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DEDICATION

This thesis is dedicated to my parents without whom I wouldn't be here.

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ABSTRACT

This thesis comprises three chapters that try to develop a framework for Italy to effectively transition towards sustainable energy technologies to enhance its energy self-sufficiency and attain its decarbonization goals. For this purpose, the first chapter of this thesis tries to understand the energy dynamic of Italy and where each energy technology stands with respect to technological, socio-political, economic, and environmental aspects. The case of the Russian-Ukraine conflict is taken as a motivation for the study which has made topics related to energy security and sustainability of great concern to Italy. The study aims to define a sustainable energy mix for Italy through which it can achieve affordable, clean, and reliable energy for the country which is also supported by Sustainable Development Goals (SDG-7). A total of thirteen sustainability criteria are used to evaluate seven energy alternatives using the Fuzzy Strength, Weakness, Opportunity, and Threat (F-SWOT) approach. The quantitative strategic decision-making approach employed in this study helps to differentiate criteria into internal and external factors the former being controllable while the latter termed as uncontrollable. The approach works on the grand strategy matrix with the ability to divide factors into categories of strengths, weaknesses, opportunities, and threats. Strengths and opportunities in this regard can be adopted to attain maximum advantage. Whereas, threats and weaknesses can be reduced to minimize losses. The results of the study highlight the importance of enhancing the capacity of renewables especially wind and solar power both showcasing significant opportunities for its further development. Wind power in particular has more potential in addressing the energy security concern of Italy more sustainably with both onshore and offshore possibilities.

The second chapter of this thesis is built on the results of the first chapter and that is to explore the potential of offshore wind power development in the case of Italy. Offshore wind power technology has several advantages over conventional onshore wind farms. The former comes in with higher capacity factors and lesser opposition from the public. However, the most challenging part with such projects is the planning phase which determines the viability of such projects. Currently, Italy does not possess an offshore wind farm based on a floating-based foundation. However, several projects are under pipeline that require a decision support framework for performing marine spatial assessments which requires attention from the researchers. The viability of such projects depends on site suitability analysis which needs to accommodate various aspects of socio-economic, environmental, and technical aspects. The

novel model developed in this study is based on employing the Geographic Information System (GIS) to manage the spatial criteria and the non-linear multi-criteria optimization approach known as the Fuzzy Full Consistency Method (F-FUCOM) to evaluate the spatial evaluation criteria. The spatial data is based on the Italian regulatory frameworks and best practices adopted in Europe. Finally, the weighted overlay tool in ArcGIS software is employed to yield the most suitable zones for the deployment of the future's first floating-based offshore wind turbines in the Sicilian Strait.

Fostering renewable energy development in Italy would require the adoption of sustainable storage technologies to address the intermittent nature of renewables and reduce reliance on fossil fuels. Green hydrogen in this regard is considered to be a storable fuel that can achieve the aforementioned objective along with the ability to decarbonize hard-to-abate sectors such as the chemical and steel industry. Like other European countries, Italy is also steering towards fostering its green hydrogen strategy. However, to ensure a smooth transition, it is important to carry out techno-economic assessments of such projects with actual data from the renewable energy plant. A deep study of the literature suggests that most of such assessments are based on assumptions hence creating biases in the results. To address this gap, the third chapter of this thesis collects data from an actual wind farm already operational in the district of Casalduni, Campania, Italy. In an off-grid configuration, the wind farm is coupled with a Proton Exchange Membrane (PEM) electrolyzer to determine the Levelized Cost of Hydrogen (LCOH). Two types of analysis, statistical and time-dependent modelling, are performed for the system with a practical electrolyzer efficiency of 61.2%. For both approaches, costs with and without a storage tank are considered. To contain the surplus energy, the size of the electrolyzer is varied to check its impact on energy consumption, capacity factors, hydrogen production, and the pertinent LCOH for each case.

Keywords: Sustainable energy, renewable energy, energy security, site suitability, green hydrogen, wind power

Introduction

In the current world where fossil fuels are depleting and climate change is a pressing issue, countries worldwide are redefining their energy policy. Energy policy aims to meet the energy demand of the public based on three important aspects, which include environmental sustainability, energy equity, and energy security. A similar direction is provided by the 7th target of the Sustainable Development Goal (SDG), which highlights the importance of affordable, reliable, sustainable, and modern energy for all. In the broader European Union (EU) context, several initiatives such as RePowerEU, Fit-for-55, and EU's green deal are aligned to move towards being more energy-autonomous and reducing carbon emissions. Hence, such nations are moving towards redefining their respective energy mix and policies to achieve the same goal. Italy, being the third largest economy in the EU, is aligning itself towards the same objective. Especially since the country is considered to be a net importer of electricity, majorly relying on natural gas, some portion of the electricity is directly infused from neighboring countries like France, Switzerland, Austria, and Slovenia. The vulnerability of the energy sector of Italy became more visible, especially due to the Russian-Ukraine conflict, which hindered the supply of natural gas from Russia. Such a geopolitical conflict subjected Italy to diversify its supply of natural gas and redefine its energy mix. However, such a transition confronted Italy with several challenges, such as high prices of electricity, which the government and the public both had to bear. Renewable energy adoption and development is considered to be a major contributor to enhancing energy security and containing Greenhouse Gas (GHG) emissions. However, such projects are time-consuming and require long-term planning, especially in the case of Italy, where permitting and legislative hurdles are prominent. The integration of renewable energy systems into the grid requires technical upgradation so that it can handle such capacities. Hence, technical support in terms of grid accessibility is one of the important parameters for sustainable energy transition. Then comes the importance of energy storage solutions, which becomes pertinent, especially due to the intermittent nature of renewables. To contain the GHG emissions, Italy has set renewable energy targets for 2030 and 2050, aiming to become carbon neutral, aligning its self with the EU ambitions. However, the viability of such projects depends on the engagement of public opinion, making public acceptance an important metric. Moreover, government investments and incentives play a crucial role in attracting investors for such projects. It is important to highlight here that the pace of such projects has been hindered by stressors such as the COVID-19 pandemic. During

the pandemic, the prices of electricity saw a sudden decline because of the slowing down of economic activity however, during the recovery phase, there was a sharp increase in the energy prices. Energy costs increased due to the disruption of natural gas supply, which further worsened the situation in both cases, triggering the energy affordability indicator. On the flip side, the current crises have given a new direction to Italy to strengthen its energy sector, making it more anti-fragile. However, to make the vision of Italy effective and achieve its desired energy goals, a facilitating framework for the same needs to be devised for which the current thesis has taken its stance.

Based on the aforementioned discussion, the first chapter of this thesis conducts an extensive review of the literature to understand the standpoint of the energy sector of Italy with respect to socio-political, economic, environmental, and technical aspects. The motivation of this study is based on the context of three important determinants, including the Russian-Ukraine conflict, the COVID-19 pandemic, and the decarbonization goals set by Italy in regard to the energy sector. To address such a concern, the study aims to determine a sustainable energy mix for Italy to ensure affordable, clean, and reliable energy in the country. The existing energy mix consisting of seven energy alternatives is evaluated based on the thirteen criteria based on the metrics of technological, socio-political, economic, and environmental aspects. The criteria are further divided into internal and external factors. In this case, internal factors are controllable, and external factors are deemed as uncontrollable. A fuzzy quantitative strategic decision-making approach known as the Fuzzy Strength, Weakness, Opportunity, and Threat (F-SWOT) tool is employed to materialize the objective. In the SWOT matrix, hydro and biopower have been placed in the first quadrant, both showcasing strengths and opportunities for development in Italy. Moreover, solar and wind power have been placed in the second quadrant, both showcasing considerable opportunities for development; however, they face a few weaknesses as well. Moreover, geothermal and coal power have been placed in the third quadrant, both showcasing weaknesses and threats to the energy security of the country. Lastly, natural gas in the fourth quadrant showcases strengths but poses a substantial threat to the energy security of the country.

The first study of the thesis develops a strong background for the following studies, especially with regard to wind energy in Italy and its potential in addressing energy targets and sustainability. Despite the long permitting procedures, wind energy has seen a substantial increase in its capacity after solar power in the last decade. Wind energy comes with enhanced installed capacity, higher capacity factors, and more constant wind resources as compared to solar power. Based on the foundation type, wind energy can be deployed both on land and

offshore in the waters. Recently, the latter has gotten much attention, especially in the case of Europe, which is leading in the particular technology. Offshore wind farms come with several techno-economic, environmental, and social benefits, especially when properly planned. In the project lifecycle of such projects, the planning, especially the site selection, is the most challenging phase. Currently, there is only one offshore wind farm in Italy. However, it is based on a fixed foundation platform. The importance of floating offshore wind farms can be gauged by the number of requests received for such projects, especially off the coast of Sicily and Sardinia. In particular, the Strait of Sicily is considered to be a hotspot for future such projects, with the Med wind project coming in with the highest capacity, attributing to 2.8 GW. However, the viability of such projects depends upon performing marine spatial assessments based on the European and local guidelines of the country. Since there are no operational floating-based offshore wind farms in Italy, a facilitating spatial decision support system needs to be developed for future such projects. The viability of such projects depends on site suitability analysis, which needs to accommodate various aspects of socio-economic, environmental, and technical aspects. The spatial data employed in this study is based on the Italian regulatory frameworks and best practices adopted in Europe. However, upon in-depth study of reports and literature, it is found that the guidelines provided for such assessments by the National Wind and Energy Association (ANEV) are inadequate. Hence, additional spatial criteria had to be considered for developing a comprehensive decision support system, which is collected from the European Marine Spatial Platform. It is pertinent to mention here that Italy has also been a member of the same platform since 2022, so the same guidelines and regulations can be applied to it as well. Following the same pattern, a total of fifteen spatial decision criteria are adopted from similar reports, which are subsequently prepped in the ArcGIS software for further analysis. For site suitability analysis, the weighted overlay tool in the aforementioned software is a well-known approach. The spatial data is further divided into inclusion and exclusion criteria to help in the decision-making process. The inclusion criteria are considered to determine the suitability of the site, e.g., the wind speed. In contrast to this, the exclusion criteria are the one that needs to be avoided and maintained a safe distance from through identifying buffer zones. The inclusion criteria are further subjected to a novel decision-making approach known as the Fuzzy Full Consistency Method (F-FUCOM), which aids in allocating importance weightage to the evaluation criteria necessary for the weighted overlay analysis. The approach helps in segregating the area of interest into five suitability zones ranging from least suitable to highly suitable zones. The highly suitable zone can be exploited to deploy future floating-based offshore wind turbines in the Sicilian Strait. The

outcome of the analysis suggests highly suitable zones to cover an area of 5951.290 Km², which is found to be very encouraging for the future offshore wind farm industry in the country. A rather conservative estimate indicates the highly suitable zones to be capable of generating 47.2 GW of wind power capacity.

With growing renewable energy capacities such as wind power, the role of storage technologies has also become of prime importance. Energy storage systems can address the intermittent nature of renewables, enhance grid stability, and reduce reliance on fossil fuels. Hydrogen, in this case, is considered to be a sustainable, storable fuel that does not produce any sort of emissions during the burning process. Its usage can be more pronounced in the sectors where electrification is not a feasible alternative. It can be further used in the hard-to-abate sectors such as the steel and refining industries to reduce GHG emissions. A sustainable way of producing hydrogen is through a process called a water electrolyzer, which is powered by renewable energy. Like other European countries, Italy is also steering towards fostering its green hydrogen strategy. However, to ensure a smooth transition, it is important to carry out techno-economic assessments of such projects with actual data from the renewable energy resource. A deep study of the literature suggests that most of such assessments are based on assumptions, thus creating biases in the results. To address this gap, this study collects data from an actual wind farm based in Casalduni, in the Campania region of Italy. In an off-grid configuration, the wind farm is coupled with a Proton Exchange Membrane (PEM) electrolyzer to determine the Levelized Cost of Hydrogen (LCOH). Two types of analysis, statistical and time-dependent modeling, are performed for the system with a practical electrolyzer efficiency of 61.2%. For both approaches, costs with and without a storage tank are considered. To contain the surplus energy, the size of the electrolyzer is varied to check its impact on energy consumption, capacity factors, hydrogen production, and the pertinent LCOH for each case. The LCOH for various configurations ranges between 3.60 to 3.79 €/kg. Moreover, the impact of electrolyzer efficiency is also checked on the values of LCOH, with the lowest hitting 2.75 €/kg for an efficiency of 80%. Additionally, at an efficiency of 70%, the CAPEX of the electrolyzer is varied for the years 2030 and 2050 to check the potential for future such projects in the country. The analysis lays a strong business case for such projects to be considered in the case of the company in question and Italy in general, thenceforth helping to achieve the hydrogen strategy of Italy.

Chapter 1. Determination of sustainable energy mix to ensure energy security in Italy amidst Russian-Ukraine crises

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1.1 Introduction

Ensuring energy security based on the 7th target of the Sustainable Development Goal (SDG) i.e., affordable, reliable, sustainable, and modern energy for all has become a challenge for European countries due to the recent Russian-Ukraine conflict. Before the 2022 crisis, Russia was considered to be the highest exporter of petroleum oil, natural gas, and oil to the European Union (EU). In particular natural gas imports had reached 41% in the third quarter of 2021. Whereas, coal and petroleum oil imports in 2021 accounted for around 45% and 25% respectively (Perdana, et al., 2022). The prices of natural gas had already increased during that time which had also increased the costs of electricity. The war erupted on 24 February 2022 and the sanctions held thereafter further worsened the situation for the EU (Boehm, 2022). In 2020, to contain the prices of electricity the EU had to disseminate subsidies amongst its public in order to reduce the prices of electricity. Such measures posed an additional economic burden on the economies (Parry, et al., 2021). Coupled with such energy crises, the EU nations are also inclined to meet its goals of diversifying their energy mix with renewables in order to be more energy-autonomous and carbon-free through its REPowerEU and fit-for-55 programs (Proedrou, 2023). Around 35% of the total Greenhouse Gas (GHG) emissions in the EU come from the energy sector, the biggest share of which is carbon dioxide (Karmellos, et al., 2021). However, according to the targets proposed in the Paris Agreement of 2015, it is suggested that 85% of the energy should come from renewable resources by the year 2050 (Siksnelyte & Zavadskas, 2019). The same agreement also demands the EU to raise its GHG emissions reduction targets by 40% towards 2030 while becoming carbon-neutral i.e., to attain a reduction of 80-95% of GHG emissions by 2050 (Jäger-Waldau, et al., 2020). Such constraints have led the EU to redefine their energy mix to be more energy-autonomous. The relevant measures

taken in this regard by the EU have cost them €280 billion by the middle of 2022 (Sgaravatti, 2023).

Italy is a founding member of the EU and has the third largest economy in the continent with a Gross Domestic Product (GDP) of \$2.058 trillion (IMF, 2022). The country produces 24% of its domestic power consumption requirements as compared to 42.5 % of production by its peers in the EU. Hence, this puts the country in the 24th position when it comes to energy self-sufficiency among the 27 other countries in the EU (CMS, 2015). For a comparative analysis of energy autonomy, Germany has a rating of 35% whereas, France has an energy self-efficiency rating of 53%. However, when it comes to renewable energy, Italy scores better than its counterparts. For example, the country meets 17.4% of its energy demand from renewable energy as compared to the EU average of 15.5%, ranking it ahead of Germany and France but behind Sweden and Latvia (Rotondi & Salzano, 2021). However, Italy is aiming to enhance 55% of its renewable energy mix by 2030, whereas, countries like Germany, Netherlands, and Spain are aiming for the 75% mark (IEA, 2020). The energy demand in Italy has been constant from the year 2015 to 2020 ranging between 324 TWh and 331 TWh. However, due to COVID-19, there was a decrease in demand by 6.3% bringing it to 307 TWh. In 2021, Italy saw a surge in energy demand attributing to a rise of 8% with respect to 2020 (Brown, 2021). The pandemic also had a retarding effect when it came to the increase in the installation of renewable energy resources due to several structural weaknesses. These obstacles had more to do with long waiting times for the authorization of new plant deployment, land disputes, and lack of consensus (International Trade Administration, 2020).

Italy's major reliance on the import of natural gas from Russia makes its energy security vulnerable. Around 50% of the electricity generated in Italy comes from natural gas as opposed to 37% in 2000 (Speak, 2022). In 2020, Italian import of natural gas contributed to a total of 92.8% of which 43% was imported from Russia (Eurostat, 2020). The imports of oil and coal from Russia in 2021 were low as opposed to natural gas. Coal imports in the same year constituted 2% of the national demand, whereas, petroleum oil constituted 10% of the demand (Andreolli, et al., 2023). To reduce dependency on the import of natural gas, Italy rolled back to the usage of coal power to meet its short-term energy demands. Currently, coal fulfills 4% of the energy generation in the country even though the country had planned to phase out the use of coal by the year 2025. However, gas-to-coal switching can potentially reduce the import of 30 bcm of Russian gas for the EU (Bianchi & Raimondi, 2022). It is pertinent to mention here that Russia has been a major source of coal imports for Italy (Balsalobre-Lorente, et al., 2023). Italy fulfills 59% of its energy demands from fossil fuels whereas the remaining 41% is

met by renewables. Such figures make Italy a net importer of electricity (Andreolli, et al., 2023). The country is hence moving in the direction of redefining its energy policy in order to be more energy secure. External drivers in this case are the goals determined by the REPowerEU program. The primary goal of this program is to foster the development of renewables in the region (European Commission, 2022). Another motivation for Italy to transition toward cleaner energy technologies is rising wholesale prices of electricity which makes renewables like solar and wind power more feasible (Brown, 2021). Rolling back to nuclear power for Italy is not an option because of its abandonment since the Chornobyl accident. Although it is considered to be a more sustainable and suitable alternative as compared to other fossil fuels (Bersano, et al., 2020).

To sum it up, the subject of energy security in Italy has taken a new shape especially due to the COVID-19 pandemic, the Russian-Ukraine conflict, and the decarbonization goals. Such stressors have raised the need for Italy to redefine its energy mix. Addressing such a problem is however a challenge for the country. Primarily, the goal of attaining energy self-sufficiency and decarbonization levels is impeded by paying more attention to the import of natural gas, its diversification, and storage systems coupled with complex regulatory frameworks. Public consent is another concern that plays an important role when formulating energy security policies (Frilingou, et al., 2023). Ensuring energy security through enhancing the capacity of renewables is a popular approach however the adoption of such technologies needs to be evaluated based on the available technical infrastructure of the country (Magazzino & Giolli, 2024). The goal of attaining affordable, reliable, sustainable, and modern energy hence needs to be backed by decision-making based on the metrics of socio-political, economic, environmental, and technical aspects. The decision-making process however has to evaluate all the existing sources of power in the country. Moreover, addressing such a complex decision-making process needs to be backed by a sound methodological approach that can handle both qualitative and quantitative sets of data (Frilingou, et al., 2023). The strategic decision-making tool known as the Fuzzy SWOT (hence F-SWOT) approach is a great fit to address such a problem. The approach works on the grand strategy matrix with the ability to divide factors into categories of strengths, weaknesses, opportunities, and threats. Strengths and opportunities in this regard can be adopted to attain maximum advantage. Whereas, threats and weaknesses can be reduced to minimize losses (Arslan & Er, 2008). With the help of such a methodology, the study aims to determine a sustainable energy mix for Italy in order to make it more energy-autonomous. The novelty of this study lies in the subject, context, methodology, and the type of data employed.

1.2 Literature review

The aim of energy policy is to meet the energy demands of the public based on three important aspects which include: energy security, environmental sustainability, and energy equity. The fourth aspect which is recently being recognized is social justice (Kuzemko, et al., 2022). Policymakers in this regard give the most importance to the aspect of energy security (Colgan, et al., 2023). Energy security has become more of a concern for the EU especially because of the recent Russian-Ukraine conflict. The cut-off of gas supply by Russia through Nord Stream 1 and 2 pipelines resulted in the shortage of natural gas and a rise in energy bills for the EU. Such adversity diverted the EU's attention to diversifying their sources of fossil fuel from Norway, Azerbaijan, and Qatar (Hasan, 2022). Germany followed by Italy were the major importers of natural gas and oil from Russia. It is suggested that such nations need to decouple projects of fossil fuel imports. However, a more aggressive decoupling of such fossil fuels might put such nations at energy risk. Hence, the process of such decoupling needs to be conducted phase-wise (Balsalobre-Lorente, et al., 2023).

Italy through its Integrated National Energy and Climate Plan aims to redefine the energy policy of its country by engaging in activities that prioritize energy security coupled with decarbonization. A deep decarbonization in the case of Italy can be achieved through engaging in the deployment of renewable energy technologies along with efficient energy conversion technologies. Such measures can cut emissions by 79%-97% with respect to the levels of 1990 by 2050 (Borasio & Moret, 2022). The impediments to the development of renewable energy systems can be classified into two groups i.e., economic and political. Investments and incentives primarily slowed down due to the COVID-19 pandemic. Shortsightedness and fragmented and complex decision-making processes are some of the political hurdles. However, technological complexities in the shape of delayed patent registrations are another reason for slow developmental processes in the renewable energy realm (Esposito & Romagnoli, 2023). Such impediments make Italy far from achieving its targets of a resilient and sustainable energy future (Bigerna, et al., 2023). The crises however have allowed the country to redefine its energy mix to be more energy-autonomous (Figini & Moreno, 2023). To tackle such a problem, the energy scenario of Italy needs to be treated as a specialized case. The current scientific literature however has limited studies addressing such a concern (Esposito & Romagnoli, 2023).

Defining energy policy for a country requires the cooperation of stakeholders both from the government and the public. The guidelines for such policymaking are driven by metrics of

sustainability which comes with an innate notion of complexity (Gatto, 2022). The role of public acceptance in adopting a new technology has an important role to play. This is evident in the case of Greece in which the public prefers renewable energy resources such as wind and solar power for achieving environmental sustainability. However, willingness to pay for such technologies is fostered by energy subsidies, education, and state support (Ntanos, et al., 2018). To achieve a more sustainable energy sector in Italy, researchers focus more on the use and adoption of renewable energy technologies with a focus on a more decentralized energy systems network (Colasante, et al., 2021). In the current scenario, hydro and nuclear power are great alternatives to fossil fuels (Bersano, et al., 2020; Percebois & Pommeret, 2021). However, nuclear power is not an option after the Chornobyl and Fukushima incidents and the general lack of public and political acceptance (Karaeva, et al., 2022; Marques & Junqueira, 2022). Other findings suggest solar and hydropower to be good alternatives to fossil fuels in Italy. Solar power in this regard seems to be a more substitutable option (Solarin, et al., 2021). Also, findings from the OECD countries suggest that wind and hydroelectricity are found to reduce the energy security risk. Whereas, biomass and solar energy do not have a significant impact on energy security (Cergibozan, 2022). The shift towards renewable energy systems is a step-wise mechanism. In the short-term scenario, ignoring the usage of coal, oil, and gas would further worsen the energy security concerns of the country. Hence, both the options of renewables and fossil fuels in this regard need to be considered and analyzed based on the competence and standing of the country. Such an approach would aid the policy makers to come up with a rational energy mix and policy (Safari, et al., 2019; Solarin & Bello, 2021). The methodologies employed to determine the energy mix in the context of Italy include the portfolio theory. This research aimed to determine the profitability associated with five renewable energy systems alternatives i.e., solar, wind, geothermal, hydel, and biomass. The results of the study are more inclined towards the installation of a mix of small power systems including hydro and wind power. To determine the optimal energy mix the research suggests that future studies should use multi-criteria decision analysis to evaluate energy technologies based on criteria involving economic, environmental, and technological aspects (Gastaldi & Trosini, 2017). Such decision-making tools have already been employed to evaluate the renewable energy systems in Pakistan based on criteria involving economic, environmental, technical, and socio-political aspects. In this case, the fuzzy AHP and qualitative SWOT approaches are used to tackle the problem at hand. The results of the study indicate wind energy to be the most suitable alternative for the country (Wang, et al., 2020). Moreover, the qualitative PESTLE and SWOT approaches are used to assess renewable energy resources in Malaysia.

For this purpose, the study uses semi-structured interviews with experts to identify the strengths, weaknesses, opportunities, and threats of introducing renewable energy systems in the country (Shadman, et al., 2021). The current study however focuses on addressing the energy security concerns of Italy which has resulted because of the recent Russia-Ukraine war. To achieve such a goal, the study aims to evaluate the existing power energy alternatives that include both renewable and non-renewable sources. The study for this purpose uses the fuzzy quantitative decision-making tool known as the F-SWOT approach to evaluate the energy alternatives based on sustainability criteria. The aim of employing the fuzzy set theory, in this case, is to address any type of uncertainty or ambiguity during the data collection process (Pramanik, et al., 2020).

The F-SWOT technique has been employed to determine strategies to eradicate electricity crises in Pakistan (Safder, et al., 2022). It has further been applied to formulate pavement management policies for airfields based on technical, financial, and reliability criteria (Vyas, et al., 2021). Moreover, its usage has been recorded for sustainable river basin management based on the social, environmental, technical, and economic aspects (Srinivas, et al., 2018). Factors contributing to the export of the tile and ceramic industry have been ranked using the same approach (Karimi, et al., 2019). The F-SWOT approach has been further employed in the development of strategies for solar energy production in an emerging economy (Karatop & Taşkan, 2021). The quantitative fuzzy SWOT approach proposed for this study has been used for supplier selection and order allocation problem (Amin, 2011). It has also been used to assess and select sustainable electric mobility for a developing country to effectively transition toward green mobility (Babar, et al., 2020). Lastly, it has been utilized to assess waste management technologies to valorize agricultural waste to transition toward the circular bio-economy approach in a developing country's context (Khan & Ali, 2022).

