriers categorised under above mentioned seven barriers (Table 2- Table 8).

Each table has comparison between pair of criteria's, evaluating importance relative to each other.

The values on the left mean greater importance with respect to another and vice – versa.

Thank you.

	Table 1: Pair wise comparison of barrier categories w.r.t. overall objectives									
	Importance of one barrier category over the other									
Criterion	Absolute	Very strong	Fairly Strong	Weak	Equal	Weak	Fairly Strong	Very strong	Absolute	Criterion
Technical barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Financial barriers
Technical barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Regulatory and Political
Technical barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Social barriers
Technical barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Supply chain barriers
Technical barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Institutional Barriers
Technical barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Geographical barriers
Financial barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Regulatory and Political
Financial barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Social barriers
Financial barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Supply chain barriers
Financial barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Institutional Barriers
Financial barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Geographical barriers

Regulatory and Political	☐	☐	☐	☐	☐	☐	☐	☐	☐	Social barriers
Regulatory and Political	☐	☐	☐	☐	☐	☐	☐	☐	☐	Supply chain barriers
Regulatory and Political	☐	☐	☐	☐	☐	☐	☐	☐	☐	Institutional Barriers
Regulatory and Political	☐	☐	☐	☐	☐	☐	☐	☐	☐	Geographical barriers
Social barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Supply chain barriers
Social barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Institutional Barriers
Social barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Geographical barriers
Supply chain barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Institutional Barriers
Supply chain barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Geographical barriers
Institutional Barriers	☐	☐	☐	☐	☐	☐	☐	☐	☐	Geographical barriers

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