The aforementioned discussion can now be summarized to identify relevant gaps in the literature. Recent studies on the subject of energy security due to the Russian-Ukraine conflict include a content analysis of the literature based on the official reports of Italy from 2000-2020. Findings suggest that the country is having a hard time diversifying its sources of fossil fuel and its replacement because of geographical and environmental constraints. The study further highlights that the target of achieving energy independence in Italy is still a far-fetched goal. With the aforementioned findings, the research however does not address the recent Russian-Ukraine crises of 2022 along with its limitation on depending on secondary datasets only (Bigerna, et al., 2023). Another attempt in the same context has been made to discuss the geo-strategic importance of Italy and its possible sources of new natural gas providers. The research

however limits its discussion to geo-politics with reliance on secondary datasets alone (Touazi, 2023). The subject of energy security in the wake of the Russian-Ukraine crises has been further addressed in the literature, however, in broader EU terms (Colgan, et al., 2023; Al-Saidi, 2023). However, policy measures derived from such an attempt cannot be attributed to a specific region due to the varying internal dynamics of each country. Hence, the literature calls to address such a concern by redefining the energy mix of Italy based on the metrics of socio-political, economic, environmental, and technical aspects (Gatto, 2022). Methodological approaches to deal with the energy security concerns of Italy include the decision-making approach known as Fuzzy Cognitive Mapping. The aforementioned approach is employed to evaluate mitigating strategies to overcome the energy security concerns of Italy. The findings of which are inclined towards the diffusion of renewables in the energy mix of Italy with less reliance on new gas infrastructure. However, further research is suggested to tackle the energy security concerns of Italy with the application of sound methodological approaches that can handle both qualitative and quantitative sets of data. The study further suggests involving experts from varying backgrounds to aid in the decision-making process (Frilingou, et al., 2023). To address such gaps in the literature, this study employs a strategic decision-making approach known as the F-SWOT approach to determine a sustainable energy mix for Italy in order to achieve energy security in the country. The technique helps divide the evaluation criteria into internal and external factors with further classification into cost and benefit criteria. The evaluation criteria gathered from the secondary literature as a result are subjected to experts from the energy sector to evaluate the seven energy alternatives. Along with the determination of the optimal energy mix, policy recommendations are provided in order to pave the way towards a more energy-secure future in Italy. The novelty of the study lies in both the context and the employed methodological approach.

1.3 Data collection

To address the issue of energy security in Italy, this study aims to assess a total of seven sources of power-generating technologies to determine the most optimal energy mix based on the metrics of sustainability. To achieve this goal, the current research employs the F-SWOT methodology which has the capability of assessing both qualitative and quantitative data. The seven energy alternatives considered in this study are assessed based on internal and external factors. Here the internal factors consist of strengths and weaknesses which are considered to be controllable Whereas, the external factors are characterized by opportunities and threats and

are considered to be uncontrollable. These factors are adopted and determined based on the metrics of sustainability that include technical, socio-political, economic, and environmental aspects.

For analyzing the energy alternatives, an exhaustive literature review was conducted to gather the sustainability criteria. After going through the relevant literature, a total of 20 sustainability criteria are adopted which are then further discussed with a panel of three energy experts. The expert's role in this regard was to determine the most essential sustainability factors for evaluating the seven energy alternatives along with removing any type of redundancy between the list of criteria. Another role of the energy experts was to segregate the criteria into their respective internal and external components. Finally, through the employment of the mini-Delphi approach, the most recurring factors from experts' assessment were narrowed down into a list of 13 internal and external criteria, the results of which are displayed in Table 1.1 below.

Sustainable aspects	<i>Internal criteria</i>	Related literature
Technical	C1. Access to grid	(Hassan, 2021; Trotter, et al., 2019; Carlini, et al., 2019)
	C2. Energy storage systems	(Sun, et al., 2020; Zsiborács, et al., 2019; Nadeem, et al., 2018)
	C3. Supportive legislation	(Lehtveer & Fridahl, 2020; Child, et al., 2019; Child, et al., 2018)
Socio-political	C4. Social acceptability	(Lowitzsch, et al., 2020; Baloch, et al., 2022; Qazi, et al., 2019)
	C5. Employment generation	(Benedek, et al., 2018; Wu, et al., 2018; Garrett-Peltier, 2017)
<i>External criteria</i>		
Environmental	C6. Land requirements	(Howard, et al., 2009; Shahsavari & Akbari, 2018; Dhar, et al., 2020)
	C7. Greenhouse gas emissions	(Wang, et al., 2019; Raybould, et al., 2020; Pfeifer, et al., 2019)
Economic	C8. Delivered cost of electricity	(Child, et al., 2019; Zsiborács, et al., 2018; Aghahosseini, et al., 2020)
	C9. Capital investment	(Liu, et al., 2018; Deng & Lv, 2020; Yang, et al., 2018)
	C10. Cost of operations and management	(Diesendorf & Elliston, 2018; Ram, et al., 2020; Lee & Chang, 2018)

Technical	C11. Capacity factor	(Nock & Baker, 2019; Dincer & Acar, 2015; Jurasz, et al., 2020)
	C12. Technological feat	(Shen, et al., 2010; Suberu, et al., 2014; González , et al., 2015)
	C13. Resource availability	(Kamran, et al., 2020; Østergaard, et al., 2020; Bódis, et al., 2019)

Table 1.1. Sustainability criteria for evaluating energy alternatives

The next step after the determination of sustainability factors was to assess the determined criteria followed by the list of energy alternatives. For this purpose, a questionnaire is prepared using Google Forms which is then sent to experts in a private energy-based company in Italy known as Renexia SpA. The company was founded in 2011 and has expertise in the deployment of wind and solar energy plants. It works in the areas of development, design, construction, and management of plants. To remove bias in the responses, the questionnaire was also shared with researchers and experts in the energy field outside the company. The demographics of the respondents is given in Table 1.2 below.

Sector involved	Position in the organization	Years of experience in the energy sector
Renexia Company	Procurement Specialist	5
	Technical employee, development and permitting	1
	Permitting, Energy Management, Asset Management	10
	Supply Chain Engineer	5
	Site engineer	3
	Lead Researcher	3
Researchers in the energy sector	Business Analyst	16
	Researcher	5
	Research Assistant	1
	Doctoral Researcher	7
	Researcher in Energy Economics	3
	Doctoral Researcher	4
	Average experience	5.9 Years

Table 1.2. Respondents and their demographics

1.4 Methodology

1.4.1 Fuzzy set theory

The experts in the first part of the questionnaire were subjected to allocate weightage to the sustainability criteria utilizing a fuzzy Likert scale which is provided in Table 1.3 below. The second part of the questionnaire dealt with the assessment of the seven energy alternatives based on the aforementioned sustainability criteria.

Linguistic variables	Associated numbers
Very Low	(1,1,3)
Low	(1,3,5)
Medium	(3,5,7)
High	(5,7,9)
Very High	(7,9,9)

Table 1.3. Fuzzy five-point Likert scale (*Source:* (Khan, et al., 2020))

The utilization of the fuzzy set theory developed by Lotfi Asgerzadeh, in this case, was to assess the levels of ambiguity during experts' judgment (Zadeh, 1965). Supporting equations for understanding the theory are given with the help of the following steps.

For example, let's suppose "C" is a set having the member function (x) , then the fuzzy set with the ordered pair becomes,

$$D = \{(x, \mu_b(x)) \mid x \in C\} \quad (1)$$

In equation 1, D is a fuzzy set that has a membership function x . The function ranges from $[0 \text{ to } 1]$ and has all real numbers. To avoid complexity, the study uses the fuzzy triangular membership function. The triangular membership function along with three distance variables denoted by (q, r, s) , showcasing lower, mean, and upper bounds is presented with the help of Figure 1.1 below.

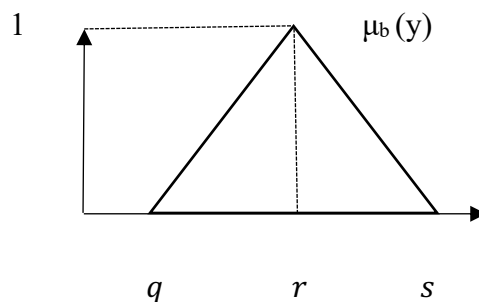


Figure 1.1. Fuzzy triangular membership function

The description of the range of the function in the case of a triangular fuzzy number is given with the help of equation 2 below.

$$\mu_b(x) = \begin{cases} (x - q) / (r - q) & q \leq x \leq r \\ (u - x) / (s - r) & r \leq x \leq s \\ 0 & otherwise \end{cases} \quad (2)$$

In equation 2, the values q, r, s are in the significance order of $q < r < s$ which are all real numbers. In this case, the value of x that lies on " s " signifies the most anticipated value i.e., $\mu_{\tilde{a}}(x) = 1$. On the other hand, the value of x that lies on " q " will signify the least expected data i.e., $\mu_{\tilde{a}}(x) = 0$. The level of ambiguity in the collected data is signified by the lower and upper bounds. To find the distance between fuzzy numbers in this case, the following equation is utilized.

$$d(\alpha, \beta) = \sqrt{\left(\frac{1}{3}\right) [q - q']^2 + [r - r']^2 + [s - s']^2} \quad (3)$$

1.4.2 Fuzzy SWOT approach

The methodology employed for the assessment of criteria and alternatives in this regard is a quantitative strategic decision-making technique known as the F-SWOT approach. The approach helps in segregating criteria into internal and external factors. The internal factors consist of strengths and weaknesses, whereas the external factors consist of opportunities and threats. The methodology has the characteristics of identifying strengths and opportunities that can be adopted to attain maximum advantages, whereas threats and opportunities can be reduced to minimize loss (Arslan & Er, 2008). The aforementioned characteristics make the approach very suitable for dealing with the problem at hand. The approach will help allocate significance to the list of internal and external criteria as well as plot the energy alternatives onto a graph that would facilitate understanding the strengths, weaknesses, opportunities, and threats. Hence, the energy alternatives that have the most strengths and opportunities will be regarded as a suitable option for meeting the energy demand of Italy more sustainably. Whereas, the energy alternatives facing weaknesses and threats can be avoided. The steps involved in the F-SWOT approach are outlined below (Amin, 2011; Babar, et al., 2020; Khan & Ali, 2022).

Step 1: The first step of the methodology deals with the selection and determination of alternatives that need to be evaluated.

Step 2: The alternatives need to be evaluated based on a criterion in this case a set of internal and external factors are determined to achieve the aforementioned goal.

Step 3: In the assessment phase, decision-makers are involved in evaluating the list of criteria and alternatives. This is done using a triangular fuzzy number in this study showcased in Table 3.

Step 4: The data collected as a result of the assessment of decision-makers is then transformed from the linguistic variables into their corresponding fuzzy numbers using Table 3. This is followed by taking an average of all the responses using equation 4 below.

$$W_{ij} = \frac{1}{K} [w_{ij}^1 + w_{ij}^2 + \dots + w_{ij}^k] \quad (4)$$

The variable K in equation 4 represents the number of respondents, whereas, $(j=1, 2, \dots, n)$ represents the number of alternatives. Moreover, $(i = 1, 2, \dots, n)$ represents the criteria's number.

Step 5: In this study, the centroid method has been used for the defuzzification of the triangular numbers (Chou & Chang, 2008).

$$(q + r + s)/3 \quad (5)$$

Step 6: For the unification of the scale, the process of normalization is done for the sustainability factors. In this case, equation 6 can be used for the normalization of cost criteria, while equation 7 can be employed for normalizing benefit criteria. moreover, the aggregated weights of alternatives are derived by taking a product of the normalized weights of criteria with alternatives. Finally, to find the benchmarking values an average sum of all the criteria is taken.

$$N_{ij(c)} = \frac{\min_j w_{ij}}{w_{ij}} \quad (6)$$

$$N_{ij(b)} = \frac{w_{ij}}{\max_j w_{ij}} \quad (7)$$

where $i = 1, 2, \dots, n, j = 1, 2, \dots, n$.

Step 7: The final step involves the determination of Cartesian coordinates for plotting the results on a graph. To find the Cartesian values, the benchmarking values are subtracted from

the normalized weights of internal and external factors. The coordinates lie between the range of $[-1, +1]$. Hence, if an energy alternative in this case has positive coordinates then it possesses strength and has opportunities in the market for further development. On the other hand, if the coordinates are negative then the particular alternative has weaknesses and is subjected to threats. Finally, the coordinates can be derived using equations 8 and 9. The determined coordinates can finally be plotted on a graph for further assessment.

$$IC_j = I_j - IB \quad (8)$$

$$EC_j = E_j - EB \quad (9)$$

For understanding purposes, an overall framework of the study has been outlined with the help of Figure 1.2 below.

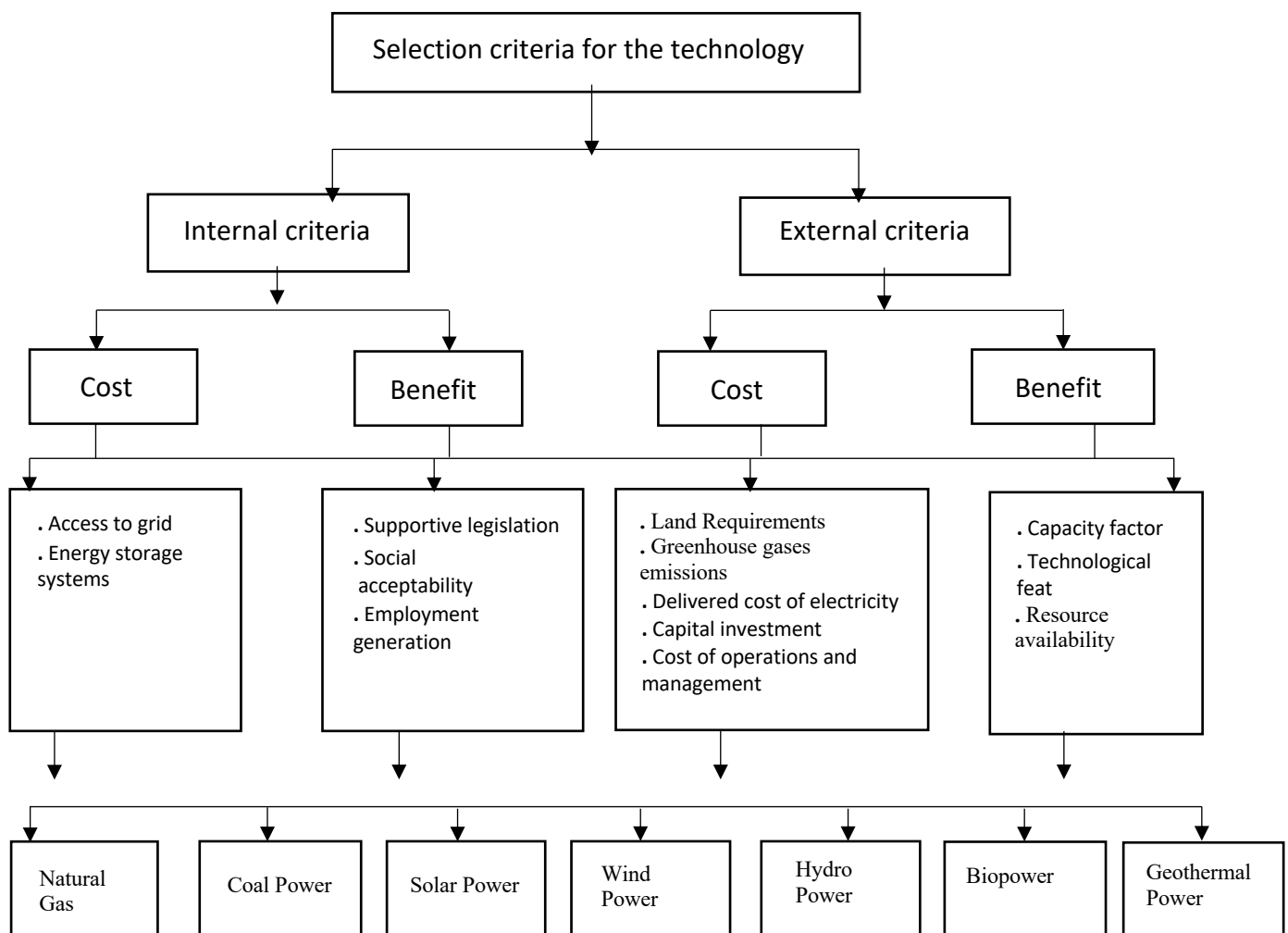


Figure 1.2. Methodological framework of the study

1.5 Results

To address the energy security problem in Italy this study aims to determine an energy mix based on the metrics of sustainability. For this purpose, a total of seven energy alternatives are considered which are gauged using a list of 13 sustainability criteria. The methodology employed for this purpose is the F-SWOT approach. For assessing the list of criteria and alternatives, experts in the energy sector were involved. In the first phase of the assessment, the decision-makers evaluated the list of internal and external factors using the fuzzy scale given in Table 3. The criteria are assessed based on the linguistic variables that are eventually converted into corresponding fuzzy numbers. Consequently, this is followed by taking an average of all the collected responses by utilizing equation 4 which is subsequently followed by the defuzzification of criteria using equation 5 through the centroid method. Normalization of the criteria is taken here to attain unification of scale. For cost criteria, the normalization is done using equation 6. Whereas, the normalization of benefit criteria is done through equation 7. The following results in Table 1.4 are found by employing the aforementioned equations.

Criteria	DM ₁	DM ₂	DM ₃	DM ₄	...	DM ₁₂	Defuzzification	Normalized
<i>Internal factors</i>								
C1. Access to grid	VH	H	VH	L	...	VH	7.444	0.2339
C2. Energy storage systems	M	VK	M	VH	...	H	6.333	0.1990
C3. Supportive legislation	M	VH	H	M	...	VH	7.222	0.2269
C4. Social acceptability	H	VH	H	VH	...	VH	5.667	0.1780
C5. Employment generation	M	H	H	H	...	M	5.167	0.1623
<i>External factors</i>								
C6. Land requirements	H	H	M	H	...	VH	6.222	0.1096
C7. Greenhouse gas emissions	M	M	VH	H	...	H	7.167	0.1262
C8. Delivered cost of electricity	M	M	H	VH	...	H	7.333	0.1292
C9. Capital investment	M	M	H	VH	...	H	7.333	0.1292
C10. Cost of operations and management	VH	VH	H	H	...	VH	6.556	0.1155
C11. Capacity factor	H	H	H	M	...	VH	7.444	0.1311
C12. Technological feat	H	M	H	H	...	M	7.500	0.1321
C13. Resource availability	H	H	VH	VH	...	VH	7.222	0.1272

Table 1.4. Weights allocated to internal and external factors by Decision Makers (DM)

After the assessment of the criteria, the experts are subjected to allocate weightage to the seven energy technologies regarding the sustainability factors. In this case, the same steps are followed to find the de-fuzzified weights for the energy alternatives. For simplicity and understanding purposes, a sample calculation for the assessment of energy alternatives based on the "on-grid access" criteria is shown in Table 1.5 below.

On-grid access	DM ₁	DM ₂	DM ₃	DM ₄	...	DM ₁₂	Weights	De-fuzzified weights
A1. Natural Gas	L	M	H	H	...	M	(3.167, 5.167, 7.000)	5.111
A2. Coal Power	VL	M	H	H	...	M	(3.167, 5.000, 6.667)	4.944
A3. Solar Power	VH	VH	H	H	...	VH	(5.167, 7.167, 8.167)	6.833
A4. Wind Power	VH	VH	H	H	...	VH	(5.500, 7.500, 8.500)	7.167
A5. Hydro Power	H	H	H	VH	...	M	(4.500, 6.500, 8.00)	6.333
A6. Biopower	M	H	H	M	...	M	(2.667, 4.667, 6.667)	4.667
A7. Geothermal Power	M	M	H	M	...	M	(3.833, 5.833, 7.833)	5.833

Table 1.5. Experts' judgements based on the "access to grid" criteria

The same steps are followed for all the criteria and alternatives, the results of which are displayed in Table 1.6 below.

<i>Internal factors</i>	A ₁	A ₂	A ₃	A ₄	A ₅	A ₆	A ₇
C1. Access to grid	5.111	4.944	6.833	7.167	6.333	4.667	5.833
C2. Energy storage systems	3.167	3.000	8.111	6.500	3.778	5.278	4.667
C3. Supportive legislation	4.722	3.778	7.833	7.556	5.944	6.222	5.778
C4. Social acceptability	4.778	3.778	7.556	6.889	5.556	6.722	5.389
C5. Employment generation	5.167	5.444	5.444	5.667	6.500	5.000	5.278
<i>External factors</i>							
C6. Land requirements	5.833	5.389	7.944	7.278	7.778	4.333	4.944
C7. Greenhouse gas emissions	5.944	8.222	2.000	2.000	2.667	4.167	3.556
C8. Delivered cost of electricity	6.556	6.056	4.889	4.889	4.667	5.056	4.944
C9. Capital investment	6.111	6.556	6.222	7.000	7.667	4.889	6.000
C10. Cost of operations and management	5.500	6.000	4.222	5.000	5.444	4.556	4.944
C11. Capacity factor	6.722	6.222	5.278	5.444	7.333	5.556	5.500
C12. Technological feat	6.444	6.222	7.167	7.278	7.056	5.778	6.278
C13. Resource availability	4.278	4.667	7.111	7.000	6.278	5.056	6.111

Table 1.6. Weights of energy technologies based on the internal and external factors

The normalized weights of all the technologies are evaluated based on the cost and benefit criteria using equations 6 and 7. The aforementioned steps correspond to the determination of normalized weights for all the alternatives, the results of which are displayed in Table 1.7 below.

<i>Internal factors</i>	NC_x	NA₁	NA₂	NA₃	NA₄	NA₅	NA₆	NA₇
C1. Access to grid	0.234	0.913	0.944	0.683	0.651	0.737	1.000	0.800
C2. Energy storage systems	0.199	0.947	1.000	0.370	0.462	0.794	0.568	0.643
C3. Supportive legislation	0.227	0.603	0.482	1.000	0.965	0.759	0.794	0.738
C4. Social acceptability	0.178	0.632	0.500	1.000	0.912	0.735	0.890	0.713
C5. Employment generation	0.162	0.795	0.838	0.838	0.872	1.000	0.769	0.812
<i>External factors</i>								
C6. Land requirements	0.110	0.743	0.804	0.545	0.595	0.557	1.000	0.876
C7. Greenhouse gas emissions	0.126	0.336	0.243	1.000	1.000	0.750	0.480	0.563
C8. Delivered cost of electricity	0.129	0.712	0.771	0.955	0.955	1.000	0.923	0.944
C9. Capital investment	0.129	0.800	0.746	0.786	0.698	0.638	1.000	0.815
C10. Cost of operations and management	0.115	0.768	0.704	1.000	0.844	0.776	0.927	0.854
C11. Capacity factor	0.131	0.917	0.848	0.720	0.742	1.000	0.758	0.750
C12. Technological feat	0.132	0.885	0.855	0.985	1.000	0.969	0.794	0.863
C13. Resource availability	0.127	0.602	0.656	1.000	0.984	0.883	0.711	0.859

Table 1.7. Normalized weights of criteria (NC_x) and energy alternatives (NA_x)

To determine the benchmarking values, it is important to take the product of the normalized weights of criteria with all the energy alternatives. This is followed by taking a sum of the resultant weights. Finally, the benchmarking values for internal and external factors are found by taking the average of all the values that were determined in the prior step. The results of the aforementioned steps are shown in Table 1.8 below.

<i>Internal factors</i>	A₁	A₂	A₃	A₄	A₅	A₆	A₇	Benchmark value
C1. Access to grid	0.214	0.221	0.160	0.152	0.172	0.234	0.187	
C2. Energy storage systems	0.188	0.199	0.074	0.092	0.158	0.113	0.128	
C3. Supportive legislation	0.137	0.109	0.227	0.219	0.172	0.180	0.167	
C4. Social acceptability	0.113	0.089	0.178	0.162	0.131	0.158	0.127	
C5. Employment generation	0.129	0.136	0.136	0.141	0.162	0.125	0.132	
Sum	0.780	0.754	0.774	0.767	0.796	0.810	0.741	0.775

External factors

C6. Land requirements	0.081	0.088	0.060	0.065	0.061	0.110	0.096	
C7. Greenhouse gas emissions	0.042	0.031	0.126	0.126	0.095	0.061	0.071	
C8. Delivered cost of electricity	0.092	0.100	0.123	0.123	0.129	0.119	0.122	
C9. Capital investment	0.103	0.096	0.101	0.090	0.082	0.129	0.105	
C10. Cost of operations and management	0.089	0.081	0.115	0.097	0.090	0.107	0.099	
C11. Capacity factor	0.120	0.111	0.094	0.097	0.131	0.099	0.098	
C12. Technological feat	0.117	0.113	0.130	0.132	0.128	0.105	0.114	
C13. Resource availability	0.077	0.083	0.127	0.125	0.112	0.090	0.109	
Sum	0.721	0.704	0.878	0.857	0.828	0.820	0.814	0.803

Table 1.8. Determination of benchmarking value

The final step is to determine the x and y coordinates to plot the values onto a graph. In this case, equation 8 is used to determine the x-coordinates, while the y-coordinated are determined utilizing equation 9. The results are displayed in Table 1.9 below.

XY - Coordinates								
Alternatives		A1	A2	A3	A4	A5	A6	A7
Internal factors	(x-axis)	0.0057	-0.0206	-0.0005	-0.0079	0.0210	0.0358	-0.0336
External factors	(y-axis)	-0.0818	-0.0997	0.0746	0.0539	0.0250	0.0169	0.0111

Table 1.9. Cartesian coordinates

The x and y coordinates shown in Table 1.9 are then subsequently plotted onto a four-quadrant graph displayed in Figure 1.3 below. The positive x and y axes are denoted by strengths and opportunities respectively, while the negative x and y axis are denoted by weaknesses and threats.

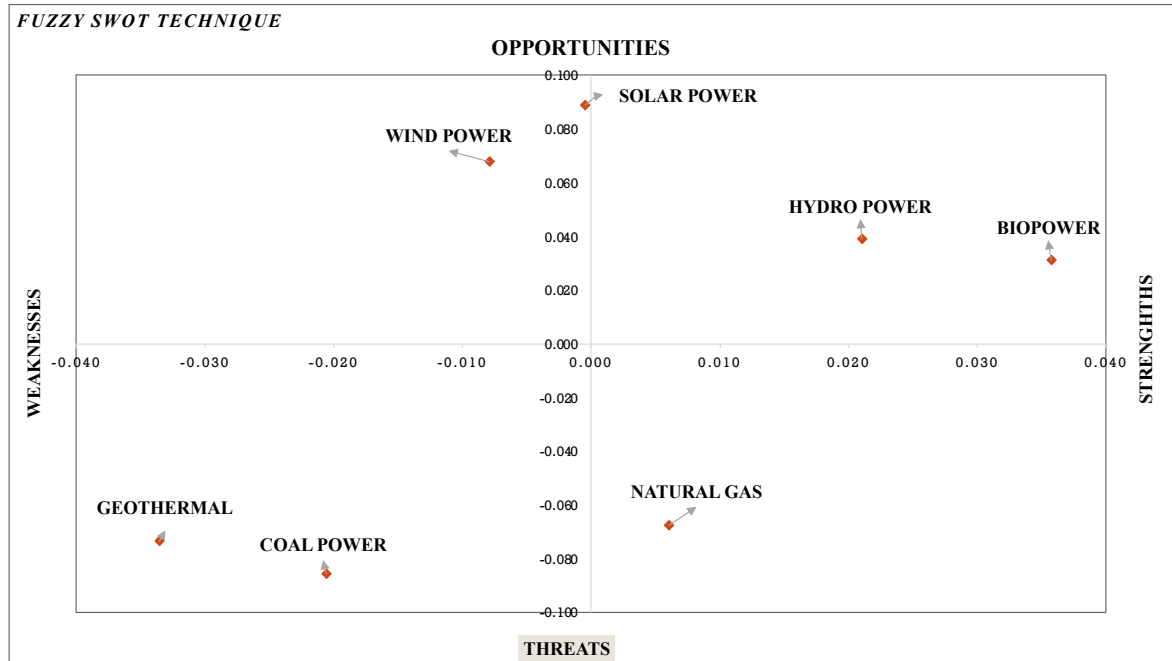


Figure 1.3. Fuzzy SWOT matrix

1.6 Discussion

The outcomes from the application of the F-SWOT approach can be explained in two phases. In the first phase, the energy experts were subjected to allocate significance to the 13 sustainability criteria. In this case, the outcomes of weighted criteria can be studied from Table 1.4 in the results section. From the list of internal factors, the experts gave the most significance to the technical criteria i.e., “access to grid” with a normalized weight of 0.2339. The aforementioned criterion is considered to be very crucial when deciding site selection for energy plants, especially in the case of renewable energy systems where the power supply is intermittent. The eminent challenge, in this case, lies in the determination of an optimal site that does not go against the sphere of exploiting protected areas. Site selection in such cases also has to account for easy access to populated areas along with a transportation network that results in lower delivery costs. (Ruiz, et al., 2020). The former point has to be further strengthened by taking into account the importance of considering a grid or substation that has adequate capacity to withstand the extra power supply (Rediske, et al., 2021). Moreover, it is also pertinent to understand that the grids need to be continuously upgraded so that challenges such as energy efficiency, storage, and the integration of various-sized renewable energy systems are integrated successfully (Meeus & Saguan, 2011).

In the case of external factors, the experts in Table 1.4, allocated the most significance to the "technological advancement" criterion. The technology advancement or maturity in this regard

corresponds to the level of deployment or installed capacity of the particular energy technology in the region. Moreover, it also deals with how much advancement the particular technology has achieved over the years in terms of technological and economic feasibility. It also corresponds to the level of technology transfer from the research and development departments in universities or other private organizations to the industry. The level of technological advancement or deployment of a particular energy source can have a significant impact on the adaptability of a particular source into the energy mix of a region. The same concept has been quite evident in one of the cities of Italy i.e., Tuscany, where the selection of hydro and geothermal-based technologies was based on the level of technology transfer and the level of installed capacity in that region (Laurentis & Pearson, 2021).

The next phase of the methodology involved the assessment of the seven energy alternatives based on the thirteen sustainability factors. The results in this case can be analyzed from the SWOT matrix in Figure 1.3 where the seven sources of power are portrayed on the four quadrants. Starting from the first quadrant, the experts rated the biopower technology to potentially have the most strengths followed by opportunities for its development in Italy. The Italian bio-economy is one of the third largest in the EU. Primarily its expertise lies more in the food and bio-based products however it extends towards the bioenergy sector as well. Italy's main source of bio-energy comes from solid fuels of organic origin and waste. The combustion of solid biomass from municipal solid waste covers half of the electricity production in the country with production figures of 18,272 GWh in 2021 (IEA, 2023). The sector pulls a turnover of €330 billion annually providing jobs to over 2 million people. However, the country aims to increase the turnover by 15% and enhance employment opportunities accordingly by 2030. The bio-economy strategy adopted in 2017 was another opportunity for the country to establish interconnection between the important pillars of the national bio-economy. The strategy aimed at promoting the production of renewable biological waste and its subsequent conversion to bioenergy, valuable food/feed, and bio-based products (Fava, et al., 2021). Other opportunities for the bio-economy sector of Italy include the EU Horizon 2020 program. The initiative funded a total of 198 projects to support bioenergy projects with a funding amount of 769 M€. Moreover, through the objectives of the Italian Recovery and Resilience Plan, the country aims to foster low-carbon technologies to attain a resilient electricity sector. For this purpose, the initiative aims to fund a sum of €2 billion for promoting projects that help in the production of biomethane by increasing the efficiency of existing biogas plants (Esposito & Romagnoli, 2023). Biogas in Italy remains the dominant source of producing electricity in the country which mainly comes from the process of anaerobic digestion. Moreover, Italy's

residential and commercial sectors are the leading consumers of pellets in the EU with consumption figures of 3.4 million tonnes (European Commission, 2022). The sector however can further strengthen its bio-economy through ensuring sustainability of its biomass production and supply chains through innovative technologies. Further socio-economic benefits and the development of bioenergy could be extended to the rural areas of Italy (Jain, et al., 2022). The growth of the sector in terms of electricity production is not quite satisfactory. For example, electricity from biomass grew from 6 TWh in 2008 to 19 TWh in 2014, however, since then the growth has rather been steady (IEA, 2021). The recent capacity of the bio-energy sector is 4.11 GW showing a steady growth rate of 1% from 2021 to 2035 (Global Data, 2022). Growth and opportunities can however be fostered through the provision of low capital costs and instruments, especially in terms of lower costs of available biomass. Moreover, apart from the heating and transport sector, the electricity sector also needs attention. The same goal could be achieved by utilizing forest wood to increase electricity and heat production from 4 and 86 to 11.5 and 116TWh respectively. Such an approach would also reduce GHG emissions in amounts of 8 million Mg of CO₂ per year (Moliner, et al., 2021).

Moving back to Figure 1.3, the energy experts placed hydropower in the first quadrant which again indicates decent opportunities and strengths for the particular alternative. Hydropower is one of the oldest sources of renewable energy in Italy, contributing the most to the renewable energy mix of the country. Hydro fulfills 36% of the total electricity generated from renewables (IEA, 2023). According to sources of Global data, the installed capacity of hydropower is expected to grow at a rate of 12% on account of total energy generation from 2022-2035. Large hydropower saw decent growth between 2010 to 2021 with a CAGR of 0.47%. However, the same is expected to grow at a CAGR of 0.13% during 2021-2035 (Global Data, 2023). The growth of the sector and its production output can be further facilitated with a few recommendations. The problem with the hydropower technology in Italy is its aging technology which is hindering the maximum exploitation of output from the source. However, if this machinery is technologically upgraded and properly maintained, it could increase the energy generated from the source by 10% each year. Such measures could increase the hydroelectric capacity by 5.8 GW which in turn would decrease carbon dioxide emissions by 2 million tons and create 2000 new jobs. The other reason for its steady nature in growth is the divergence of attention to other renewables such as solar and wind power (Enel, 2021). The mini-hydro facilities have however seen a decent growth in recent times because such projects are easy to procure and maintain. In Italy, 80% of the largest hydropower plants are installed on the northern side, whereas, the rest of them are evenly distributed in the center and south.

The installation of such small turbines, especially in the southern part, for example in Calabria, could be a game changer for the country (Algieri, et al., 2020).

Solar power in Figure 1.3 has been placed in the second quadrant which means the technology has the most opportunities for its development amongst all the energy alternatives. However, the technology also faces a few weaknesses. Italy has come a long way when it comes to producing electricity from solar power. In 2011, the electricity produced from solar power in Italy was 3.60%, however, this figure has increased to 8.64% in 2021 (Hive Power, 2021). Supporting policy measures such as those facilitated by the EU through its regulations of 2018/1999 go along in the same direction for Italy in attaining its energy and climate vision. Such policy measures can foster the development of solar power to grow by 50 TWh (IEA , 2021). The share of solar power in Italy is equal to 20% due to a sharp increase from 2011 to 2013, however, afterward, the output from the particular source has shown a rather slower increasing trend as opposed to wind power plants (Enel, 2021). To address this, the Italian government has come up with supporting legislation and policies that would increase the trend of solar power in the country. These policies include the enhancement of solar capacity by 3.37 GW in 2022 and the allocation of subsidies in electricity to photovoltaic systems having a capacity of over 20kW. Other subsidies include an allocation of 267 million euros to help small and medium enterprises promote solar system installations (Hive Power, 2021). According to the CEO of Solar Power Europe, the potential of solar power is very high but its full capacity cannot be reached unless administrative hurdles are overcome. These hurdles can be overcome by the removal of permitting restrictions in Italy and by making the whole process of photovoltaic installation simpler (Electricity Future, 2021). Italy through its Integrated Energy and Climate Plan has pledged to increase its renewable share by 55% till 2030 and increase its solar capacity to 52 GW from its current capacity of 22 GW. To achieve such a goal, the country needs to install 3 GW of solar power capacity each year as opposed to the current installation of 1 GW each year (Ford, 2021).

Wind power in Figure 1.3 has been placed in the second quadrant which indicates decent opportunities for its development in the country but rather faces a few weaknesses as well. The installation of wind power plants in Italy is at a rather slower pace as opposed to the rest of the EU countries. Despite the current pace, the country has already installed 5000 wind turbines. These wind turbines run at a unitary capacity of 20 and 200 kW. However, if advanced technology is adopted the capacity as well as the feasibility of these plants could be improved (Enel, 2021). This is possible if the country adopts newer technology that other EU countries like Germany have adopted along with establishing reforms that avoid long durations for

issuing permits. A considerable number of projects are waiting for approval from the public authorities for the installation of such projects. Due to these structural bottlenecks, an onshore wind farm can approximately take five years to its approved. The EU's Renewable Energy Directive however requires its member states to grant permits for such projects for not more than two years. Whereas, for repowering projects, it should not take more than one year (Reve, 22). Due to favorable conditions for the installation of wind power plants in the south of Italy, the country is now focusing on adopting mini-wind turbines to achieve its objective of green and economical energy. Such wind turbines under 60 MW are faster and easier to build and maintain (Yzquierdo & Sánchez-Bayón, 2020). Despite the favorable conditions for onshore wind farms in the south, there is reservation among the public over the installation of such turbines as they are affecting the landscape of the locality. Hence, this makes the social acceptance parameter very important when promoting such projects (Caporale & Lucia, 2015). These constraints are however being addressed by offshore wind power projects. The growing size and capacity of wind turbines are now paving the way for offshore wind turbines which have higher performance and cost savings. These floating offshore wind turbines have paved the way towards several benefits in terms of constant winds, fewer visual obstructions, and lesser acoustic noise requirements. Currently, the country has an offshore wind farm with a fixed-bottom platform along the port of Taranto in the south. Projects with floating-based platforms are however in the pipeline of developmental and permitting processes. Such projects tend to have high-capacity factors and Levelized Cost of Electricity (LCOE). Such opportunities have made wind turbines very favorable for ensuring energy security in the country (Barooni, et al., 2023). To make such projects feasible, the transmission system operator in Italy needs to overcome technical and operational challenges (Carlini, et al., 2022). Lastly, output from wind power in Italy can achieved through the repowering of existing wind turbines (Doukas, et al., 2022).

Geothermal in Figure 1.3 showcases both weaknesses and threats and therefore is not considered suitable to address the energy security concerns of Italy. Geothermal only delivers 2% of the energy consumption in Italy, making its share in the renewable market up to 4.8% (International Trade Administration, 2022). The level of output from the particular source lies between 5-6 TWh, which has remained fairly constant over the past decades (IEA, 2021). Despite Italy being the seventh largest producer of electricity from geothermal in the world, the contribution to the national energy mix is fairly marginal. Most of the geothermal plants in Italy are situated in the Tuscany region. Studies show that the technology is posing a threat in terms of environmental, health, and technical risks. Some of these risks include; skin,

respiratory, cardiovascular, and reproductive disease because of Arsenic exposure amongst the young male population of Tuscany (Profili, et al., 2018). Other weaknesses associated with the technology include; changes in the landscape, heat and soil pollution, challenges with waste disposal, noise pollution, and acid rains (Kabeyi, 2019). Hence, the low output in terms of electricity and the aforementioned threats and weaknesses do not make it a favorable energy alternative for Italy.

Coal power in Figure 1.3 has been placed in the third quadrant, making the technology more prone to threats however it has fewer weaknesses as compared to geothermal power. In Italy the share of electricity from coal has been fairly constant attributing to 15% of the total energy consumption by 2015, however, in recent times it had come down to 6% because of the enhanced energy production from renewables. However, the crises that have originated because of the Russian-Ukraine conflict have subjected Italy towards the refunctioning of its coal power plants. This is done to meet the short-term energy demands of the country because of the lack of natural gas supply. The rationale behind the functioning of coal power plants was also to store enough gas to meet the energy demands of the country in the winter season (Meredith, 2022). However, if Italy wants to eradicate the use of coal-fired stations by 2025 it should focus on enhancing the capacity of its renewable resources such as wind and solar which have considerable opportunities for its development in the country (Thimet & Mavromatidis, 2022). Lastly, natural gas in Figure 1.3 has been placed in the fourth quadrant showcasing some strengths but has severe threats to the energy security of the country. Around 43% of the energy demand in Italy is met through natural gas. Amongst other fossil fuels, natural gas is considered to be the most environmentally friendly alternative. The strengths of the fossil fuel extend towards its nature of being a consistent source of electricity with high-capacity factors and output efficiency. The threat to Italy with respect to natural gas is its dependency on its imports from Russia. To compensate for this, the country is looking to diversify its supply from other countries including Qatar, Algeria, Azerbaijan, the United States, and others. To meet short-term energy demands, the country had to shift towards the reignition of coal power plants to stock natural gas for the years 2022 and 2023. Having said that, the importance of natural gas and its existence in the energy mix cannot be neglected especially in the shorter run. In this case, the policies of the United States and Italy are aligned, both are in efforts to diversify their natural gas suppliers and at the same time reduce their reliance on natural gas by investing more in renewables. (International Trade Administration, 2022). However, when sourcing natural gas, it is important to procure the fossil fuel at affordable rates considering the current rise in its prices in order to ensure affordable electricity. The crises have however created an

opportunity for Italy to increase its import from North Africa by coming into an agreement with Algeria, where the volume of the gas would be enhanced from 21 bcm to 30 bcm by the end of 2023. Such an import via Tunisia has greater strategic importance for the country (Ghilès, 2022). Moreover, investments in regasification vessels will help the country acquire additional gas from far-flung areas apart from the existing pipelines. This as a result will help the country to store additional gas for uncertain times and situations. Having said that, the decline of the share of natural gas in the Italian energy mix is bound to decrease at significant levels by 2030. However, it is only possible if the country stays on track with its ambitious plans of enhancing the capacity of renewable energy sources consisting of solar and wind by 100 TWh until 2050 (Thimet & Mavromatidis, 2022).

Hence, it can be concluded that the four renewable energy technologies consisting of biomass, hydro, solar, and wind sources can be considered the most promising technologies in addressing the energy security concerns of Italy. Particularly, biomass and hydropower enjoy decent strengths and opportunities in the current energy scenario of Italy. Solar and wind power have the desired opportunities for substantial growth in the future however it comes with a few weaknesses that when addressed can address the energy security concerns of the country. Particularly, wind power has more opportunities as opposed to solar power, especially with offshore options and capabilities. However, it is pertinent to mention here that the importance of natural gas in the current energy mix cannot be neglected and will be a part of the Italian energy mix for the foreseeable future. Despite the strengths of natural gas, the percentage of its contribution to the Italian energy mix needs to be reduced by focusing more on the aforementioned renewable energy alternatives. The COVID-19 pandemic has though affected the pace of the ongoing projects in the country but on the other hand, the goals set by the Italian government are quite clear and ambitious, and if the legislative hurdles are removed the country will be able to meet its energy demands more effectively. All of these developments have also paved the way towards collaborative dynamics between other EU countries in working towards energy security in a broader context. According to an estimate, the target of 30% energy efficiency by the EU till 2030 has the potential to reduce 12% import of fossil fuels bringing savings of €70 billion. It will also bring along other macroeconomic benefits in terms of GDP growth and the creation of 400,000 new jobs (Malinauskaite, et al., 2019). The concept of cogeneration of electricity is another avenue where renewable energy technologies are used in hybridity to achieve both thermal and electricity demands. The role of energy-efficient conversion technologies in this case can be beneficial in integrating the heating, transportation, and power sectors in general which as a result would minimize environmental degradation and

minimize the cost of electricity (Borasio & Moret, 2022). The co-generation concept can be further extended towards the extraction of energy from hybrid forms of renewable energy resources working in a synergetic dynamic (Monforti, et al., 2014). Lastly, the energy crises that have emerged due to the recent conflict in the case of Italy should be taken as an opportunity to enhance the resilience or anti-fragility of its power sector. The concept of anti-fragility has been developed by Nassim Taleb which indicates that when a system is subjected to a certain crisis, it helps the policy makers to observe the shortcomings in the system. When these shortcomings are addressed and mitigated the system as a result becomes more anti-fragile, making it fighting fit towards future crises or disasters (Khan, et al., 2022).

1.7 Conclusion and policy implications

The energy crises that emerged in the wake of the Russian-Ukraine war have subjected countries like Italy to redefine their energy mix. Italy's goal of achieving energy security is currently led by diversifying its sources of natural gas from countries other than Russia. Initiatives taken by the EU such as the REPowerEU and integrated national and action plan of Italy require achieving the same goal through deploying renewable energy system and a decarbonization of the sector. A sustainable and resilient energy sector would in essence require redefining the existing energy mix based on the metrics of socio-political, economic, environmental, and technical aspects. To address this concern, the study carefully analyzes the current energy scenario of Italy which is subsequently followed by determining a sustainable energy mix for the country in order to make it more energy-autonomous. The research in this regard corresponds to both primary and secondary datasets and employs the strategic decision-making tool known as the F-SWOT approach to address the aforementioned goal. The approach is capable of handling both qualitative and quantitative sets of data, unlike other qualitative SWOT approaches. Secondary data sets in this regard are referred to determine the internal and external factors for evaluating the seven energy alternatives in the country. Internal factors are those that consist of strengths and weaknesses and are considered to be controllable, whereas, external factors consist of opportunities and threats and are considered to be uncontrollable. The factors are further classified into cost and benefit criteria to aid in a more rational decision-making process. The evaluation of such factors and energy alternatives is aided by experts from the energy sector of Italy.

The first phase of the analysis prioritizes and allocates significance to the internal and external factors. Amongst the list of internal factors, the experts allocated the most weightage to the

"access to grid" criteria having a normalized weightage of 0.2339. As for the external factors, the decision-makers allocated the most significance to the "delivered cost of electricity" and "capital investment" criteria with a weightage of 0.1292. Moving to the SWOT matrix, based on the sustainability factors, the experts placed biopower in the first quadrant coming in with the most strengths as opposed to other alternatives. Biopower is considered to be the only source of renewable which can cater to the energy demands of electricity, heating, and the transport sector. Italy plans to exorcise further advantages from the source by incentivizing the upgradation of existing biogas plants to produce biomethane. Such a source can be a sustainable alternative to natural gas in meeting the energy demands of Italy. Moreover, forest wood is considered as a great source of improving the electricity and heating demands of the country. It is suggested that the socio-economic benefits of such projects should also be extended to rural areas. Moreover, the cost of biomass should be made available at affordable rates to further foster the development of the sector. Hydropower has also been placed in the first quadrant with decent strengths and opportunities for its development in the country. The renewable source however can be further made favorable through technological upgradation and maintenance of its current machinery. Moreover, mini-hydro projects should be facilitated in the country because of their feasible nature in terms of capital investment and maintenance activities.

Thirdly, solar power has been placed in the second quadrant making it an alternative with the most opportunities for its development in the country. The weaknesses in the case of solar power are fairly marginal. To achieve maximum output from the source, it is suggested that the permitting procedures for such projects need to be simplified. Wind power in the SWOT matrix has also been placed in the second quadrant hence showcasing great opportunities with a few weaknesses. Wind power is considered to be the most favorable renewable at the current time, especially with the installation of offshore wind power plants. Installation of mini-wind turbines in the south of Italy can further bring along socio-economic and technical benefits. To extract further benefits, legislative hurdles in terms of long permitting procedures need to be curtailed. Moreover, the public's engagement in the development of such projects needs to be ensured. Lastly, the repowering of existing wind turbines should be made on a priority basis to further enhance the output from the source.

Geothermal in Figure 1.3 is placed in the third quadrant coming in with the most weaknesses and threats. Geothermal contributes the least to the energy mix of Italy. Also, the public does not approve of such projects due to related emissions, hazards of contaminating and depletion of water, and induced seismic activities. Such weaknesses do not make the alternative a

favorable fit for meeting the energy demands of Italy's sustainability. Moving away from geothermal, coal power has been placed in the same quadrant showing more threats but rather few weaknesses as opposed to geothermal power. Before the Russian-Ukraine conflict, the use of coal had gradually decreased over the years. However, to meet the short-term energy demands of the country, the functioning of coal power plants remained to be the only rational option. It is however suggested that if the country wants to reduce its reliance on coal by 2025 the country has to foster the development of renewable energy alternatives. Lastly, natural gas has been placed in the fourth quadrant signifying threats to the energy security of Italy however coming in with a few strengths as well. Since most of the energy demand in Italy is met by natural gas, therefore, its importance in the current energy scenario of the country cannot be neglected. The strength of natural gas is its ability to provide an uninterrupted supply of energy with high-capacity factor values. Through initiatives such as the REPowerEU program, it is suggested that such countries diversify their sources of natural gas. In this case, Italy is shifting its source of natural gas from Russia to Northern African countries to meet its energy demands. Italy's strategic location gives it an advantage to procure gas at affordable prices.

To facilitate the growth of renewables in Italy it is pertinent to address the legislative and permitting procedures which are found to be known problems of Italy. Local acceptance of deploying such technologies also needs to be ensured. Incentivization and educating the public are known to be effective instruments in such cases. The other problem in the energy sector of Italy is the lack of coordination amongst multi-state levels concerning energy-related issues. Such a phenomenon has been seen during the shift of power with respect to energy governance from the center to the periphery and vice versa. The decentralization and re-centralization of such a power shift have had a paradoxical effect on the energy sector of Italy. Issues with such a phenomenon have had a rather negative impact on the siting and deployment of renewable energy projects. The recent developments in terms of achieving a 55% target of renewables by 2030 and the update in support schemes have rather been problematic, especially for larger wind and solar farm installations. The primary obstacle again is the nature of complex and lengthy authorization procedures (Nucci & Prontera , 2023).

The results achieved from the SWOT matrix are very interesting because the findings are in line with the secondary data hence making the resultant devised policies more credible for policy implementation. Despite the type of data employed and the methodological strengths of the study, a few limitations however can be addressed by future studies on such a subject. The list of internal and external factors gathered from secondary sources can be updated with more relevant and recent sustainability criteria. Future studies could also involve experts from

government bodies in the decision-making process. In terms of methodology, the F-SWOT approach can be used in a hybrid combination with other multi-criteria decision analysis or optimization tools. Instead of relying on standard fuzzy sets, extended versions of fuzzy sets such as type 2 or neutrosophic fuzzy sets could be employed. Moreover, future studies can also focus on the feasibility of wind and solar power plant installation in Italy by employing techno-economic assessments, geographic information systems, or HomerPro software. In addition to this, a feasibility study related to the diversification of natural gas supply and storage facilities in the context of Italy can also be taken into consideration. Subjects such as energy poverty could be an interesting topic in the case of Italy especially when the prices of electricity are all-time high.

Chapter 2. A comprehensive spatial decision support system for future floating offshore wind farm development in Italy

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2.1 Introduction

Being the third largest economy in the EU, Italy has also embarked on the journey of decarbonizing its energy sector along with making it more energy secure. Through measures such as fit-for-55, the country aims to reduce its greenhouse gas emissions by 55% till 2030 and become almost carbon neutral by 2050 (European Council, 2024). To achieve such a goal, the transmission system operator of Italy (Terna) in this regard has geared itself to promote investments in grid infrastructure, renewable energy integration, latest storage and digital technologies. To prevent any sort of delays, it is important to overcome any sort of technical, economic, and administrative hurdles if the country has to achieve the target of 75% renewable energy integration by 2030. The same plan which has been developed by the Plan for Developing Renewable Energies (PNIEC) aims to meet Italy's goal of 55% of power consumption through renewable energy resources which currently stands at 39% (NS Energy, 2023). Such tremendous sustainable energy goals have to be backed by renewable energy sources that have the potential to meet such targets. In this case, wind power especially offshore wind farm has the potential as well as the technological feat to meet the energy targets of Italy. The Italian waters are deemed to be fairly suitable to accommodate such projects far off the shore with floating-based foundations. The potential and interest corresponding to such projects can be gauged by the number of requests received for such projects from the South of Italy. Water off the coast of Sardinia and Sicily are on the top of the list with respect to such projects (Terna, 2023). With a capacity of 30 MW, Italy as of now has only one standing offshore wind farm, however, with a fixed-based monopile foundation off the port of Taranto. The project took off in 2008 and after lengthy administrative hurdles, the project started its operation in 2022. Since this was the first project of its kind it opened doors for other such projects in the country. According to the National Wind Energy Association (ANEV), Italy has the potential to deploy approximately 5.5 GW off offshore wind projects by 2030. Sardinia and Sicily are amongst the most suitable sites where the average wind speeds reach up to 8.05 m/s. Wind developers in Italy, have set a range of 50 km off-coast for the deployment of floating

offshore wind farms due to better bathymetry and decent capacity factors ranging between 25-45% (Serri, et al., 2020).

Offshore wind farms come with two types of foundations i.e., fixed and floating-based technologies. Amongst fixed foundations, monopile technology is considered to be the most mature and economical and is deployed in water depths of 50 m. Other fixed foundations include jackets, gravity bases, tripods, and suction buckets each having its own characteristics. Floating-based foundations come in when water depths exceed 50 m. The semi-submersible floater is amongst such foundations that are deployed at a water depth greater than 40 m. The multiple columns in such foundation type provide additional support and buoyancy. Moreover, the spar floater foundation is deployed in water depths greater than 100 m. The spar technology is considered to be more stable but the installation phase is considered to be the most challenging one. Next comes the tension-leg platform which has the same columns and pontoons as that of a semi-submersible but is considered to be more stable, however, the installation phase is rather challenging and expensive.

Offshore wind turbines are considered to be more sustainable as opposed to onshore wind turbines. Despite several advantages of offshore wind turbines, site selection is the most complex and challenging phase in the entire project life cycle for such projects. Various environmental, technical, economic, and social factors play an important role in determining the most feasible site for such projects. In Europe, Marine Spatial Planning has been regarded as the most important step towards the feasibility of such projects. This is because an inadequate site selection can contribute to a disturbance in the ecosystem, conflict among stakeholders, and reduction of economic and technical feasibility. Hence exhaustive metocean knowledge and local regulations need to be considered for such projects to be feasible. Such challenges need to be avoided through proper planning in order for such projects to be granted their necessary permits. This is especially important in the case of Italy which is known for its complex and lengthy regulatory and permitting procedures. The Geographic Information System (GIS) in this regard is considered to be an important tool in handling such data and projects. In this case, European Maritime Spatial Planning Platforms coupled with the local regulations are an important source of guidelines for performing such site suitability assessments. To avoid any sort of conflict amongst the stakeholders in such complex decision-making processes, the integration of Multi-Criteria Decision-Making (MCDM) approaches is also known to be an effective tool in gauging the spatial decision criteria. The steps involved in performing such analysis include; identification of the problem, specifying the evaluation or exclusion/risk criteria, data collection of the spatial layers of the determined criteria, assigning

weights to the criteria through utilizing MCDM tools and finally applying the weighted linear combination approach to yield the final suitability map (Al-Anbar, et al., 2018).

The area of interest in this case i.e., the Strait of Sicily works as a connection between eastern and western Mediterranean basins with a width and length of 150 and 600 km respectively. The deepest part is a central region with a width of 50-100 km and a depth of 700-900 m with the deepest trenches reaching a depth of 1800 m (Astrald, et al., 2001). The geo-strategic importance of Sicily makes it an electricity hub in the Mediterranean region making it the interconnector between North Africa and central Europe (also Northern Italy). Region wise, Sicily has the third most consumption of electricity in the country. Most of the pollution comes from the energy and transport sector which are still largely dependent on fossil fuels. To address such concerns, Sicily aims to decarbonize its energy sector and make it more energy secure by increasing levels of renewable energy integration to 70% by 2030. In the best-case scenario, the strait of Sicily is expected to contribute 6-7 GW of capacity by the year 2030 (Hexicon, 2022). Consequently, most of the developers are focusing on the strait of Sicily for their future floating offshore wind parks. The most promising project in this case is the Med Wind Offshore Wind Park developed by Renexia SpA, a subsidiary of Toto Group. Subject to the completion of the permitting phase by 2025 and its subsequent construction, the project is expected to commence its operational phase by 2030. The project comes with a 2.8 GW capacity, producing an annual electricity of 9 TWh along with the provision of several jobs and reduction of carbon dioxide emissions.

The deep waters along the Sicilian coast are considered to be favorable for floating foundation-based wind farms. However, feasibility studies for such projects are missing for the particular region which might hinder the pace such projects in the future. The EU and Italy have strict guidelines when performing marine spatial analysis for such projects. Hence to address such concerns, the regulations developed by Italy for such projects have been taken into consideration for performing marine spatial assessment for this project. Since this is the first project that proposes such a decision support system for performing such analysis, the study goes one step forward and includes the technical regulations developed by the European marine spatial platform. The reason for this is that Italy has also recently joined the same platform for developing their future floating offshore wind platforms. The other reason is that the guidelines provided by the Italian Association for Wind Energy (ANEV) are limited hence unable to provide a more practical and comprehensive spatial decision support framework. Such decision criteria are based on the metrics of environmental, economic, social, and technical perspectives, the importance of which is discussed in more detail in the subsequent sections.

Steps involved in the formulation of the decision support framework include the determination of the sustainability spatial criteria for performing the marine spatial analysis. This is done through a rigorous and extensive review of literature and relevant reports. The same resulted in the determination of the inclusion and exclusion criteria which will help in the evaluation of the most suitable zones in the Sicilian strait for floating-based offshore wind farms. The collected criteria in the form of geographical layers are subsequently processed and prepped in the ArcGIS software. The novel non-linear optimization-based decision analysis approach known as the Fuzzy Full Consistency Method (F-FUCOM) is introduced to evaluate and gauge the importance of the inclusion or evaluation criteria. Finally, the geographical layers are subjected to the weighted overlay analysis for the determination of the final suitability map through the ArcGIS software to obtain optimal sites for the construction of floating offshore wind farms along the Sicilian strait. Interestingly, such type of study is not covered by the literature which makes it novel and interesting for both academicians and government bodies in terms of future offshore wind park development and making the energy targets of 2030 attainable for Italy. The novelty of the study lies both in the methodology, the determination of spatial criteria and the context to which is applied. A detailed summary of the novelties covered by this study is covered through table 3.1 in the literature review section as well.

2.2 Literature review

Offshore site selection or finding suitability maps can be an intricate problem that requires rational decision-making tools. The GIS tool in this case is regarded in the literature as a standard means of dealing with such problems. Problems such as offshore wind site selection can be dealt with through inclusion and exclusion criteria which as a result would enhance the sustainability and minimize the shortcomings in the process (Yap, et al., 2019). Due to the inherent nature of such problems, the results are further strengthened through the application of MCDM tools. Such approaches can be very useful in dealing with conflicting criteria consequently dealing with both qualitative and quantitative sets of data (Shao, et al., 2024). The aforementioned tools have been employed lately in several renewable energy site selection problems. To further deal with complexity and ambiguity during the data collection process the use of fuzzy membership function has been employed by certain studies. The criteria selection in most cases is adopted through a literature review and consultation with the experts. The greatest frequency of studies for renewable energy site selection is based in China. In terms of MCDM approaches the most frequently used approach is the Analytical Hierarchy Process

approach (AHP). Until 2020, the greatest number of studies regarding wind energy have been performed for onshore wind park site selection (Shao, et al., 2020). Recent trends however focus more on on-site selection for floating foundations especially in the context of Europe where such type of technology is mostly adopted to curb environmental degradation and enhance energy security and autonomy. The studies in the European context showcase a linkage between academia and industry. Every country has its own set of regulations and constraints for developing offshore wind parks, however, most such studies in the European context do not keep that into consideration. Hence, the findings in such cases lose credibility (Peters, et al., 2020).

The role of inclusion and exclusion criteria for the GIS layer play an important role in determining the Levelized Cost of Electricity (LCOE) of a project. The LCOE is an important metric that portrays the viability of a project. For validation purposes, an investigation was carried out in the case of the Mediterranean Sea where areas with the most wind potential had the lowest LCOE values. The Strait of Sicily in this regard showcased moderate LCOE (Martinez & Iglesias, 2021). Amongst water depth and distance to shore constraints, it was found that distance to shore had more impact on the final values of LCOE in the case of Atlantic European waters (Martinez & Iglesias, 2022). The criteria for site suitability for floating offshore wind parks in Italy have been outlined in the yearly report by the Italian Association for Wind Energy (ANEV, 2021). The same set of criteria that falls under the category of technical, spatial, economic, environmental, and social metrics have also been outlined in the context of other European countries. Some of the most important and repeated decision criteria include wind speed, water depth, sediment thickness, airports, distance to the power grid, ports, shoreline, and tourism spots; on the contrary, distance to cables, shipping routes, protected areas, migratory bird routes, blue flag beaches, and exclusive economic zones are included as exclusion or buffer zones (Taoufik & Fekri, 2021).

Problems on site suitability analysis are usually addressed through the weighted overlay approach. The GIS tool is adopted for carrying out such analysis. The advantage of the methodology is its ability to deal with various conflicting spatial input criteria and transform them into a suitability map based on the importance of each criterion derived through MCDM tools (Tercan, et al., 2020). The majority of the studies in offshore site selection employ the AHP approach for allocating weights to the spatial layers neglecting the application of fuzzy set theory to capture the levels of ambiguity during the decision-making process (Sánchez-Lozano, et al., 2022). The technique proposed in this study is based on a non-linear multi-criteria optimization technique that is considered to be more reliable and robust as opposed to

conventional AHP and BWM approaches. The validity of the model has been confirmed by comparing it with other MCDM approaches such as fuzzy BWM and fuzzy AHP (Feizi, et al., 2021). The advantage of the proposed approach corresponds to being hassle-free due to the generation of lesser pairwise comparison of criteria along with the provision of more reliable and consistent results (Khan & Ali, 2022).

The integrated GIS-based FUCOM approach has been employed for suitable site selection for a maize cultivation farm in the north-west of Turkey (Everest, et al., 2022). The same combination of approaches has been further utilized for site selection of textile manufacturing in Turkey (Ulutas & Karakus, 2021). Moreover, suitable site selection for a biogas facility employs the same methodological approach (Tulun, et al., 2023). To determine the impact of land subsidence on transmission lines the FUCOM approach is employed to determine the weightage of causative factors. Whereas, the GIS is employed to perform overlay analysis for the final land subsidence susceptibility maps (Sadegh, et al., 2023). The selection of a solar power plant site selection in Pakistan employs the FUCOM approach for allocating significance to the decision criteria. Whereas, the weighted overlay function in the GIS is used to determine the final suitability map (Khan, et al., 2023). In the case of floating offshore wind farm site selection, only one study uses the fuzzy FUCOM approach along with another MCDM approach. However, the study only focuses on the selection problem amongst a list of four pre-determined locations in Norway (Deveci, et al., 2022). A summarization of the literature in the context of this topic can be covered by Table 2.1 that will present the novelty of each study both in the context of the methodology, spatial criteria and the geographical region to which it is applied.

Region	Methodology	Spatial criteria	Source
Gulf of Maine (USA)	AHP and GIS tool	Wind speed, Bathymetry, Wave height, Water quality, Point of Common Coupling (PCC) distance (km), Ground distance, Distance to ports, CAPEX, OPEX, DECEX	(Gil-García, et al., 2022)
Morocco	Fuzzy AHP and GIS	Wind speed, water depth, power grid, ports, shoreline, tourism, airports, sediment thickness, submarine telecommunication cables, shipping routes, protected areas, exclusive economic zone, blue flag beaches, migratory bird routes	(Taoufik & Fekri, 2021)

Great Britain	AHP and GIS	wind energy density, wind speed, water depth and distance from shoreline	(Li , et al., 2022)
France	AHP and GIS	Elevation, slope, wind speed, protected areas, roads and substations	(Ifkirne, et al., 2022)
South Aegean—Greece	AHP and GIS	Wind velocity, population served, shipping density, distance from protected area	(Vagiona & Kamilakis, 2018)
Both sides of Aegean sea- Greece	Fuzzy AHP and GIS	Wind velocity, water depth, distance from shorelines, distance from shipping routes, Distance from environmental protection and military zones, distance from ports, distance from fishing areas, airports and subcables	(Tercan, et al., 2020)
Island of Crete- Greece	AHP and GIS	Submerged Cables, Areas of Environmental Interest, Shipping/Air Routes, National Grid, Military areas, Shoreline, Fishing Areas, Existing Roads, Heritage Sites, Cities and Settlements, Mining Areas and Activities and also Wind resources, Water Depth, Seabed substrate, Noise Level, and Optical Disturbance	(Gkeka-Serpetsidaki & Tsoutsos, 2021)
North Aegean Sea and Marmara Sea (Turkey)	Fuzzy BWM and GIS	Wind speed, water depth, pipe and cable line, Capacity factor distribution, Submarine geo-morphology, Tourism density and beach sites, cost, sea traffic, sea sunken areas, bird migration routes, visual impact, seismicity, distance to power lines, distance to ports, distance to coast lines, distance to islands, distance to airports.	(Konurhan, et al., 2023)

Table 2.1. Summarization of the literature to find literature gap

To understand and highlight the novelties of this study, it is pertinent to present an explanation of Table 2.1. Methodological wise, most of the study focuses on employing the AHP methodology to prioritize the spatial decision criteria. Few of the studies employs the fuzzy set theory. Geographically most of the studies are based on the European context and this makes sense as the particular technology is the most popular and widespread in this region. The determination of spatial criteria in most of the studies is not consistent. Some missing the most important evaluation and exclusion criteria. It is important to point out that only those studies are covered in Table 2.1 that using the MCDM approach for the sake of prioritizing the decision criteria. Most studies that are not mentioned in Table 2.1 in similar context were because of

nature of the usage of MCDM for ranking pre-determined locations which is not the aim of this study. In fact, the aim of this study was to minimize subjectivity and employ data and spatial criteria based on regulation of Italy and best practices adopted by the EU through their marine spatial planning platform. This could also be the reason for other studies to have such variations in their spatial criteria selection. Interestingly, none of the studies considers existing “offshore oil and gas rigs’ as their exclusion criteria which this study covers. Moreover, none of the studies in the literature addresses a policy and decision support framework for promoting and installation floating offshore wind farm in the case of Italy which makes it pertinent to cover such geographical location making it the most important novelty of this study. The importance of Italy as the study area is also important as it is currently shifting towards the new technology making such decision framework not only for Sicily but other potential regions such as Sardinia and Puglia. Hence, such a study will act as a benchmark for other studies to follow for the same region. Moreover, the employment of the fuzzy FUCOM approach for the prioritization of the decision criteria is another novelty of this study as none of the study in the literature applies the same approach in such a context. The superiority of Fuzzy FUCOM over AHP and BWM is covered in detail in the methodological section and even more by the developers of such methodology (Ecer & Pamucar, 2020). To sum it up, the novelties of this study extend towards the context to which it’s applied, the selection of spatial criteria and the methodology employed.

For price competitiveness and desired values of LCOE for offshore wind development along the Sicilian coast, it is pertinent to consider all the relevant criteria for optimal site selection. At present, there is not a single project deployed in the deep waters of the Western Sicilian coast. Most of such projects are in the pipeline however they have to go through a lengthy permitting procedure. Most of the time such projects are invested in planning and feasibility analysis. The desired levels of offshore capacity for Sicily cannot be achieved unless such hurdles are removed. It is important for such feasibility studies to consider the local legislation for the development of such plans which in certain cases is neglected. To achieve the aforementioned goal, based on the dynamics of Italy, this study proposes site suitability analysis for the development of an offshore wind park along the coast of Sicily. For this purpose, the study would help identify all the relevant criteria constraints based on the regulations of Italy. The decision and exclusion criteria would in turn be utilized in the ArcGIS software to perform the weighted overlay technique. The employment of fuzzy FUCOM would come in allocating weights to the list of evaluation spatial criteria for the final suitability map.

2.3 Data collection

2.3.1 *Area of interest*

Sicily is the fifth most populated region enjoying an autonomous status. The covered area along with dependent regions accumulates to be 27,708 Km² which makes it the biggest amongst all the regions in the country. The coastline from north to south if considered a straight line corresponds to 280 km long. Whereas, the eastern coast measures to be 180 km long. The area of interest i.e., the Strait of Sicily is 145 km wide which divides the Tyrrhenian and the western Mediterranean Sea from the eastern Mediterranean Sea. The Sicilian Strait lies between Tunisia to the east and Sicily and Malta bank to the northern side. The strait acts as a connection between the eastern and western Mediterranean Sea with a total length of 600 km. The strait has two different channels between Sicily and Tunisia with more depth alongside Sicily corresponding to 430 m of depth (Astraldi, et al., 1999). The Sicilian waters have been backed by several studies in the literature to have decent wind potential and are more viable for the development of floating-based wind farms. The Sicilian coast has received special attention from wind developers for their future offshore projects in the region. According to sources such as “4C offshore”, as many as 20 such projects are in the planning and developmental phases expected to be deployed in the Sicilian Strait (4C Offshore , 2023).

Due to the better conditions for floating offshore wind farms, all the expected projects are to be deployed along the western coast of Sicily (Sicilian Strait). Hence, the area of interest in this study would take the Sicilian Strait into account for determining the most optimal sites for floating offshore wind farm development. The area of interest determined for this study considers a range of 50 km from the Sicilian coast. The scope of the study area has been kept inside the boundaries of the exclusive economic zones set between Italy and Tunisia. The 50 km range is considered because such distances in the marine waters of Italy come with decent wind resources and water depths of up to 1000 m. Hence, the present-day developers of such projects in Italy have set a limit of 50 km from the coast. The limit reaching to 200 km in other such cases corresponds to the Northern European countries (Serri, et al., 2020). The area of interest considered for this study is illustrated in Figure 2.1 below.

AREA OF INTEREST

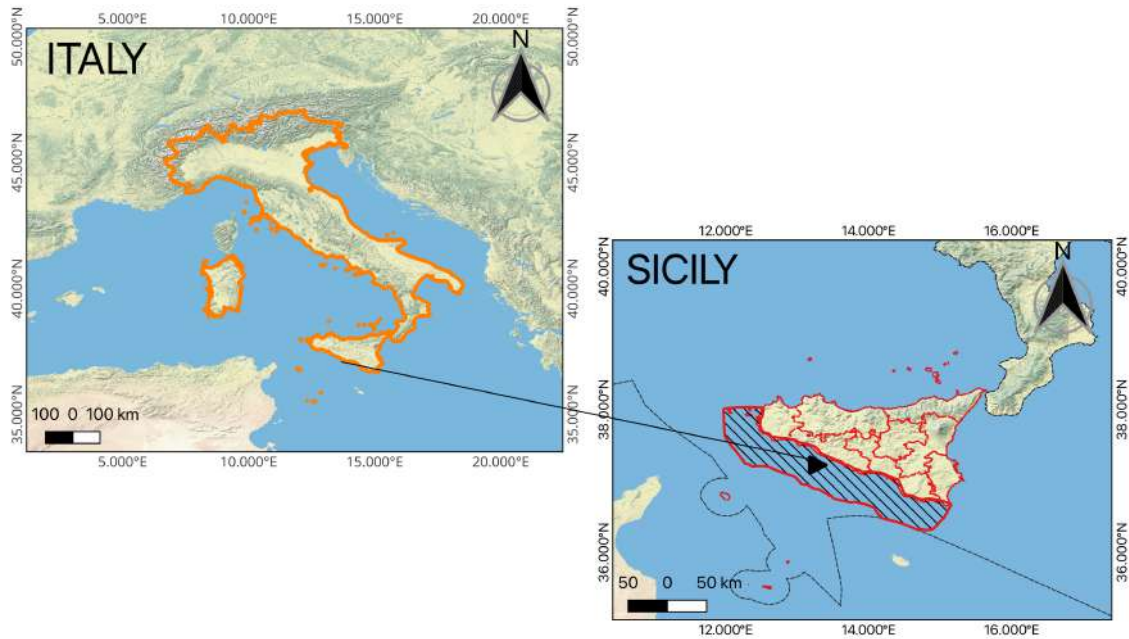


Figure 2.3. Area of interest

2.3.2 Determination of suitability criteria

The determination of evaluation and exclusion criteria for marine spatial assessment in the case of such projects is a rather challenging task. This is because all the relevant stakeholders have to take on board which can be ensured through respecting the guidelines and regulations of the region in question. The concept of floating foundation-based offshore wind energy is still novel in Italy. The guidelines provided by such authorities as the ANEV in Italy are not elaborate enough to be relied on for conducting such an intricate analysis. Hence, along with considering Italian guidelines, the regulations and best practices in the EU were also taken into consideration. The additional review of the literature helped identify additional constraints and also aided in the determination of important buffer zones along with the reclassification scale. Keeping the anemological potential of different sites in Italy, the ANEV at a minimum speed of 6.5 m/s and 70 m height has outlined constraints that need to be met for such projects (ANEV, 2021). These constraints include; the protection of natura 2000 sites, environmental landscapes and archeological sites, important shipping lanes, military easements, airports, maintaining a distance of at least 4 km from the coastline, depth of the water, and the type of

seabed and its topography, and distance to power grids. Hence, keeping the Italian context into consideration the list of evaluation and exclusion criteria presented in Table 2.2 is proposed.

Sustainability metrics	Spatial criteria	Data format	Source
Technical	Wind speed (evaluation criteria)	Raster	(Global Wind Atlas, 2023; AEOLIAN, 2023)
	Water depth (evaluation criteria)	Raster	(European Commission, 2023; (GEBCO, 2023; Global Wind Atlas, 2023)
	Sediment Thickness (evaluation criteria)	Raster	(Straume, et al., 2019)
	Airports (evaluation criteria)	Shapefile	(Open Street Map, 2023; ZES Sicilia Orientale, 2023)
	Vessel density (exclusion criteria)	Raster	(EMODnet Map Viewer, 2023)
	Oil and gas installations (exclusion criteria)	Shapefile	(EMODnet Map Viewer, 2023)
	Submarine telecommunication cables (exclusion criteria)	Shapefile	(EMODnet Map Viewer, 2023)
	Exclusive Economic Zone (exclusion criteria)	Shapefile	(Emodnet Map Viewer, 2023)
Socio-economic	Ports (evaluation criteria)	Shapefile	(EMODnet Map Viewer, 2023)
	Shoreline (evaluation criteria)	Shapefile	(Wessel & Smith, 1996)
	Distance from the power grid (evaluation criteria)	Shapefile	(Terna, 2023; Entsoe, 2023)
	Tourism density (evaluation criteria)	Shapefile	(Open Street Map, 2023; Sicilian Region, 2023)
	Blue flag beaches (exclusion criteria)	Shapefile	(Blue Flag , 2023)
Environmental	Protected areas (Natura 2000 sites) (exclusion criteria)	Shapefile	(European Environmental Agency, 2020; ArcGIS online, 2023; United Nations, 2023),
	Migratory bird routes (exclusion criteria)	Shapefile	(Bird Life International, 2023), (Movebank, 2023; Kays, et al., 2022; Spanoghe, et al., 2023; Brønnvik, et al., 2022)

Table 2.2. Determination of evaluation and exclusion criteria

In Table 2.2, certain criteria are additional which are not indicated by the ANEV but hold considerable importance when performing marine spatial assessments for such sort of projects. Some of these additional criteria include offshore oil and gas installations, blue flag beaches, and migratory bird routes. Moreover, other important details such as the criteria for important shipping lanes do not specify which type of fishing vessels need to be protected. For such and other details the literature was thoroughly studied to verify and come up with such additional details based on Italian context. The characteristics and a brief explanation of the criteria given in Table 2.2 are given below.

2.3.3 *Wind speed (m/s)*

Wind speed measured in m/s is considered to be an important evaluation parameter because it determines the output potential and the delivered cost of electricity to the consumers. The mean annual wind speed in this case is recorded at a height of 100 m. The height of 100 m was taken into consideration because according to latest developments the cumulative average hub height amounts to 88.60 m (Bilgili, et al., 2023). It is important to understand that with technological advancement there is a trend of increased height of the hubs each year.

2.3.4 *Water depth (m)*

Bathymetric data is like topographic maps that use lines to depict the elevation and shape of land features. Such type of data determines the type of floating foundation needed to be deployed. Floating foundations are deployed at water depths between 50-1000 m.

2.3.5 *Sediment thickness (m)*

Seafloor topography measured in meters has a pivotal role to play especially during the design, construction, and operation processes. Dredging, creation of foundation pits, installation of underwater cables, etc., are some of the major processes. Scouring or sediment transport is something that happens during operational phases. The seafloor of the Sicilian strait is flat for the most part except for some shallow banks. The middle part of the strait has the deepest pits reaching to a depth of 1650 m.

2.3.6 *Distance from airports*

The proximity of wind farms to the nearby airports can cause visual distraction and collision risk. It can also interfere with the radar system affecting the navigational aids and disrupting the air traffic monitoring. Italy does not have standards set, however, the civil aviation authority

in the European context recommends a minimum distance of 3 km from the airports (Gigović, et al., 2017).

2.3.7 Vessel density

Major shipping lanes need to be respected to avoid any sort of collision and conflict. Such shipping lanes need to be put in a restriction zone when performing site suitability assessment. Important shipping lanes in Italy include fishing, passenger, cargo, tanker, and military and law enforcement vessels all of which are gathered from the European Marine Observation and Data Network (EMODnet) in this case. The United Nations Convention on the Law of Sea (UNCLOS) in which the EU is also a part proposes a safe distance of 500 m from such shipping lanes.

2.3.8 Offshore oil and gas rigs

Active offshore oil and gas infrastructure are authorized to engage in activities such as exploring, drilling, producing, processing, and or storing hydrocarbons and other fluids. According to EU standards such infrastructure needs to be put in exclusionary zones when performing marine spatial analysis. The buffer distance from such infrastructure is not covered by the Italian regulations or the EU guidelines. However, a joint report by the Strategic Environmental Assessment North Seas Energy (SEANSE) and the European Maritime and Fisheries Fund proposes that such sites be kept in exclusion zones when performing marine spatial assessment (SEANSE, 2020).

2.3.9 Distance from submarine cables

Subsea cables predominantly telecommunication cables need to be protected from any sort of damage during the construction and operational phases. According to the European maritime spatial platform, it is recommended by the International Cable Protection Committee (ICPC) to maintain a buffer zone of 500m from such cables. The same guidelines have also been proposed in a report presented by the Netherlands through the Ministry of Infrastructure and Environment (The Ministry of Infrastructure and the Environment, 2014).

2.3.10 Exclusive Economic Zone (EEZ)

The legal territorial waters of any country help them to exploit their rights of conserving and managing fisheries along with the generation of renewable energy. The area of interest for marine spatial assessment should be inside such boundaries.

2.3.11 Distance to ports

Distance from the ports has a direct impact on the costs of installation, operation, and maintenance activities and finally the decommissioning costs. Most of the European turbines are installed close to the ports to reduce the total investment costs.

2.3.12 Distance from shoreline

Maintaining a certain distance from the coast is attributed to several factors which depend upon the coastal waters of the corresponding regions. In Italy, the extant set by the developers for the deployment of floating offshore wind turbines is 50 km (Serri, et al., 2020). An optimum distance from the coast is important because it impacts the costs of installation, CAPEX, OPEX, and export cables. For Sicily, a distance of 50 km from the coast corresponds to a maximum water depth of around 970 m and an average wind speed of around 8 m/s. In essence, the wind farms should be near the ports and power grids. On the flip side, the wind farms should be a safe distance from the coast when it comes to tourist zones to avoid visual impact.

2.3.13 Distance from power grids

Distance to the electric grid is considered to be the most important factor in determining the LCOE of an offshore wind farm as it impacts the cost of energy production and the cost incurred on the export cable (Martinez & Iglesias, 2022). Distance from the grid determines the transmission efficiency, installation cost, permitting procedures, energy supply reliability, and maintenance costs. Power from the offshore facility to the onshore facility is transmitted through two alternatives i.e., through HVAC or HVDC lines. The choice of transmission is made depending on the distance from the onshore power grid. For shorter distances, the HVAC transmission system is adopted. However, for longer distances to avoid transmission losses the HVDC system is adopted. Both transmission lines have their voltage requirements and thresholds to carry voltage from offshore to onshore platforms. Modern wind turbines produce voltage up to 66 kV which are further stepped up through either HVDC or HVAC options. The voltages in HVAC are stepped up to 220 kV which is further stepped up to 380 kV (in the case of Italy as it is the highest voltage available) to reduce the losses for on-grid connection. For HVDC the transmission voltage is 320 kV and 380 kV for on grid connection. To enhance grid resilience for future offshore wind farms, the transmission system operator of Italy (Terna) has stepped into the upgradation of the current 220 kV substations to 380 kV. This is done to integrate future renewable energy systems into the power grid and enhance the resilience,

efficiency, and reliable exchange of energy between southern and northern Italy. Such investments in the region have made the Sicily in the first place. Some of the substations that are currently going through the phases of upgradation include the construction of 3 new 380 kV lines i.e., "Chiaramonte Gulfi - Ciminna", "Sorgente - Ciminna" and "Paternò - Priolo". The upgrade of the Ciminna substation to 380 kV is also included. The upgradation of a new double circuit line between Sorgente and Rizziconi. A single circuit line of 380 kV Partanna and Ciminna. Finally, a new single circuit line between Partinico and Fulgatore in Western Sicily (Terna, 2023). Based on the aforementioned data and best practices, the shape file of the power grid is created. Instead of taking proximity to transmission and distribution lines like most of the studies have considered, this study takes proximity to substations. To reduce losses only the substations of 380 kV are taken into consideration for Sicily. This is because most of the projects that are in the planning phase along the western coast of Sicily, have a capacity greater than 600 MW and go up to 2.8 GW (4C Offshore , 2023).

2.3.14 Tourism density

Avoidance of visual aesthetics for the public and touristic sites is one of the important goals of offshore wind turbines. To contain this issue, the Sicilian Department of the Territory and Environment through the decree of 10 September 2003 has set a minimum distance of 4 nautical miles from the coast and such attractions for the construction of such sites.

2.3.15 Blue flag beaches

Blue Flag beaches are known for their environmental standards which hold great importance for the local economy in terms of tourism and economic activities. Local communities have sentiments attached to such places so stakeholder engagement in this regard is essential. Such areas are prone to stringent environmental regulations so developers need to be careful during the planning processes to avoid delays in the permitting process. A study based in Greece suggests keeping a buffer zone of at least 1.5 km in the case of such beaches (Vagion & Kamilakis, 2018). A total of eight blue flag beaches are certified as blue flag beaches along the Sicilian coast.

2.3.16 Protected areas

Protected areas in Italy are defined through the Natura 2000 sites that comply with the two directives "Habitats" and "Birds" Directive that stretch across the EU for the conservation of biodiversity. Italy does not specify the buffer zone for such sites; however, the importance of

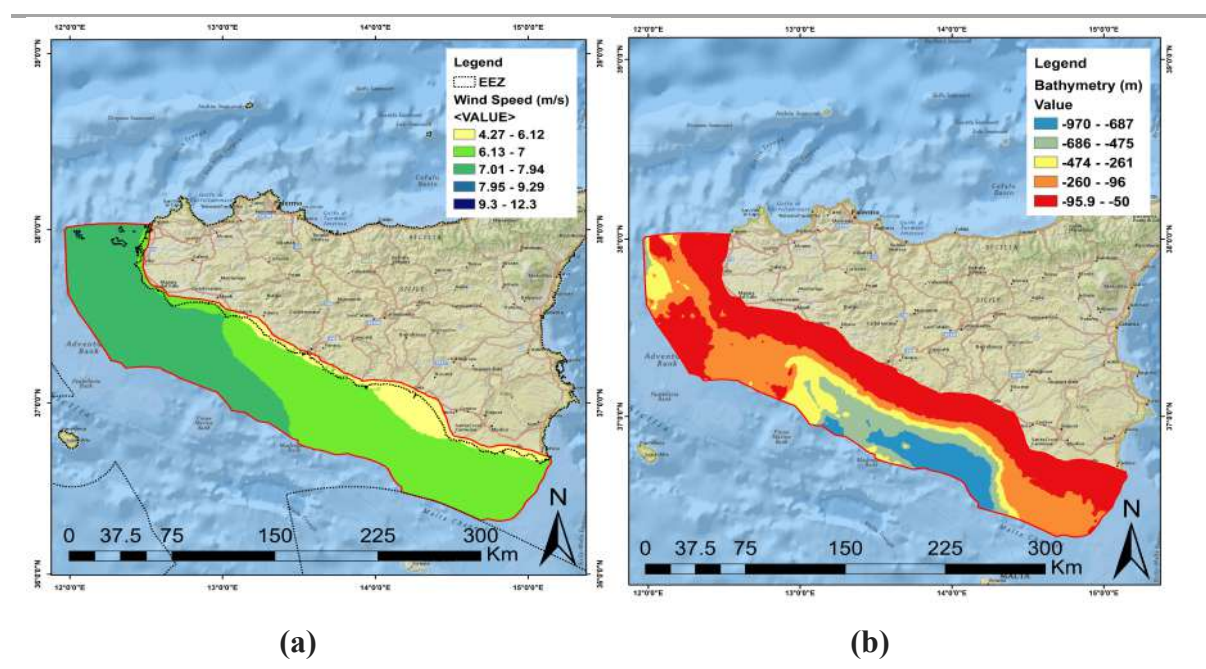
such sites and their boundaries are well explained in the European maritime spatial planning platform. Hence, respecting those boundaries, the EU countries such as Greece, Portugal, and the Danish Maritime Authority have designated a buffer zone of 1 km for such protected zones.

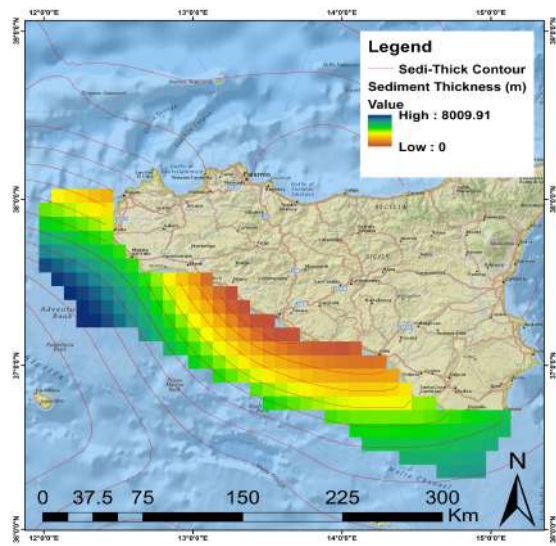
2.3.17 Migratory bird routes

The erection of offshore wind farms may have a certain detrimental impact on the bird's migratory routes. These effects include inducing short- and long-term habitat loss during construction and operational phases. The turbines may cause a barrier during migration periods. In some cases, it might disrupt the patterns of roosting and feeding activities. The Max Planck Institute of Animal Behavior in Germany through its investigation on a certain bird species experienced that when birds come across such turbines, they maintain a distance of 1 km indicating it as a safe distance (Santos, et al., 2022). Some of the species that pass through the area of interest include, White Stork Vorarlberg, European Honey Buzzards, and Montagu's harrier. The shapefiles in this case have been sourced from the Movebank database which is an online database for animal tracking, hosted by the Max Planck Institute of Animal Behavior. The shapefile for the specific bird species and its migration routes sourced from the authors themselves have been cited in the sources section in Table 2.2.

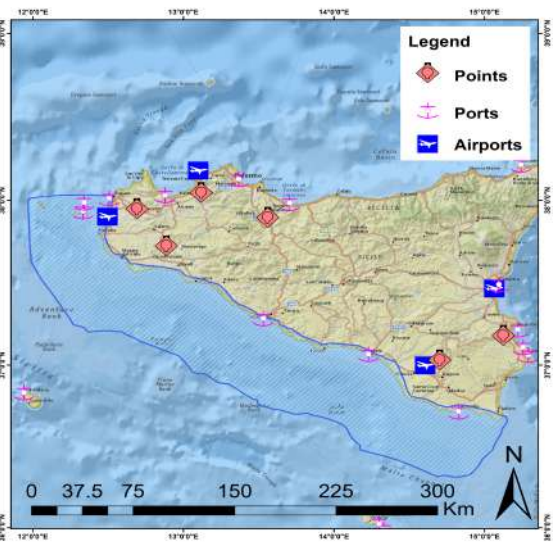
2.3.18 Criteria and their geographical layers

The gathered spatial layers for each criterion are now processed and prepped in the ArcGIS software to extract maps given in Figure 2.2 below.

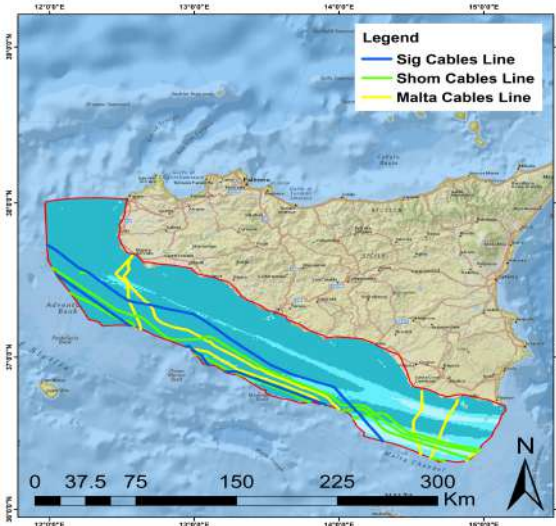




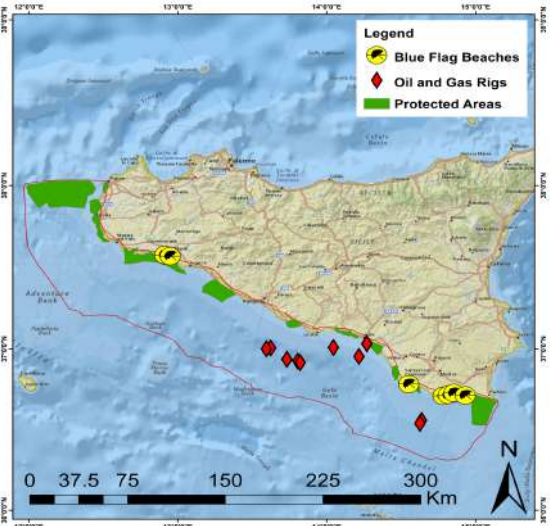
(c)



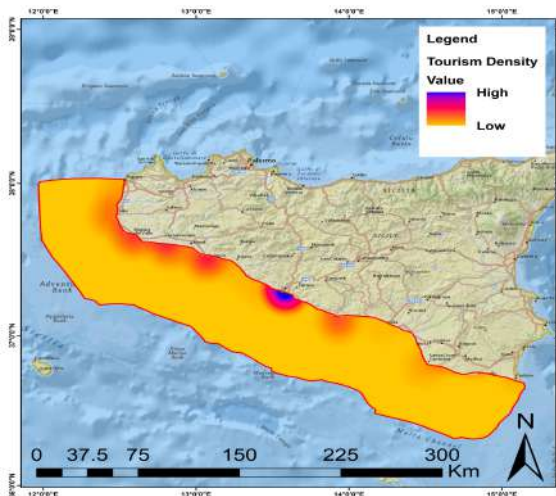
(d)



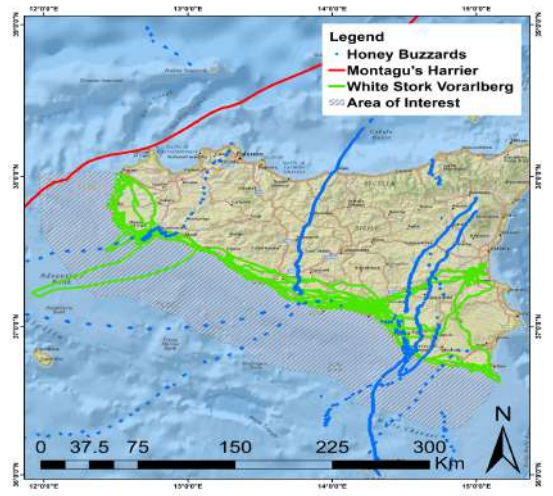
(e)



(f)



(g)



(h)

Figure 2.2. Spatial layers and their corresponding description: (a) Wind Speed (b) Water Depth (c) Sediment thickness (d) Power grids, ports and airports (e) Subsea telecommunication cables and vessel density (f) Blue flag beaches, oil and gas rigs and protected areas (natura 2000 sites) (g) Tourism density (h) Migratory bird routes

The vessel density criteria cover the fishing routes thus avoiding the concerns of fishermen, however, when it comes to the fishing habitat itself, it is known that such habitat is subjected to varying types of stresses that include electromagnetic waves, vibration, underwater noise, and particular motion, etc. However, offshore wind farms and their foundation structures also provide a favorable environment for such habitat. The sub-structure of the wind turbines in particular is known to protect such benthos. Compared to the presence of natural reefs, it is found that such structures promote the population of marine life better especially in the longer run (Galparsoro, et al., 2022; Bergström, et al., 2013).

The type of seabed is another constraint that is promoted by the ANEV to keep into consideration when performing such marine spatial assessments. The particular criteria hold importance during the installation of turbine sub-structures which consequently determines the structural integrity of those turbines. The type of seabed substrate also determines the type of foundation that needs to be deployed (Vázquez, et al., 2022). The area of interest considered in this study has uniform seabed conditions of mud to muddy sand as shown in Figure 2.3 below (EMODnet Map Viewer, 2023).

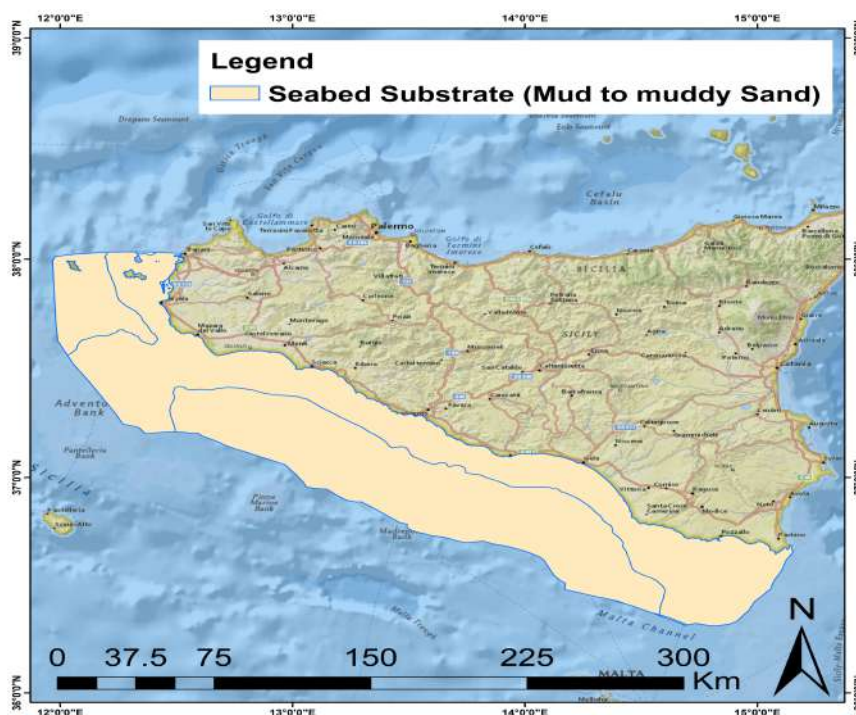


Figure 2.3. Seabed substrate of the study area

The selection of the type of foundation can be made based on varying water depths and the type of seabed substrate given with the help of Table 2.3 below.

<i>Mud to muddy sand sea substrate</i>	
Selection of foundation type	
Water depth (m)	
60 – 70	Monopile
70 – 100	Semi-Submersible, Tension-Leg-Buoy
100 – 200	Semi-Submersible, Tension-Leg-Buoy and spar-type support.
200 – 1000	Semi-Submersible and spar-type support

Table 2.3. Selection of the type of floating foundation (source: (Vázquez, et al., 2022)).

2.4 Methodology

2.4.1 Determination of buffer zones for exclusion criteria

Before moving to the analysis corresponding to site suitability analysis, the buffer zones for the exclusion criteria are determined to avoid any sort of conflict amongst the stakeholders. The buffer zones for the exclusion criteria are primarily based on the guidelines of the Italian guidelines for such projects where possible. If the buffer zone for a certain criterion was not covered by the Italian guidelines, then the best practices adopted by the EU were taken into account. The European Maritime Spatial Planning Platform was the first choice for determining such buffer zones. Table 2.4 below lists the exclusion criteria along with their corresponding buffer zones. The “Euclidean distance” tool in the ArcGIS is used to create such restriction zones.

Exclusion criteria	Buffer zone
Vessel density	500 m
Oil and gas installations	Exclude
Submarine telecommunication cables	500 m
Exclusive Economic Zone	Exclude outside boundaries
Blue flag beaches	1500 m
Protected areas (Natura 2000 sites)	1000 m
Migratory bird routes	1000 m

Table 2.4. Exclusion criteria and their buffer zones

2.4.2 Determining suitability scores for evaluation criteria

For the weighted overlay approach, it is imperative to reclassify the evaluation criteria to yield the final suitability map. With such measure, the least suitable zones are given the rating of zero, whereas, the most suitable zones are given a rating of five. The range of suitability of the scores are devised based on the Italian regulations and standards. In the weighted overlay approach, this step is called the reclassification of criteria which is done to achieve a unification of scale so that the respective data layers can be added together for further analysis. Table 2.5 below showcases the evaluation criteria with their respective suitability scores.

<i>Evaluation criteria</i>	<i>Suitability score</i>					
	0	1	2	3	4	5
Wind speed (m/s)	<4.2	4.27–5.62	5.61–6.27	6.27–6.77	6.77–7.24	7.24–7.93
Water depth (m)	>900	500–900	200–500	100–200	60–100	<60
Sediment thickness (m)	>250	226–250	193–226	141–193	57–141	0–57
Distance to airports (km)	<3	3–5	5–6	6–8	8–10	>10
Distance from ports (km)	<4, >50	40–50	35–40	30–35	25–30	<25
Distance from shoreline (km)	<4	4–8	8–12	12–16	16–20	>20, <50
Distance from power grid (km)	–	45–50	40–45	35–40	30–35	<30
Tourism density	–	VHD	HD	MD	LD	VLD

Table 2.5. Reclassification of evaluation criteria

2.4.3 Fuzzy FUCOM

The introduction of the MCDM approach in this study is to involve experts in the field of the energy sector to allocate importance to the list of evaluation criteria. This will help in understanding the importance of each criterion and its contribution to the final suitability map. For this purpose, a total of five experts took part in the decision-making process. The experts involved are primarily researchers who work in the same line of projects. The minimum experience amongst the list of respondents is 4 years whereas, the maximum amongst the respondents had an experience of 9 years. Such respondents, in this case, were involved

because of their up-to-date technical knowledge and interest in the energy sector of Italy. The data was collected using Google Forms through linguistic variables ranging from Very Low to Very High given in Table 2.6. The fuzzy set theory in this regard was employed to deal with the notion of uncertainty during the decision-making process. The theory was developed by Lotfi Asgharzadeh in 1965 and since then has been widely used to deal with issues of uncertainty. (Zadeh, 1965). For simplification, the triangular fuzzy numbers were employed in this study. The fuzzy set theory works on the membership function that ranges between $[0, 1]$. The membership function can be represented by equation 1 below in which Z is a member of the set having numbers s .

$$P = \{(s, \mu_f(s)) \mid s \in Z\}. \quad (1)$$

The degree of membership can be gauged by the extent of membership of (s) in the fuzzy set denoted by P . The triangular fuzzy numbers are represented by three distance variables denoted by (a, b, c) shown in Figure 2.4 below.

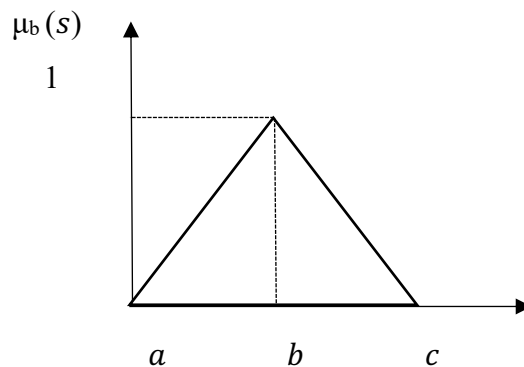


Figure 2.4. Illustration of triangular fuzzy number

The membership of the triangular fuzzy numbers can be denoted by equation 2 below in which (a, b, c) are all real numbers where $a < b < c$.

$$\mu_b(z) = \begin{cases} s - a / b - a & a \leq s \leq b \\ c - s / a - b & b \leq s \leq c \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

Let's suppose $L = (a_1, b_1, c_1)$ and $M = (a_2, b_2, c_2)$ are two triangular fuzzy numbers the following mathematical operations are possible.

$$\text{Addition: } L + M = (a1 + a2, b1 + b2, c1 + c2) \quad (3)$$

$$\text{Product: } L \times M = (a1 \times b2, b1 \times b2, c1 \times c2) \quad (4)$$

$$\text{Division: } \frac{L}{M} = (\frac{a1}{c2}, \frac{b1}{b2}, \frac{c1}{a2}) \quad (5)$$

The FUCOM approach is a non-linear multi-criteria optimization tool that was developed by Dragan Pamucar in 2018 (Pamučar, et al., 2018). The technique works on the principle of pairwise comparison of criteria along with the ability to validate the results through the determination of deviation from full consistency. The advantage of the FUCOM approach over traditional AHP and BWM is its ability to yield lesser pairwise comparison of criteria (n-1) which in essence saves time. The questionnaire is also simple and easy for the decision-makers to comprehend and less time taking. To avoid the innate notion of uncertainty during the decision-making process, Fatih Ecer and Dragan Pamucar incorporated the fuzzy set theory in the FUCOM approach, making it more reliable and robust (Ecer & Pamucar, 2020). The steps involved with the F-FUCOM approach are presented below.

Step 1: The first step in any MCDM approach is the determination of criteria that need to be rated by the decision-makers. In this case, the criteria (n) can range from say (m=1, 2 ... n), represented by a set $C = \{C_1, C_2 \dots C_n\}$.

Step 2: The criteria are allocated weights through linguistic terms given in Table 2.6 below. Based on the weights allocated the resultant criteria are ordered in descending order of their respective significance such that;

$$C_{m(1)} > C_{m(2)} > \dots > C_{m(p)} \quad (6)$$

Linguistic variables	Fuzzy number
Very Low (VL)	(1,1,3)
Low (L)	(1,3,5)
Medium (M)	(3,5,7)
High (H)	(5,7,9)

Table 2.6. Fuzzy scale (source: (Sodhi & T.V, 2012; Khan, et al., 2020))

Step 3: The pairwise comparison of criteria ($\varpi_{C_{m(n)}}$) is carried out in this step. The ordered criteria in step 2 are subjected to comparison, starting from the first criteria with itself (its significance is $\varpi_{C_{m(1)=EI}}$). The comparison follows by moving on to comparing with the next ordered criteria yielding in (n-1) criteria. Equation 7 below helps in the determination of a fuzzy comparative significance $\phi_{n/(n+1)}$ such that:

$$\phi_{p/(p+1)} = \frac{\varpi_{C_{m(p+1)}}}{\varpi_{C_{m(p)}}} = \frac{(\varpi_{C_{m(p+1)}}^u, \varpi_{C_{m(p+1)}}^v, \varpi_{C_{m(p+1)}}^x)}{(\varpi_{C_{m(p)}}^u, \varpi_{C_{m(p)}}^v, \varpi_{C_{m(p)}}^x)} \quad (7)$$

Operation through equation 8 should yield the following fuzzy vector of comparison criteria.

$$\phi = \phi_{1/2}, \phi_{2/3}, \dots, \phi_{p/(p+1)} \quad (8)$$

Here, $\phi_{p/(p+1)}$ shows the weightage of criterion $C_{m(p)}$ in relation to $C_{m(j-1)}$.

Step 4: The fuzzy weights of the criteria $(w_1, w_1, \dots, w_n)^T$ are estimated based on the following two conditions.

Condition 1: The ratio of the weight coefficient of the evaluated criteria i.e., ($C_{m(p)}$ and $C_{m(p-1)}$) should be in equivalence to its respective comparative significance ($\phi_{j/(n+1)}$) such that;

$$\frac{w_m}{w_{m+1}} = \phi_{m/(m+1)} \quad (9)$$

Condition 2: The weight coefficient should satisfy transitivity $\phi_{m/(m+1)} \times \phi_{m+1/(m+2)} = \phi_{m/(m+2)}$ i.e., $\frac{w_m}{w_{m+1}} \times \frac{w_{m+1}}{w_{m+2}} = \frac{w_m}{w_{m+2}}$, making the following formation in equation 10.

$$\frac{w_m}{w_{m+2}} = \phi_{m/(m+1)} \times \phi_{m+1/(m+2)} \quad (10)$$

The solution would yield minimum deviation if $\chi = 0$ and that is possible if equation 11 is fully satisfied.

To obtain maximum consistency, the condition i.e., $\frac{w_m}{w_{m+1}} - \phi_{\frac{m}{m+1}} = 0$ and $\frac{w_m}{w_{m+2}} - \phi_{m/(m+1)} \times \phi_{m+1/(m+2)} = 0$ need to be satisfied.

The non-linear model can now be solved through the minimization of χ .

$$\left\{ \begin{array}{l} \text{Min } \chi \\ \text{S.t.} \\ |w_m - w_{m+1} \times \phi_{m/(m+1)}| \leq \chi \quad \forall p \\ |w_m - w_{m+2} \times \phi_{\frac{m}{m+1}} \times \phi_{m+\frac{1}{m+2}}| \leq \chi \quad \forall p \\ \sum_{p=1}^m w_p = 1, \forall p, \\ w_p^a \leq w_p^b \leq w_p^c, \\ w_p^u \geq 0, \forall p, \quad p = 1, 2, \dots, n \\ \text{Where, } w_p = (w_p^a, w_p^b, w_p^c) \text{ and } \phi_{m/(m+1)} = (\phi_{\frac{a}{m+1}}, \phi_{\frac{b}{m+1}}, \phi_{\frac{c}{m+1}}). \end{array} \right. \quad (11)$$

Step 5: The fuzzy weights are now prepared to be de-fuzzified using equation 12 below.

$$DF = (W_a, W_b, W_c)^{\frac{1}{3}} \quad (12)$$

2.4.4 Weighted overlay analysis

To analyze various conflicting spatial layers (criteria) for determining optimal site selection the weighted overlay tool is a well-known approach. The approach works on the principle of the weighted linear combination method that deals with the spatial layers adopted from the secondary sources and the important weight allocated to each layer through primary sources. The final scores allocated to the raster layers yield the most suitable area. The approach works on three important steps. The first step ensures all the layers are rasterized and brought to a unified scale through a process called reclassification. The resulting cell values are subjected to the multiplication of importance weights derived from the MCDM approach to each input raster. Finally, the resultant raster layers are added together to yield an output raster or

suitability map based on varying importance. The higher the score allocated to a certain cell the higher are its chances to be considered to be the most suitable area. The final values are transformed into a new cell to yield the most optimal sites for offshore wind farms in this case. The ArcGIS software in this case is utilized to perform the aforementioned steps. Equation 13 below summarizes the steps involved in the weighted linear combination approach. Figure 2.5 below gives a better illustration of the steps involved in the weighted overlay analysis.

$$SI = \sum_{j=1}^n W_j \times x_{ij} \quad (13)$$

In equation 14, SI denotes the suitability index of the offshore wind farm, whereas, W_j denotes the importance weight of the criteria j and x_{ij} is the standardized score of the raster layers corresponding to cell i and criteria j .

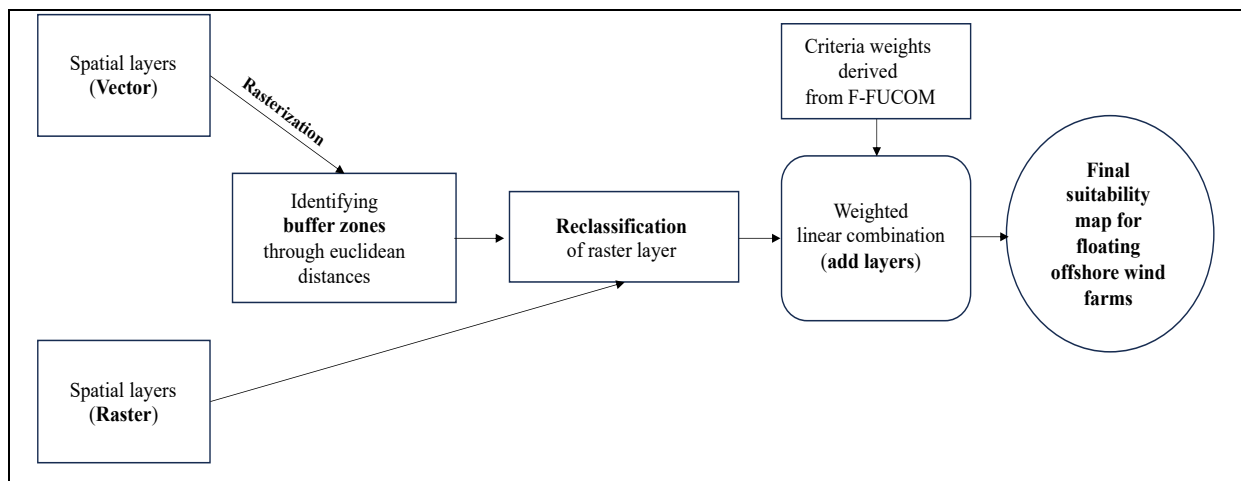


Figure 2.5. Weighted overlay analysis

2.5 Results and discussion

The GIS-based F-FUCOM model initiates through the determination of the evaluation and the exclusion criteria in terms of geographical layers that are processed in the ArcGIS software for the weighted overlay analysis. In the first step, the shapefiles or the vector data set are rasterized through the definition of restriction or buffer zones given in Table 2.4. The Euclidean distance tool in the GIS is used to find the distances from the exclusion criteria. Before adding all the layers together, the evaluation criteria are subjected to the reclassification scale (Table 2.5) to achieve unification of scale. After the conversion all the layers to raster format and hence being unitless are now fit to be added together. However, before moving to the final suitability map, the next step is the process of allocating weights to the evaluation criteria with the help of

energy experts. The weights are derived using the non-linear optimization approach known as FUCOM. The fuzzy set approach is involved in the decision-making process to attain results that avoids the notion of uncertainty. Linguistic variables in Table 2.6 are used to allocate weights to the evaluation criteria. The weighted criteria are then subjected to descending order where the pairwise comparison of criteria takes place. After this process, two conditions with the help of equations 10 and 11 need to be satisfied. Finally, the non-linear model established in equation 12 can be subjected to minimization. The developed model can now be solved in the LINGO software. The code for solving the non-linear model is presented in Appendix A. The results of triangular fuzzy weights can now be de-fuzzified using equation 13. The weights derived from the F-FUCOM approach are presented in Table 2.7 based on their relative significance in descending order below.

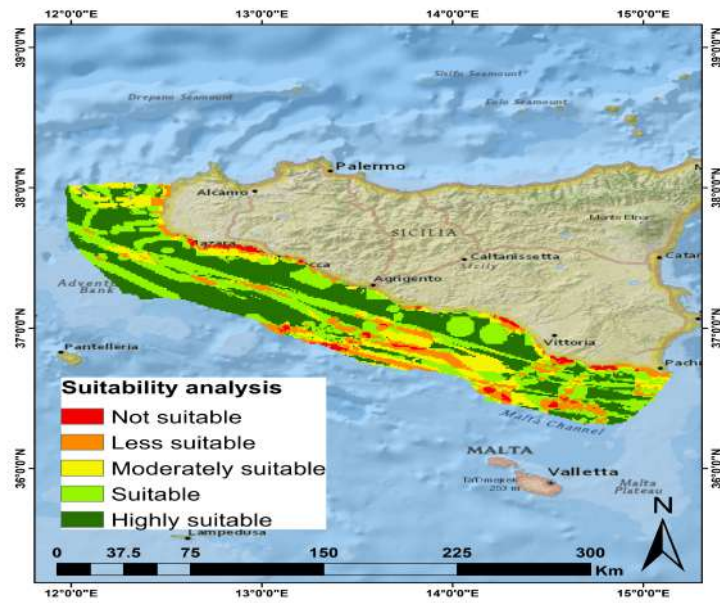
Evaluation criteria	Triangular fuzzy weights			De-fuzzified weights	Importance Ranking
Wind Speed	W1	a	0.1203517	0.156	1
		b	0.177602		
		c	0.177602		
Water Depth	W2	a	8.14E-02	0.120	4
		b	0.1454005		
		c	0.1454005		
Sediment Thickness	W3	a	3.23E-02	0.062	7
		b	8.69E-02		
		c	8.69E-02		
Distance from power grids	W4	a	0.1079086	0.148	2
		b	0.1736981		
		c	0.1736981		
Distance from ports	W5	a	5.08E-02	0.088	6
		b	0.1149103		
		c	0.1149103		
Distance from shoreline	W6	a	6.13E-02	0.099	5
		b	0.1253187		
		c	0.1253187		
Distance from airports	W7	a	1.76E-02	0.061	8
		b	9.85E-02		
		c	0.1316222		
Tourism density	W8	a	9.85E-02	0.134	3
		b	0.157027		

		c	0.157027		
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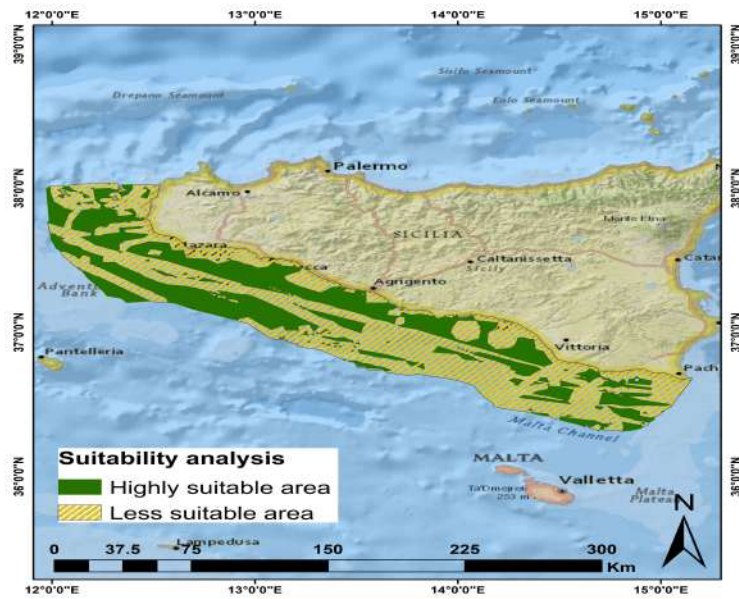
Table 2.7. Importance ranking of evaluation criteria

Experts allocated the most significance to wind speed, followed by distance from the power grid and tourism density. The production of energy from wind turbines is greatly influenced by wind speed which in turn determines the cost of electricity. Higher wind speeds result in lower values of LCOE which means more profitability and lesser cost of electricity. Distance from the power grid is another factor that majorly influences the overall cost of the project. Longer distances from the grid or shore may result in higher costs of cable. It may also result in line losses and difficulties in maintenance activities. Hence, the higher priority of such criteria makes the technical aspects of such projects more important. The socio-economic criteria i.e., tourism density hold importance, especially in the case of Sicily which is famous for its tourism activities, especially in the summer around the beach areas. Hence, the visual impact of such projects needs to be avoided at all costs.

The derived weights are now multiplied to their respective raster layers using the raster calculator which ultimately results in the suitability map. The suitability map in this case has five classes ranging from least or not suitable, less suitable, moderately suitable, highly suitable, and most suitable. The values 2, 4, 6, 8, and 10 are allocated to each class based on the suitability of the criteria and its respective classes. For example, a rating of 2 would mean least suitable, whereas, a rating of 10 would indicate most suitability. The final map derived based on the aforementioned steps is given in Figure 2.6 below.



(a)



(b)

Figure 2.6. Suitability maps (a) Classified suitability map (b) Highly suitable and least suitable areas

From Figure 2.6 (a), it can be seen that the area of interest has been divided into five classes in order of suitability. Developers can consider highly suitable areas for their offshore wind power plants. This will ensure maximum benefits and minimize risks. The same will also aid them in their permitting procedures to be relatively quick considering all the prerequisites issued by the ANEV are met. Figure 2.6 (b) is an even easier illustration of the suitability zones. The area of interest in this case has been divided into two classes; the green zones indicate highly suitable areas, whereas, the yellow zones indicate areas with lower levels of suitability. The next interesting step is to determine the covered area for the most suitable zones which can aid in forecasting and or estimating possible offshore wind farm deployment in the region. For this purpose, the area from the raster image is calculated in the ArcGIS software. The total area of interest in this case has a pixel size of 15854.31982 Km² whereas the pixel size for each class is given with the help of Table 2.8 below.

Suitability zone (classes)	Pixel size (Km ²)
Not suitable	797.71486
Less suitable	2097.42180
Moderately suitable	3473.95351
Suitable	3533.93999
Highly suitable	5951.28965

Table 2.8. Suitability zones and their respective covered areas

The pixel size for the highly suitable zone is very encouraging with an area coverage of 5951.290 Km². This area can be used to forecast and or estimate the offshore wind power capacity that can potentially be installed in highly suitable zones. To attain a rough estimate a conservative estimation can include a standard 5 MW turbine having 126 rotor diameters and having crosswind and downwind spacing factors of 5 and 10 rotor diameters respectively. For optimum operational efficiency, the array spacing between the wind turbines can be determined from equation 15 below (Sheridan, et al., 2012).

$$\text{array spacing} = (\text{rotor diameter})^2 \times \text{downward spacing factor} \times \text{crosswind spacing factor} \quad (15)$$

Employing the aforementioned specification of the wind turbine, the spacing factor yields to be 0.794 km². Using the same calculations, one square kilometer of oceanic water can

accommodate 6.3 MW of installed capacity. Additionally, the number of turbines can be evaluated by employing equation 16 below.

$$\text{Number of turbines} = \text{total available area} \div \text{array spacing} \quad (16)$$

To find the total installed capacity concerning the area of interest, the capacity of each turbine can be multiplied by the total number of turbines.

In the case of the current study, the highly suitable zone covers an area of 5951.290 Km². The number of turbines in this case becomes 7,496. The total installed capacity can thereby be determined by multiplying the nameplate capacity of a single turbine. In this case, $7496 (\text{turbines}) \times 6.3(\text{MW}) = 47224.8 \text{ MW OR } 47.2 \text{ GW}$. According to Terna, Italy's goal is to raise its renewable energy targets from 55 to 65% in the energy mix of the country by 2030. Using 2019 as the base year means the country has to produce an additional installed capacity of 70 GW from renewables. The conservative estimated power from the most feasible sites in the case of this study would mean the country can potentially achieve 67% of the aforementioned target from Sicily alone.

2.6 Conclusion

Offshore wind power is seen as a great opportunity in Europe to enhance their renewable energy capacity and be more energy-autonomous. With floating-based foundations, it is now possible to deploy wind turbines far off the coast to avoid any visual obstruction and yield high capacity factors. However, the most crucial phase with such projects is the site selection problem. An optimal site selection ensures the project harnesses maximum output without having any environmental, socioeconomic, or technical drawbacks. Such site selection frameworks require the determination of spatial criteria that conform to local regulations of the locality. Like other European countries, Italy is also looking forward to enhancing its offshore wind capacity. For this purpose, the National Wind Energy Association (ANEV) has promulgated certain guidelines that need to be followed when developing such wind farms. Hence, based on the dynamics of Italy, such decision criteria are investigated and determined for suitability assessment in the case of Sicily. The Sicilian strait is considered to be one of the potential zones for the deployment of future offshore wind farm development in the country. For marine spatial assessment, the determined spatial criteria are segregated into inclusion and exclusion criteria. The spatial data of 15 decision criteria are gathered from secondary sources which are subsequently handled in the ArcGIS software. The exclusion criteria in this case are

subjected to buffer zones whereas the suitability scores are developed for the evaluation criteria. Before yielding the final suitability map through the weighted overlay analysis, the evaluation criteria are assessed by experts through a novel decision-making approach as F-FUCOM. This step further validates the evaluation criteria and aids in a more definitive and practical suitability map. Finally, the weighted overlay tool is employed to yield a suitability map based on five classes. From the F-FUCOM analysis, the experts allocated the most significance to wind speed, followed by distance from the power grid and tourism density. The highly suitable zones from the suitability maps indicate an area of 5951.290 Km² which is quite encouraging for the future offshore wind industry in the country. Following a conservative estimate, the same area is capable of generating 47.2 GW of power which is good enough to meet 67% of the renewable energy target set by the Italian government for 2030.

Such a site suitability assessment in the case of Sicily, Italy is a first attempt which makes it the novelty of this study. The decision criteria adopted for this study follow all the aspects of sustainability making it the most extensive set of factors in the literature for conducting such assessments. Instead of employing traditional MCDM approaches that come with certain disadvantages, this study employs a novel decision-making approach known as F-FUCOM which can yield more credible ranking. Moreover, the fuzzy set theory is employed to aid the decision-making process and capture any sort of ambiguity in the decision-maker's judgment. The comprehensive decision support framework and the sources from which the spatial criteria is adopted can be used as model for solving site selection problems for other regions in Italy e.g., Sardinia and Apulia. Apart from such contributions, the study comes with a few limitations that can be addressed by future studies. The research on floating-based wind farms is still in the phase of development and so future offshore wind farms can be subjected to different or new regulations, especially in the case of Italy which is new to such technology. Hence, new sets of criteria need to be determined and evaluated in such cases.

Chapter 3. Techno-economic assessment of green hydrogen production from an actual onshore wind farm in Campania, Italy

A six-month joint project with Renexia SpA company

3.1 Introduction

In 2022, hydrogen consumption accounted for less than 2% of Europe's energy requirements. Its usage has been predominantly seen in the chemical industry, especially for the production of plastics and fertilizers. However, 96% of such hydrogen was produced from natural gas, resulting in high levels of CO₂ emissions (European Commission, 2023). To contain such emissions, several initiatives such as the EU's hydrogen strategy and the REPowerEU are devised to produce green hydrogen from water electrolysis through renewable energy sources such as wind and solar power. The aim is to achieve energy self-sufficiency and attain decarbonization goals at the same time. Hydrogen can aid in a sustainable energy shift in many ways. Firstly, it can be a storable fuel that produces no emission during its combustion process. Hence, it can replace fossil fuel in the final uses where electrification is not a feasible alternative such as in heavy loads e.g., maritime transport. Secondly, it can replace carbon as a reactant in hard-to-abate industries such as steel and refining. Thirdly, it can complement the intermittency nature of renewables acting as a storage solution to meet energy demands in times of low output.

To understand the standpoint of Italy on the hydrogen paradigm it's important to evaluate the country's current consumption of the fuel. The current production of hydrogen amounting to 480,000 tH₂/year is predominantly used in the refining and the production of ammonia. Replacing it with green hydrogen would require additional renewable electricity amounting to 23-27.6 TWh/year (Marco, 2022). Italy being the 11th largest producer of steel in the EU is another sector that can directly use clean hydrogen to replace natural gas. However, this would require an additional 21-25 TWh of renewable electricity (Vogl, et al., 2018). Besides the energy-intensive industries such as glass, ceramic, paper, and cement in which electrification is a more conducive alternative, heavy-duty transport such as railways, trucks, and buses represents another space that can be decarbonized. The transport sector is projected to require 57,330- 156,800 tH₂ of green hydrogen by 2030, hence, requiring an additional 3.15-8.64 TWh of additional renewable electricity (Gérard, et al., 2020). Moreover, a blending of about 10-15% of hydrogen can be achieved in the gas distribution network without major alteration. This

could be deemed as a short-term remedy to cater to the heating and power generation demands because a 100% hydrogen integration is not considered feasible. The contribution of natural gas to power production attributed to 44.6 percent of the demand in 2019. The blended usage of hydrogen can ease the import of natural gas it is projected to combust the same for power generation in the order of 17-172 GWh by 2030 (Marco, 2022). However, it is pertinent to mention that hydrogen can be used as a long-term storage minimizing reliance on natural gas. According to the revised plan by the National Energy and Climate Plan, Italy aims to achieve 65% of renewable energy generation by 2030 (ITA, 2024). Hence, this means there is a higher potential of achieving the Italian hydrogen strategy. To achieve such a strategy, a target of 2% of hydrogen consumption in the final energy demand is to be met by 2030 (Ministry of Economic Development, 2020). The sectors that are targeted for such a demand are heavy-duty transport, industrial usage which includes chemical and refineries, and blending hydrogen with natural gas network. To achieve such a goal, Italy plans to achieve 5 GW of electrolyzer capacity by 2030 classifying it as a high ambition country amongst other EU countries such as the Netherlands (IEA, 2021). Several funding initiatives are proposed both by the EU and the Italian government which are broadly covered with two main initiatives. On the European level, the Important Projects of Common European Interest (IPCEI) cover funding corresponding to the entire value chain of such projects. On the national level, the National Recovery and Resilience Plan (PNRR) plays a rather crucial role. The funding promotes decarbonizing hard-to-abate sectors and creates hydrogen supply chains known as “hydrogen valleys” by leveraging on abandoned industrial sites. More funding details and their geographical targeting in the case of Italy are extensively covered (Gandiglio & Marocco, 2024).

Wind and solar power are the two most exploited sources of energy for the production of green hydrogen. However, wind power often exhibits higher capacity factors which means they have a more consistent supply of energy to the electrolyzer producing more hydrogen and lesser associated costs. In Italy, regions with good wind potential such as the Puglia, Campania, and Sicily have great potential to take on Italy's hydrogen strategy. Campania region leads Sicily boasting a production of 3.209 GWh contributing 17.1% of Italy's wind power production (Eniscoula, 2022). The feasibility of such projects is determined through the Levelized Cost of Hydrogen (LCOH) which represents the per-unit cost of producing hydrogen over the project lifetime (Man, et al., 2024). The final system cost of electricity i.e., the Levelized Cost of Energy (LCOE) has a major contribution towards the determination of LCOH. Onshore wind farms in general and Italy have relatively cheaper LCOE values. In fact, in 2020, the LCOE for such projects corresponded to between 22.28 to 40.43 EUR/MWh (Vidas, et al., 2024).

Wind resource plays a crucial role in the determination of the cost of energy, hence, regions with high wind resources such as Campania can lower the cost of electricity from such projects. A good comparison has been drawn between the case of Argentina and Italy where scenarios of producing hydrogen from wind energy have been drawn. The determination has been made through the role of capacity factors and the LCOE of such projects. In the case of Italy, the average cost of electricity and capacity factor was considered to be 65 €/MWh and 25% respectively. The LCOH was found to be higher in the case of Italy with respect to Argentina which has better wind resources, higher capacity factors, and hence lower LCOE (Correa , et al., 2022). Therefore, it is deduced that the role of wind resources and the type of wind generator used plays a crucial role in carrying out techno-economic assessments for such projects. A more realistic picture of checking the viability of producing green hydrogen can be drawn by working on actual data sets and the type of turbine utilized rather than working on assumptions on which most of the literature is based. This will not only determine the true costs of LCOH but will also guide the investors and the policymakers in the right direction.

To investigate such an actual case study, this study takes on an existing onshore wind farm in Italy owned by a company named Renexia that has been financed through the issuance of green bonds and the Contract for Difference (CFD) scheme. The company issued its first green bond in the year 2020 which amounted to 49.1 million euros and is set to expire at the end of 2029. The project already operational in 2022 is located in the region of Campania in the province called Benevento. The wind farm has a total capacity of 34.65 MW and according to the COO of the company has the highest capacity factors in the country. To mitigate the risk associated with the project the CFD was reached with an off-taker, in this case, Gestore dei Servizi Energetica (GSE). The Casalduni district in which the wind farm coupled with the Siemens Gamesa turbine is located has an average wind speed of 7.5 m/s which makes the project LCOE amongst the lowest in the country. However, when the off-taker such as the GSE is involved the cost of electricity is increased when it is sold to the wholesale market and part to the final consumer. The market energy price for such projects lies in the range of 100-110 €/MWh which according to the COO kills the case for linking such projects with green hydrogen production. A stronger case could be built if the generator (in this case Renexia) is directly involved in taking up the task of producing green hydrogen. In this case, the LCOE at the point of generation with no intermediates can range between 50-70 €/MWh which could essentially lower the LCOH values. Hence, this study takes on this task to find the viability of producing green hydrogen directly involving the generator with no intermediates and the Transmission System Operator to make a study case for the company. Hence, an off-grid configuration for

the electrolyzer is considered which makes the Green Index of hydrogen 100%. This will not only give the company a picture of its potential but also check if it can incorporate the same idea for its future wind power projects. According to the COO building a case for such projects is a difficult task especially if the developer is looking to gain incentives from the government. For this purpose, the data related to the 34.65 MW wind farm is collected from the company which is subsequently linked to a Proton Exchange Membrane (PEM) electrolyzer. The study uses both statistical and time-dependent approaches to evaluate the LCOH for the project. Sensitivity cases are also built to check the most optimal configuration for the project.

3.2 Literature review

The European hydrogen strategy aims to achieve 40 GW of electrolyzer capacity by 2030. This will ensure commercialization and technological development on a mass level decreasing the costs of electrolyzer. In Italy, the main barrier to the high LCOH values is because high costs of renewable electricity. However, in the most optimistic scenario, it will be attainable to achieve LCOH costs lower than 2.44 €/kg-H₂ (Pastore, et al., 2022). To decarbonize the hard-to-abate sector such as the steel industry, a techno-economic assessment has been conducted working on an actual wind farm coupled with an alkaline electrolyzer. The cost of components such as batteries, storage tanks, and electrolyzer is varied to check their impact on the LCOH. The cost of the electrolyzer had the most impact on the LCOH. On the other hand, the cost of electricity was termed to be high in the case of Italy and not predictable for the future. Moreover, to achieve a 100% Green Index, it is suggested to couple the electrolyzer directly to the electrolyzer especially in the case of Italy (Superchi, et al., 2023). A similar attempt has been made to decarbonize the transport sector and blending of hydrogen in the natural gas grid. A PEM electrolyzer via water electrolyzer is paired with the grid and renewable energy systems such as solar, wind, and geothermal to evaluate the viability of the systems. Two main sensitivity scenarios are taken into consideration, the first through the variation in the cost of electricity i.e., between 50-100 €/MWh under the Power Purchasing Agreement (PPA), and the other through varying the transport potential of the stored hydrogen. The facility in Capo Suvero, powered with wind energy yielded the best business case with LCOH standing at 6.9 €/kg for a PPA of 50 €/MWh (Fragiacomo & Genovese, 2020).

Onshore wind farms yield lower LCOH values as opposed to offshore wind farms. The same conclusion has been drawn through a comparison between Italy and Portugal. Results suggested that capacity factors of solar/wind play a crucial role in determining the LCOH for

such projects. In such as case, Italy had an average LCOH of 7.25 EUR/kg, whereas a similar configuration for Portugal yielded 6.85 EUR/kg due to higher capacity factors (Vidas, et al., 2024). Another techno-economic approach has been applied to a case study in Italy in which average capacity factors for onshore wind farms have taken to 19.5% for the year 2016. Coupled with a PEM electrolyzer an LCOH value of 5.76 €/kg has been achieved. It is recommended that future studies should focus on other geographical locations in Italy to check the impact of capacity factors on the LCOH of such projects (Marocco, et al., 2024). Working on actual data from a wind farm coupled with an electrolyzer gives more credible findings and removes biases. Also, for more competitive LCOH values it is recommended to invest in bigger system modules this will ensure economies of scale and more economical components costs (Superchi, et al., 2023). A similar pattern has been found in another case study for the Apulia region in which a comparison has been drawn between wind farms of different sizes and their impact on the LCOH values. It is found that along with the enhanced capacity factors of wind power over solar plants, the wind farm with higher capacity yielded more economical LCOH values. However, the final results are still not competitive with respect to natural gas (Colangelo, et al., 2024). Currently, the PEM electrolyzer is considered to be the most suitable option for integrating with intermittent renewable energy sources such as wind power. Such electrolyzer have faster dynamic response as opposed to alkaline electrolyzer which has a rather slower response and need a consistent supply of power. The latter is more suitable for industrial uses where backup power is available. Furthermore, the former has higher current density, and extended module range, yielding purer hydrogen and enhanced stability over its life cycle (Correa, et al., 2022).

The aforementioned summarization of the literature presented in the case of Italy suggests that Italy is still far from achieving its target of 5 GW of electrolyzer capacity by 2030. Most of the studies conducted are based on hypothetical assumptions that have the notion of bias and therefore cannot paint a real picture for future Italian hydrogen strategy. It has also been determined that extensive feasibility studies are required in different geographical locations of Italy to gauge the impact of capacity factors on the final LCOH values. The literature also suggests that PEM electrolyzer is extensively used for pairing with renewable energy sources due to its quick starting and stopping advantage over alkaline electrolyzer. Moreover, the price of renewable electricity which has a major role to play in the determination of LCOH is still higher in Italy as opposed to other European counterparts. The cost of components such as the electrolyzer would reduce with economies of scale and so it would further reduce the LCOH for such projects. To produce green hydrogen with a higher green index in a country like Italy

whose electricity grid still has fossil fuels contributing to the electricity generation, it is suggested to couple electrolyzer directly to the wind farms. Such an approach would essentially decarbonize the targeted sectors more effectively. Hence, to fulfill such literature gaps, this study aims to work on an actual wind farm in the Campania region of Italy by coupling it to a PEM electrolyzer and determine the feasibility of the project. The project has unique features coming in with the highest capacity factors in the country along with a competitive LCOE figure. Having the LCOE parameters fixed, the study would essentially revolve around other system parameters and check their variation and their impact on the final LCOH values.

3.3 Data collection and methodology

The current project is a collaboration with the company Renexia SpA, which is a subsidiary of the Toto Group that specializes in renewable energy management and development. The company has completed several projects ranging from onshore to offshore and also worked on the development of solar-based projects along with expertise in developing charging infrastructure for electric vehicles. The current study focuses on one of their onshore wind farms that started its operation in 2023 in a district called Casalduni. The project is composed of 10 Siemens Gamesa G-132 each having a capacity of 3,465 MW. A detailed technical specification of the wind turbine is given in Table 3.1 below.

General details	
Rated power	3.465 MW
Flexible power rating	3.0-3.65 MW
Control	Pitch and variable speed
Noise level (1)	104.0 dBA
Standard operating temperature	Range from -20°C to 30°C (2)
Velocity (m/s)	Cut-in 3 m/s - Cut-off 25m/s - Rated velocity 14 m/s
Rotor	
Diameter	132 m
Swept area	13,685 m ²
Power density	253.20 W/m ²
Blades	
Length	64.5 m
Airfoils	Siemens Gamesa
Tower	

Height	114m
Gearbox	
Type	3 stages
Generator	
Type	Doubly-fed induction machine
Frequency	50 Hz/60 Hz

Table 3.1. Technical specifications of the wind turbine (adopted from the manufacturer (Siemens Gamesa, 2025))

The project is exactly located in the hills of Calore Irpino with a Latitude of 41.1343 and longitude of 14.8556 where the average yearly wind speed happens to be 7.5 m/s. The wind farm runs at a very decent capacity factor of 41%. To understand the pattern of wind speed in the area, an illustration of the monthly wind speed is given in Figure 3.1 below. The wind speed data can be derived for the area of interest from two possible sources. The first is from a source called Renewables Ninja where data for solar and wind power resources could be gathered, developed by Imperial College of London and Federal Institute of Technology Zurich (Climate Action Programme, 2025). Alternatively, the same data can be retrieved through employing the Homer Pro software which gathers data from Atmosphere Science Data Centre (NASA) for evaluating wind resource data for such projects.

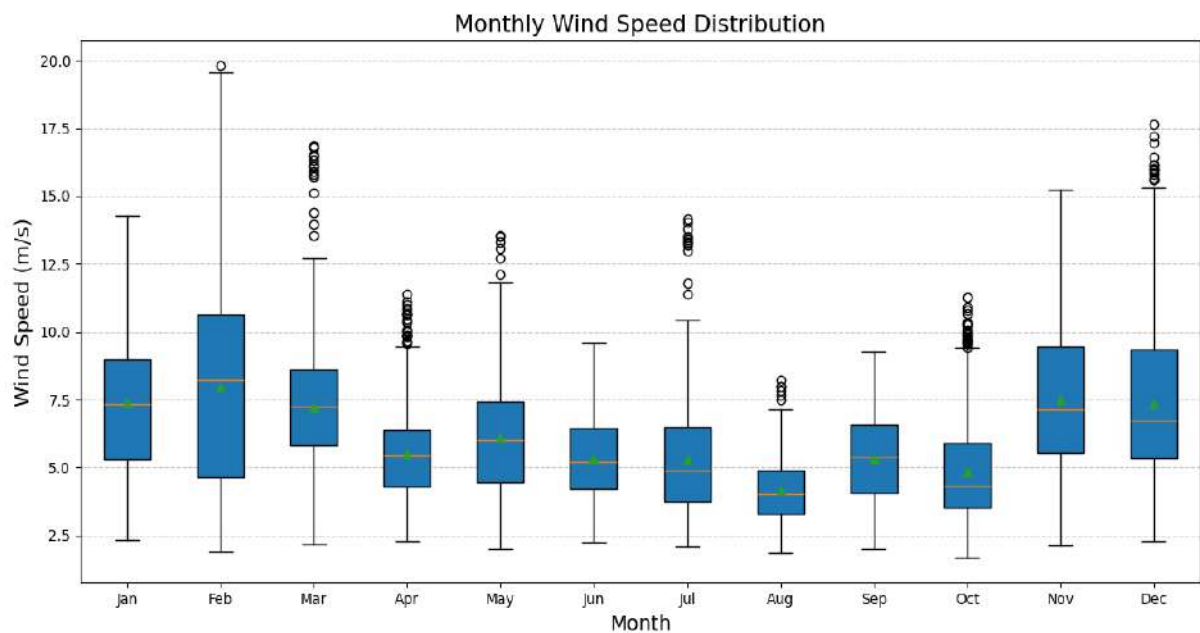


Figure 3.1. Typical wind speed distribution for Calore Irpino

The power curve of the turbine (KW) at various Air Densities [kg/m³] and wind speed (m/s) can be showcased in Figure 3.2 below.

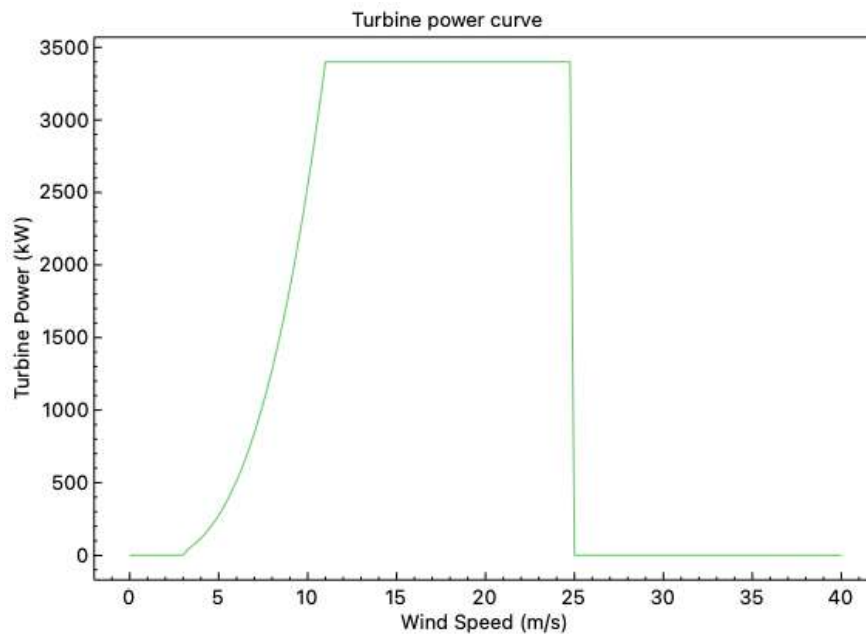


Figure 3.2. Power curve of Siemens Gamesa S-132

The data related to the wind farm especially the monthly Annual Energy Production (AEP) was taken from Renexia. The data is then extrapolated based on an hourly configuration to understand the time-dependent modeling of the electrolyzer and subsequently the hourly production of hydrogen. Along with such data the LCOE of the wind farm was also shared by the company. This is the most important part of the data as it will portray a true possibility and viability of integrating with an electrolyzer yielding credible values for LCOH. To understand the hourly generation from the wind farm, Figure 3.3 below indicates the same for the whole year. It will help to understand the potential of green hydrogen production on an hourly basis and indicate during which time of the year the production is low or high making arrangements for its utilization accordingly.

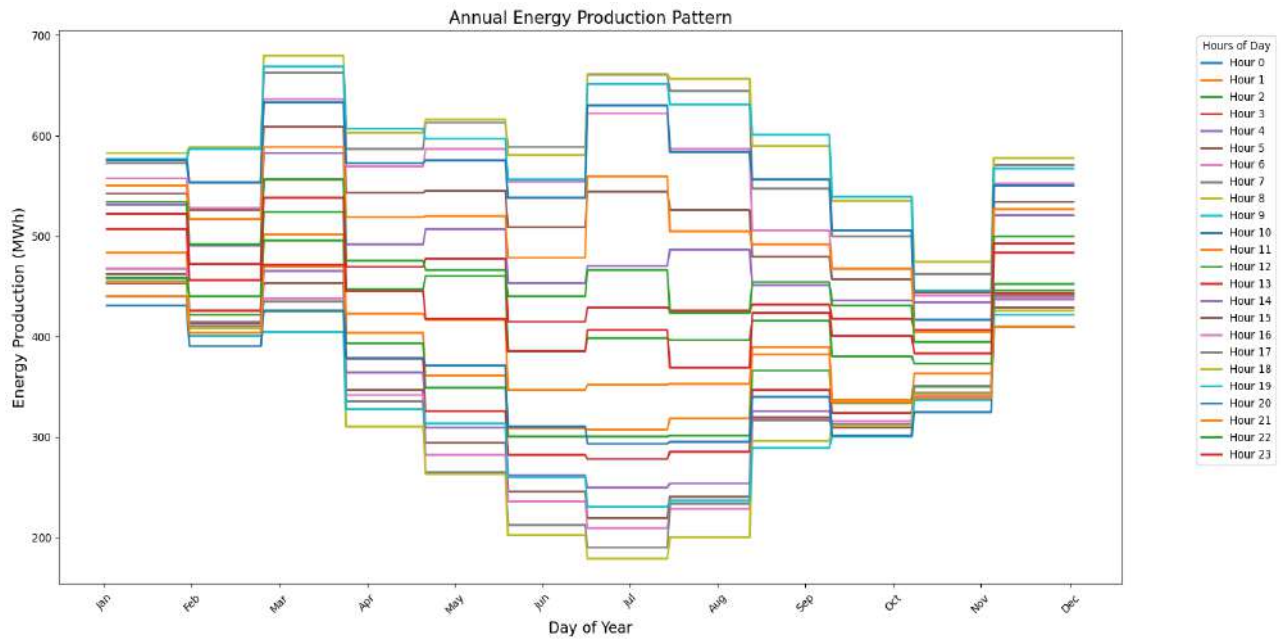


Figure 3.3. Hourly energy generation from the wind farm

The month of January is characterized by the most electricity generation, while the month of June corresponds to the least electricity generation. The total AEP of the wind farm corresponds to 125,606 MWh.

The wind farm is coupled with a PEM electrolyzer due to its unique and dynamic features. The electrolyzer is connected to the wind farm in an off-grid configuration hence PEM electrolyzer due to its fast response time and dynamic operation can withstand the intermittency nature of the input energy. Another advantage is its ability to provide 99.99% pure hydrogen which does not need further refinement and can be readily used in various sectors. PEM electrolyzer due to its high stack price is still a challenge however this would be overcome when economies of scale are achieved. The standard parameters of the PEM electrolyzer considered for this study based on actual market conditions in the EU are given in Table 3.2 below (Marocco, et al., 2024).

Efficiency (LHV)	61.2% or 54.47 kWh/kg-H ₂
CAPEX (stack + Balance of Plant)	1188 €/kW
Replacement cost (stack)	30% (% of CAPEX)
OPEX (annual)	3% (% of CAPEX)
Lifetime of the stack	73,000 h

Table 3.2. Techno-economic parameters of the PEM electrolyzer

The current stack life of the PEM electrolyzer ranges between 60,000 to 80,000 h, however, since the lifetime of the wind farm is 25 years, the stack replacement time has been determined to be 73,000 h (Yates, et al., 2020). This means the stack would be replaced on an equal interval i.e., 3 times during the lifetime of the project.

The techno-economic feasibility of the project is based on three important parameters that include the AEP, LCOE, and finally the LCOH. The latter is the economic indicator on which the optimal system design is based. Data related to AEP and LCOE pertaining to the wind farm is already shared by the company which makes the goal straightforward forward which is to calculate the final LCOH. The LCOE which accounts for both the CAPEX and OPEX of the wind farm happens to be 48 €/MW. To understand how the LCOE is evaluated, equation 1 can be used.

$$LCOE = \frac{\sum_{t=1}^T (C_t + O_t) \cdot (1+r)^{-t}}{\sum_{t=1}^T E_t \cdot (1+r)^{-t}} \quad (1)$$

C_t : Capital expenditures in year t (initial investment, often concentrated at t=0).

O_t : Operational expenditures in the year t (annual OPEX costs, e.g., maintenance, repairs).

E_t : Energy generated in year t (e.g., wind power output).

r : Discount rate.

T : Lifetime of the project.

Subsequently, the LCOH is calculated which determines the feasibility of the project and involves both the energy and electrolyzer costs. The equation to determine the same is given below.

$$LCOH = \frac{\frac{\text{Annualized capex (electrolyzer)} \cdot CRF}{T} + \text{annual Opex (electrolyzer)} + \text{Stack Replacement Cost (Annual)} + \text{annual energy costs}}{\text{Annual hydrogen production}} \quad (2)$$

In equation 2, the Capital Recovery Factor (CRF) in equation 3 is a factor that helps convert the upfront CAPEX into an equivalent annualized cost considering a fixed interest or discount rate over the lifetime of the project. It ensures the time value of money by evenly distributing the capital cost across each year of the electrolyzer operational life in present-value terms.

$$CRF = \frac{r \cdot (1+r)^T}{(1+r)^T - 1} \quad (3)$$

r : Discount rate (interest rate, as a decimal).

n : Lifetime of the electrolyzer (years).

Similarly in equation 2, the annual energy costs are characterized by the product of electricity used per year in kWh and LCOE in €/kWh. The energy usage in this case depends upon the electrolyzer efficiency and hydrogen production. Moreover, hydrogen production (kg/year) is characterized by the product of electrolyzer efficiency (kWh/kg-H₂) and the total energy consumed per year (kWh).

An interesting comparison can be drawn by following two distinct approaches for the determination of LCOH which are termed statistical and time-dependent modeling (Travaglini, et al., 2024). The statistical approach corresponds to the evaluation of LCOH based on the aggregated AEP while keeping the production fixed at 18.36 kg/MWh attributing to an efficiency of 54.47 kWh/kg-H₂. For a comparative analysis, this approach ensures uniformity hence not accounting for the variations of the hydrogen production on an hourly basis and hence not accounting for the intermittency of the input power. In contrast to this, the time-dependent model works on the temporal resolution of 1 h as energy input to the electrolyzer corresponding to the hourly energy production from the wind farm. Sensitivity cases are subsequently built to determine the most optimal configuration for yielding the least LCOH values. The analysis is performed in Python both for statistical and time-dependent modeling. The size of the electrolyzer based on the average capacity factor is determined to be 14,206.5kW or 14.2 MW. However, the aim is to ensure that surplus energy beyond the electrolyzer capacity is minimized. For this purpose, the size of the electrolyzer would be varied to account for maximum energy utilization hydrogen production, and subsequent profitability.

3.4 Results and discussion

3.4.1 Statistical analysis

Scenario 1: without storage costs

Following the set parameters, the base scenario corresponds to the determination of LCOH without considering the storage costs. Hence, it is assumed that the hydrogen is consumed directly at the production end (Travaglini, et al., 2024). The summary of the results using such an approach is outlined in a table derived from such an approach provided in Table 3.3 below.

Annualized Electrolyzer CAPEX:	€1,080,312.48
Annual Stack Replacement Cost	€607,562.21
Annual Energy Cost	€6,029,088.00
Total Annual Cost	€8,223,264.53
Annual Hydrogen Production	2,305,966.59 kg or 2305 tons
Levelized Cost of Hydrogen (LCOH)	3.57 €/kg

Table 3.3. Summary of the results for Scenario 1

The cost contribution of the most important components i.e., the electrolyzer and energy costs can be better portrayed through a pie chart given in Figure 3.4 below.

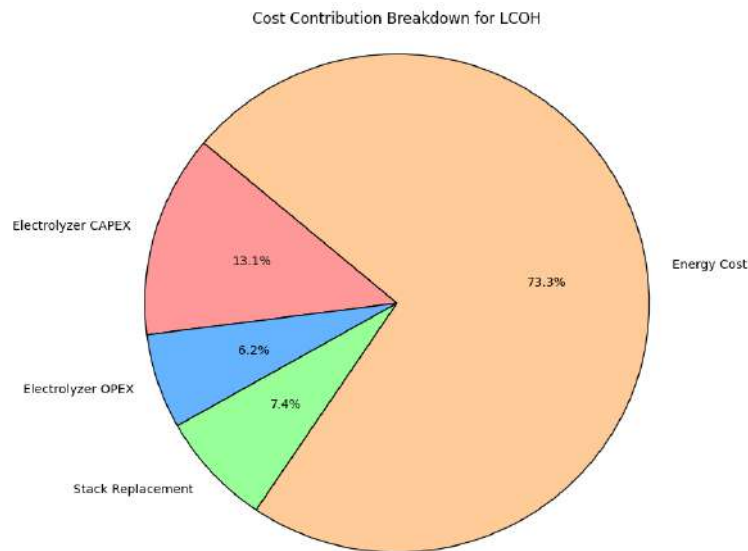


Figure 3.4. Cost contribution of each component towards the LCOH (without storage costs)

Scenario 2: with storage costs

The outlet pressure of hydrogen from the PEM electrolyzer depends upon several factors such as the system size, energy efficiency, or application requirements. Generally, the outlet pressure for various configurations ranges between 30-100 bar or even more depending upon the specific operation and design consideration (U.S. Department of Energy, 2014). However, since the application of hydrogen is out of the scope of this study, the hydrogen is assumed to be produced at a pressure of 30 bar. Such compression configuration inside the electrolyzer ensures higher efficiency and reduction in the overall CAPEX of the system eliminating the requirement for extra compression modules (Hancke, et al., 2024). The CAPEX of such a

hydrogen tank is considered to be 460 €/kg. The lifetime of the same is considered to be 25 years and the OPEX is considered to be 1% of the CAPEX (Superchi , et al., 2023). The daily hydrogen production from an efficiency of 54.47 kWh/kg-H₂ and AEP of 125,606 MW is attributed to 6320 kg. However, maintaining a buffer of two days before the consumption the storage capacity of the tank is set at 12640 kg. While all the other system costs are the same, the costs of storage and the corresponding LCOH are reported in Table 3.4 below. The cost contribution towards the LCOH is outlined in a pie chart in Figure 3.5.

Annualized Storage CAPEX	€372,191.16
Annual OPEX (Storage):	€58,144.00
Total Annual Cost	€8,653,599.69
Levelized Cost of Hydrogen (LCOH):	3.75 €/kg

Table 3.4. Costs of storage and LCOH

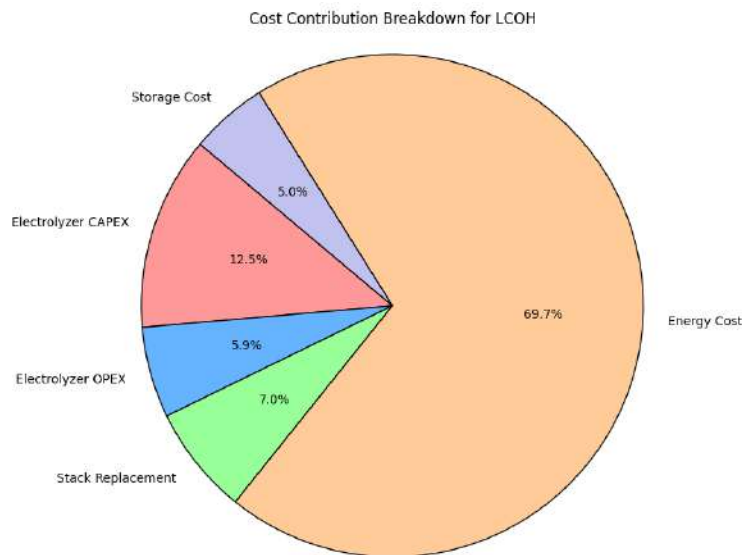


Figure 3.5. Cost contribution breakdown for LCOH

3.4.2 Time-dependent modeling

Following the same techno-economic parameters listed in Table 3.2, this approach uses real input power from the wind farm based on 1 h resolution accounting for the variability of the system. An optimal configuration would subsequently be determined through varying the system parameters hence to converge to the point where the LCOH values are minimized. This will ensure a configuration with the best business case for the wind farm and future such projects. For the preliminary analysis, the same system parameters adopted for the statistical

analysis are taken into consideration. Sensitivity cases are then followed to achieve the most optimal configuration.

Scenario 3: without storage costs

The first scenario for the time-dependent analysis considers a 14.2 MW electrolyzer with no storage tank. The results for this scenario are outlined in Table 3.5 below, while the cost contribution of each component is outlined in the form of a pie chart in Figure 3.6 below.

Total Annual Hydrogen Production	2214.59 tons
Annualized Electrolyzer CAPEX	€1,079,856.21
Annual OPEX (Electrolyzer)	€506,088.00
Annual Stack Replacement Cost	€607,305.60
Annual Energy Cost	€5,790,175.77
Levelized Cost of Hydrogen (LCOH)	3.60 €/kg
Surplus Energy	35579.39 MWh

Table 3.5. Results for time-dependent approach without storage costs

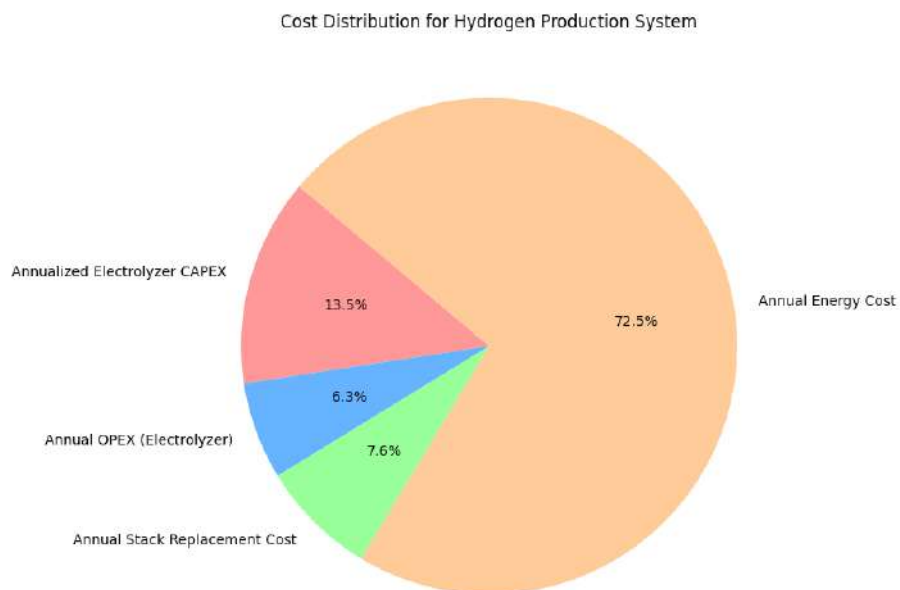


Figure 3.4. Cost contribution for time-dependent approach

Scenario 4: with storage costs

The storage costs are accounted for in the determination of the LCOH in this case. The average daily production from the 14.2 MW electrolyzer is 6067 kg/day. Applying the two-day buffer

for the utilization of the produced hydrogen, the storage tank is assumed to be of 12,134 kg capacity. The LCOH and the costs related to storage are in Table 3.6.

Annualized Storage CAPEX	€357,291.73
Annual Storage OPEX	€55,816.40
Levelized Cost of Hydrogen (LCOH)	3.79 €/kg

Table 3.6. Determination of LCOH using storage costs

From Table 3.5, it can be observed that there is an annual surplus energy of 35579.39 MWh that is not utilized by the electrolyzer for the 14.2 MW electrolyzer. Hence, to account for this surplus energy, the size of the electrolyzer is varied to understand its impact on energy utilization and LCOH values. For this purpose, the electrolyzer size is varied between 9 to 29 MW. The particular range is selected because the minimum and maximum hourly generation from the wind farm ranges between 92240.550 kW and 28870.04 kW respectively. Figure 3.7 below shows the interaction between electrolyzer size, surplus energy, and LCOH values.

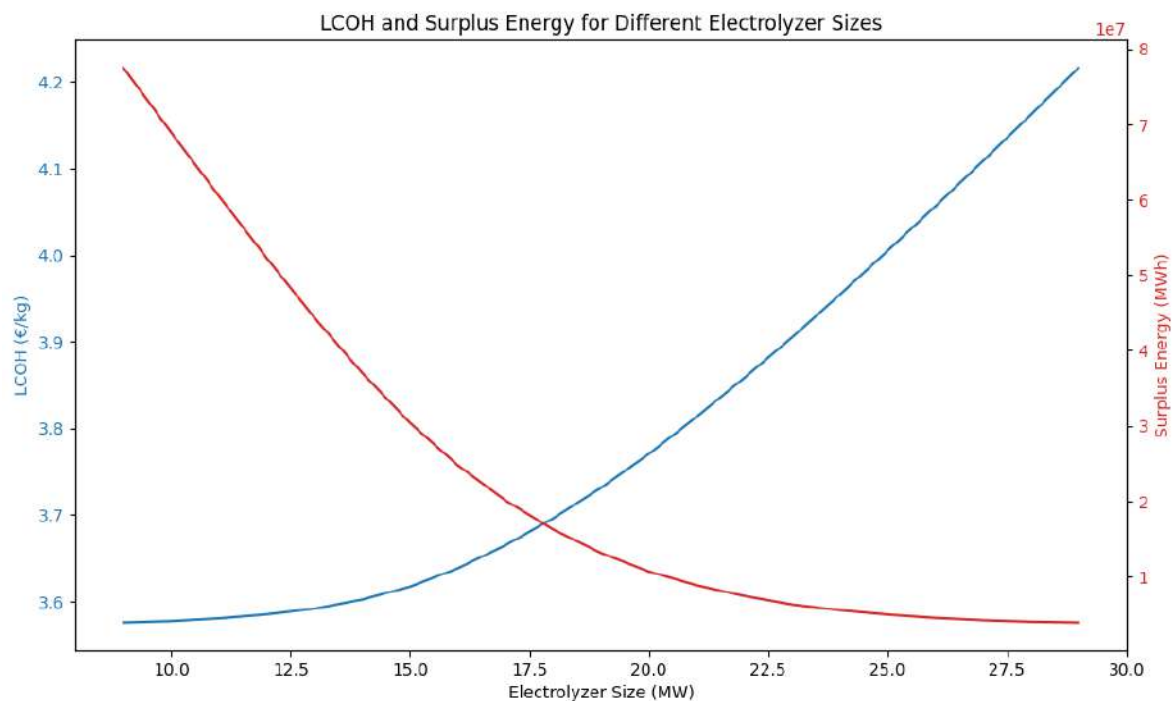


Figure 3.5. Interaction between electrolyzer size vs surplus energy vs LCOH values

From Figure 3.7 it can be observed that until the electrolyzer capacity of 17.6 MW (with LCOH of 3.67 €/kg), there is a slight increase in the LCOH values. However, after an increase in the size of the electrolyzer beyond such capacity, there is an exponential increase in the values of

LCOH. Moreover, there is a sharp decrease in the surplus energy until the aforementioned electrolyzer capacity, however, beyond such capacity, there is a mild decrease in the surplus energy. To understand the impact and importance of electrolyzer size in more detail, the capacity factor with varying size is further introduced in Figure 3.8.

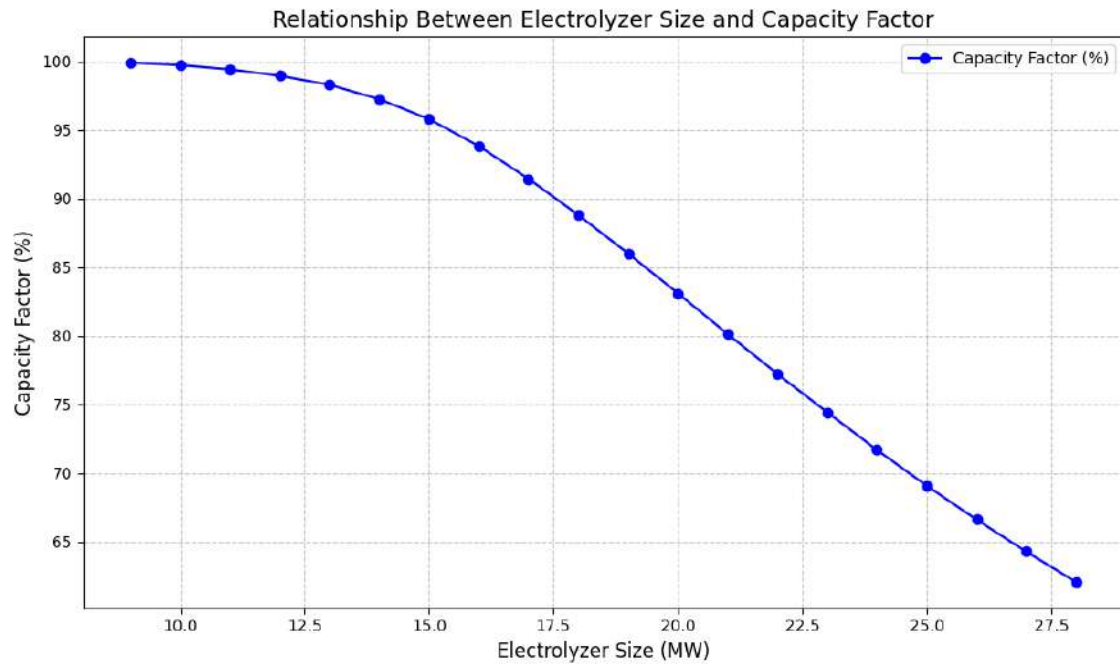


Figure 3.6. Interaction between electrolyzer size and corresponding capacity factors

From Figure 3.8, it can be observed that as the size of the electrolyzer increases the capacity factor also decreases. The capacity factors experience a mild decrease until 15 MW (standing at a capacity factor of 96% and an LCOH of 3.62 €/kg), however, beyond such size the capacity factor rather experiences a sharp decrease. The size of the electrolyzer can be further gauged through its impact on hydrogen production in Figure 3.9 below.

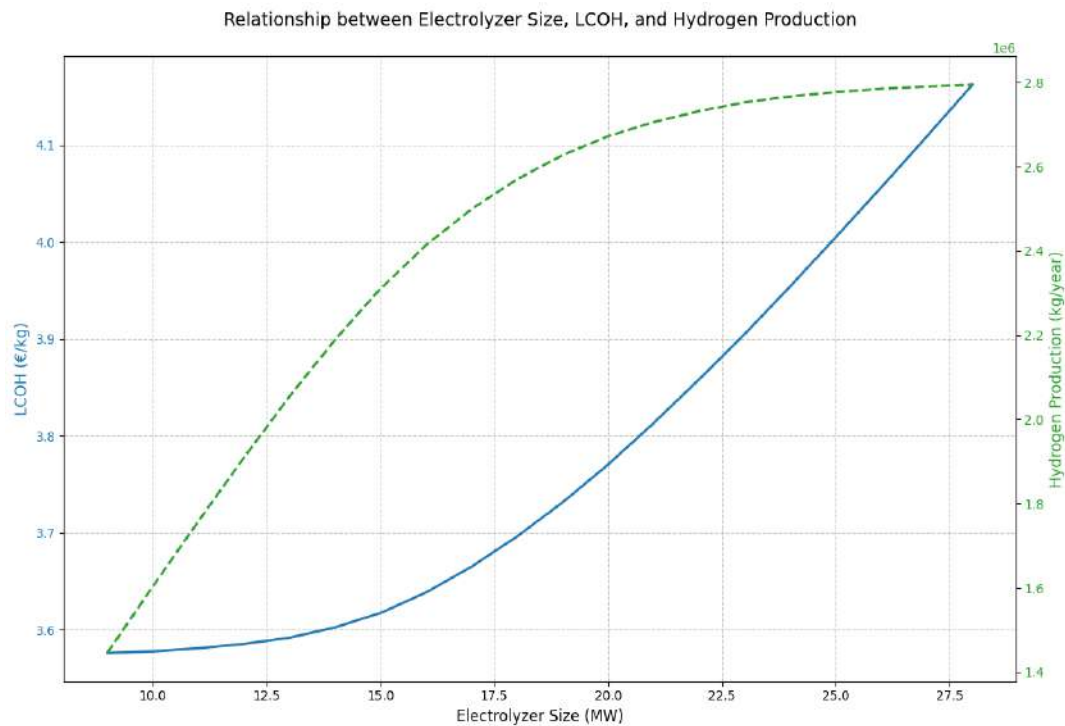


Figure 3.7. Impact of electrolyzer size on hydrogen production and LCOH

Interestingly, the same pattern can be gauged from Figure 3.9, where a sharp increase in hydrogen production is experienced until 15 MW of electrolyzer capacity. However, beyond the 20 MW capacity (LCOH of 3.77 €/kg) a saturation point is reached after which a downward trend in hydrogen production is experienced.

From the aforementioned results, it can be deduced that four different sizes of electrolyzer can be considered for the Casalduni wind farm that includes 14.2, 15, 17.6, and lastly 20 MW. As the size of the electrolyzer increases the values of LCOH increase. In contrast, with an increase in the size of the electrolyzer the capacity factor decreases. Hence, there is a trade-off between increased hydrogen production and LCOH values. The surplus energy in each case can be stored in a battery and diverted to the electrolyzer in time of low energy generation which is outside the scope of this study.

The results presented so far provide a business case or benchmark for Renexia to see the potential of diverting itself towards future such projects. However, to make it more interesting, it would be prudent to also check the influence of variable electrolyzer efficiencies and CAPEX on the LCOH values. In terms of efficiency improvements, the International Renewable Energy Agency (IRENA) has set a target by 2050 to decrease cell energy consumption to <42 kWh/kg. Such a feat would also proportionally decrease the LCOH. Typical commercial operating current densities for PEM electrolyzers such as 1.8 A cm^{-2} and 1.77 V cells equate to an

efficiency of 83% (HHV) and an energy consumption of $47.5 \text{ kWh kg}^{-1} \text{ H}_2$. However, a recent groundbreaking development has now made it possible for an alkaline electrolyzer to achieve an efficiency of 98% (HHV) with a consumption of only $40.4 \text{ kWh kg}^{-1} \text{ H}_2$ by using the capillary-fed electrolysis technology (Hodges, et al., 2022). Similar milestones have been achieved for the PEM electrolyzer from a project coordinated by the National Research Council of Italy through a joint project funded by the EU called ELECTROHYPEM. This project aimed to reduce stack and system costs and improve the durability, performance, and efficiency of the PEM electrolyzer. The project resulted in achieving efficiency better than 80% (LHV) (Aricò, 2015). As for the CAPEX of the PEM electrolyzer, it is projected for 2030 to achieve a cost of 701 €/kW and 314 €/kW by 2050 (Böhm, et al., 2020). Based on such projections, the same wind farm data is used to determine LCOH values for such efficiencies and costs of the electrolyzer. In Figure 3.10 below the efficiencies (LHV-based) are varied between 60 to 80 % to check its impact on the LCOH values.

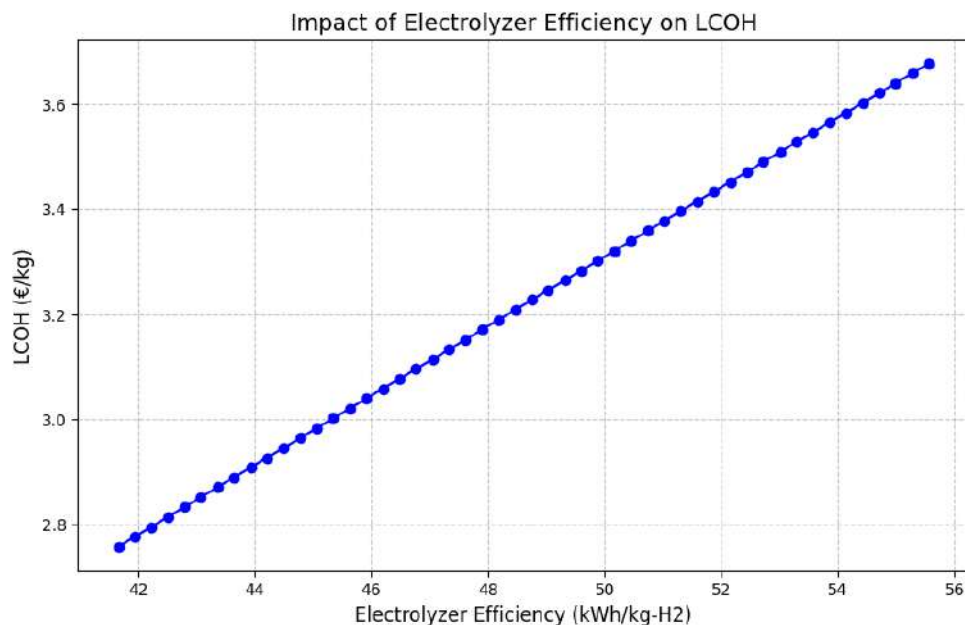


Figure 3.8. Impact of electrolyzer efficiency on LCOH values

In Figure 3.10 a linear relationship between electrolyzer efficiency and LCOH values is observed, also determined by IRENA. An LCOH value of 2.7571 €/kg is achieved at an efficiency of 80% with the same wind farm data. Finally, keeping an efficiency of 70% (LHV), the impact of different costs of electrolyzer accounting for the current, 2030, and 2050 forecast is also checked on the LCOH values in Table 3.7 below.

Electrolyzer CAPEX (Böhm, et al., 2020)	LCOH
1188 €/kW (current)	3.15 €/kg
701 €/kW (2030)	2.79 €/kg
314 €/kW (2050)	2.51 €/kg

Table 3.7. CAPEX of electrolyzer and its impact on LCOH (at 70% electrolyzer efficiency)

3.5 Conclusion

For achieving net zero emissions, the role of green hydrogen is pertinent which has been realized by the EU. To achieve individual targets, countries like Italy have set targets for 2030 and 2050 to include green hydrogen in their energy mix. The aim is to decarbonize hard-to-abate sectors and become energy-autonomous at the same time. However, to foster the national green hydrogen strategy it is pertinent to engage in performing techno-economic assessments which could realize the importance of each system parameter and provide a good business case for the developers of such projects. Such an approach will help developers of such projects to understand the true potential of green hydrogen and take benefits from various incentives available for such projects especially in the case of Italy. An in-depth review of the literature in the case of Italy suggests performing techno-economic assessments for various geographical regions in the country accounting for various available wind resources and capacity factors. It is also found that Italy has high prices of renewable electricity, especially wind power as compared to other European counterparts. The same problem is also highlighted during the interview phase with the developer of the wind farm used as a case study for this research terming the end prices to be a “*killer for the electrolyzer*”. Hence, to account for such shortcomings in the literature, the current research aims to perform a techno-economic assessment of an already operational wind farm in the district of Casalduni in the Campania region of Italy. The wind farm comes in with the highest capacity factors in the country along with a very competitive LCOE figure. The literature as well as the interviewee suggested for the wind farm to be integrated with the electrolyzer in an off-grid configuration taking benefit from the low cost of energy and hence making a strong business case. Data such as wind turbine specifications, AEP, and the LCOE of the project are collected directly from the developer of the wind farm. The wind farm is subsequently coupled with a PEM electrolyzer due to its known dynamic capabilities.

Two sets of analyses consisting of statistical and time-dependent modeling are performed for the electrolyzer in the Python environment. In both cases, the size of the electrolyzer is fixed

at 14.2 MW which is estimated based on the capacity factor and total installed capacity of the wind farm (34.65 MW). In statistical analysis the output from the electrolyzer is fixed at 18.36 kg/MWh (based on an efficiency of 61.2%) since the total AEP from the wind farm is known to be 125,606 MWh/year. The values of LCOH are determined for both with (3.75 €/kg) and without (3.57 €/kg) storage tank costs for hydrogen at 30 bar pressure. In both cases, the cost distribution of the system shows that energy costs contribute to around 70% of the final LCOH hence showcasing the importance of such a component. In contrast to this, a granular resolution of 1 h time step of energy from the wind farm is provided to the electrolyzer for the time-dependent modeling. The LCOH figures for both with and without storage costs are again considered for the analysis. The LCOH without storage cost is attributed to 3.60 €/kg, whereas, the with storage tank costs reaches an LCOH value of 3.79 €/kg. The difference in the LCOH values between the two approaches is little however, the time-dependent modelling accounts for the intermittency and variation in the production of hydrogen hence making a good picture for handling the transportation of the produced hydrogen. For the same analysis, the surplus energy not utilized by the electrolyzer is also taken into consideration. Since there is no battery for storing the surplus energy which could also be the limitation of the study, it is aimed to minimize this surplus energy by varying the electrolyzer size. For this purpose, the size of the electrolyzer is varied between 9 and 28 MW based on the production pattern of the wind farm, and its impact is subsequently checked upon the surplus energy and LCOH values. The two parameters meet at a capacity of 17.6 MW where the LCOH (3.67 €/kg) and the surplus energy is at the lowest. To further understand the impact of the size of the electrolyzer the capacity factors for changing electrolyzer capacities are also checked. The trend shows decreasing capacity factors as the size of the electrolyzer increases. The impact of electrolyzer size is also checked on the hydrogen production, the trend shows that until 15 MW there is a sharp increase in the production of hydrogen, however, a further increase in size rather mellows down the production. Additionally, to account for the various electrolyzer efficiencies forecasted by IRENA and the technological feat achieved so far, the impact of the same is also checked on the LCOH values. The results mark an LCOH value of 2.5 €/kg for a CAPEX of 314 €/kW. For all of the analysis, the value of LCOE is fixed due to the actual data from the wind farm hence legitimizing the results of the study.

The study provides a good business case for the wind developer in question and for other such projects in the country. Energy costs have a major contribution to play in the determination of the LCOH, hence, a further decrease in the energy costs would drastically decrease the LCOH values. An off-grid configuration for the electrolyzer would always be the best approach both

in ensuring the lowest LCOE and hydrogen with a 100% green index especially in the case of Italy where the grid still consists of fossil fuels. Moreover, technological feats in terms of advancing electrolyzer efficiencies and decreasing CAPEX of the same would make green hydrogen cost competitive as opposed to other alternatives.

Conclusion and implications

The 7th Target of SDGs i.e., “affordable, reliable, sustainable and modern energy for all” has become of prime importance, especially in times when energy security and decarbonization goals are being prioritized by nations around the world. Italy the third largest economy in Europe is moving along the same path of being more energy-autonomous and lowering its GHG emissions. The need to redefine the energy policy of Italy became more imminent after the energy crises caused due to the Russian-Ukraine conflict. Italy being a net importer of electricity also relied on the import of natural gas to meet its energy demands. The disruption in the supply of natural gas caused an increase in the energy bills and Italy had to diversify its import of natural gas to meet the major portion of its energy demands. Along with the diversification of its natural gas imports, there is also an increased pressure to reduce reliance on fossil fuels and shift towards the adoption of more sustainable energy alternatives explicitly under the REPowerEU program. Hence, understanding the current energy policy of Italy and providing a facilitating framework to make the energy sector more energy secure and sustainable becomes pertinent. This is what the first chapter of the thesis aims to achieve and that is to determine and define the most sustainable energy mix in the case of Italy for it to be more energy-autonomous and sustainable. For this purpose, the study in the first phase determines the current energy mix of Italy and its contribution towards the final energy demand. It is found that the energy mix is majorly composed of seven energy technologies consisting of natural gas, coal power, solar power, wind power, hydropower, bio power, and geothermal power. The aforementioned energy mix is then gauged by sustainability criteria consisting of socio-political, economic, environmental, and technical aspects. The thirteen sustainability criteria considered for the evaluation process is determined through an extensive literature review. The F-SWOT methodology is employed to materialize the goal which has the capability of handling both qualitative and quantitative sets of data. The methodology helps in identifying the strengths, weaknesses, opportunities, and threats of each energy alternative. It also helps to segregate the criteria into internal and external factors, helping to identify which are controllable and which are uncontrollable. Based on the judgment of the experts, both the criteria and the energy alternatives are evaluated and subsequently displayed on the SWOT matrix. The experts, in this case, allocated the most importance to the “access to grid” criteria followed by “delivered cost of electricity” and “capital investment”. As for the energy alternatives, Biopower, solar, and hydro have been placed in the first quadrant all showcasing

strengths and opportunities. Moreover, wind power has been placed in the second quadrant showcasing decent opportunities but a few weaknesses as well. Geothermal and coal power are placed in the third quadrant both showcasing weaknesses and threats. Lastly, natural gas is placed in the fourth quadrant showcasing significant threats however, it possesses some strengths as well. In the current scenario, it is suggested that the supply of natural gas should be diversified shifting from Russia to North African countries. However, in the longer run, dependence on natural gas can be reduced by enhancing the capacity of renewable energy systems, especially wind power. With respect to renewable energy systems, solar and wind power have the most opportunities to be further enhanced and developed. However, the most eminent problem with such projects is the lengthy of legislative and permitting procedures which needs to be addressed.

From Chapter 1, it is also found that wind power with both onshore and offshore capabilities has more potential to address the energy security concerns of Italy more sustainably. Such projects come in with higher capacity factors and installed capacity which can help achieve Italy's renewable energy production and consumption targets more promptly and effectively subject to quick authorization procedures. With respect to offshore wind farms, Italy currently has only one such project based on a fixed foundation platform. However, newer technology with the floating-based foundation has more potential with respect to techno-economic, environmental, and social aspects. Recently, wind developers in this regard have shown increasing interest in the floating-based offshore wind farms. The same can be gauged by the requests received for such projects especially in the case of Sardinia and Sicily. Most of these projects are in their planning phase which happens to be the most challenging part of the lifecycle of such projects. Particularly site suitability analysis through marine spatial assessments is considered to be rather challenging because such projects have to conform to the local regulations, enhancing the techno-economic parameters and reducing social and environmental constraints. Some of the projects with the largest installed capacity such as the Med wind project having a capacity of 2.8 GW are currently in the planning phase to be deployed in the Strait of Sicily. The viability and pace of such projects can be enhanced if a facilitating decision support system is developed that is able to address all the regulations important for planning such projects. The second chapter of this thesis aims to achieve the same objective and that is to develop a model for performing site suitability analysis for floating offshore wind farms in the case of Italy (in this case the Sicilian Strait). The facilitating framework developed in this study aims to conform to the regulations and standards set for such projects. Through a thorough review of the literature, it is found that the regulations set

by the ANEV for such projects are inadequate lacking several constraints and description. Hence, along with conforming to the local regulations of Italy, European regulations are also taken into consideration. The logic for such is that Italy is already a member of the European marine spatial platform which aims to provide a guideline for planning such projects. Hence, through an extensive literature review, a total of fifteen spatial criteria based on socio-economic, environmental, and technical aspects are taken into consideration. The spatial criteria are further divided into evaluation and exclusion criteria, the former deciding suitability index whereas the latter acting as a constraint. An additional exclusion criterion i.e., “oil and gas installations” is also taken into consideration which most of the research neglects. The spatial criteria are in the form of vector and raster formats which are managed in the ArcGIS software for further analysis. The weighted overlay tool in the software is used to determine the site suitability analysis for the Strait of Sicily. To allocate importance to the evaluation criteria the novel MCDM approach known as Fuzzy FUCOM approach is employed. The results of the study help in segregating the area of interest into five suitability zones ranging from least suitable to highly suitable areas. The highly suitable zones can be considered by future wind farm developers to deploy their projects in the Sicilian strait. The model developed in the study can be further extended to other regions of Italy such as Sardinia and Puglia which are also considered to be suitable for floating-based offshore wind farms.

With growing renewable energy capacities such as wind power the need to store excess energy can be an effective way to address the intermittent nature of such resources and reduce reliance on the grid. It becomes more important in the case of Italy since the grid is still powered by fossil fuels. Green hydrogen in this regard is considered to be a storable fuel that is produced through a process called water electrolysis powered through renewables. Apart from the energy sector, hydrogen has uses in multiple other sectors such as the transportation, chemical, and steel industry hence making it a great promoter in reducing reliance on fossil fuels. Due to such characteristics, European countries including Italy have set targets to integrate hydrogen into the energy mix of the country. Italy itself has a national hydrogen strategy that aims to achieve 2% of hydrogen consumption by 2030. Achieving a 5 GW target of electrolyzer capacity is also set by 2030. To achieve such ambitions and to make green hydrogen more price competitive with respect to that produced from fossil fuels, it becomes important to perform techno-economic assessments of such projects. Such an approach aids in an effective decision-making process regarding investments in such projects both from the government and private entities. Wind power is considered to have a great potential to power electrolyzers due to its consistent nature of supplying energy as compared to solar power, the former coming in with

higher capacity factors and installed capacity. Most of the literature that has performed techno-economic assessments on such projects are based on hypothetical assumptions thus creating the notion of bias. Hence, to fill such gaps in the literature, the third chapter aims to perform a techno-economic assessment of an actual wind farm located in Italy which is coupled to a PEM electrolyzer to configure the most optimal configuration to account for the least LCOH value. The wind farm is located in the region of Campania in a district called Casalduni. It comes with a decent capacity factor along with a competitive LCOE value. The wind farm is installed and operated by a company called Renexia from whom the data related to the wind farm is collected. The PEM electrolyzer is selected to be coupled with the wind farm because of its dynamic capabilities as opposed to the Alkaline electrolyzer. Real-world techno-economic parameters of the PEM electrolyzer are considered to achieve results with the most practicality. The system is configured in an off-grid configuration to take maximum advantage of the lower LCOE value. The literature suggests the same for such projects to be configured in an off-grid configuration to lower the LCOH values and achieve a 100% green index. The analysis is performed in the Python environment with two types of approaches consisting of statistical and time-dependent modelling for the electrolyzer. For both the statistical and time-dependent modeling, cases with and without hydrogen storage are considered. The size of the electrolyzer is varied to understand the best configuration for the system with the lowest LCOH figure. The impact of the size of the electrolyzer is further analyzed by checking its effect on the capacity factors and hydrogen production. To further strengthen the business case for the company and future such projects the efficiency and Capex of the electrolyzer are varied to account for the least LCOH values. The LCOH for various configurations ranges between 3.60 to 3.79 €/kg which is found to be very competitive with respect to similar projects in the literature. The results also indicate that the LCOE figure contributes to around 70% of the final LCOH figure. Hence, further reducing the LCOE figure of such projects through better financing strategies can be an effective strategy in making green hydrogen more competitive as opposed to fossil fuel-based hydrogen. Moreover, a reduction in the capex of electrolyzer can be achieved through economies of scale which would further make green hydrogen more competitive. Similarly, improving the efficiency of such electrolyzers through research and development would further lower the LCOH figure for such projects. Fortunately, there are funding opportunities on both European and Italian level that aims to achieved similar objectives. However, such efforts should be further enhanced and provided across all regions of Italy so that renewable energy developers can benefit from it. Also, similar viability studies should be further extended to other geographical regions to account for various capacity factors of

renewable energy technologies. This would provide a benchmark for companies like Renexia which can make their decisions towards such projects more effectively and can engage with the government to aid these projects.

References

- Perdana, S., Vielle, . M. & Schenckery, M., 2022. European Economic impacts of cutting energy imports from Russia: A computable general equilibrium analysis. *Energy Strategy Reviews*, 44(1), p. 101006.
- Boehm, L., 2022. *Russia's war on Ukraine: Implications for EU energy supply*, Strasbourg: European Parliament.
- Parry, I., Black, S. & Vernon, N., 2021. *Still Not Getting Energy Prices Right: A Global and Country Update of Fossil Fuel Subsidies*, Washington, D.C.: International Monetary Fund.
- Proedrou, F., 2023. EU Decarbonization under Geopolitical Pressure: Changing Paradigms and Implications for Energy and Climate Policy. *Sustainability*, 15(6), p. 5083.
- Karmellos, M. et al., 2021. A decomposition and decoupling analysis of carbon dioxide emissions from electricity generation: Evidence from the EU-27 and the UK. *Energy*, 231(1), p. 120861.
- Siksnyte , I. & Zavadskas, E. K., 2019. Achievements of the European Union Countries in Seeking a Sustainable Electricity Sector. *Energies* , 12(12), p. 2254.
- Jäger-Waldau, A., Kougias, I., Taylor, N. & Thiel, C., 2020. How photovoltaics can contribute to GHG emission reductions of 55% in the EU by 2030. *Renewable and Sustainable Energy Reviews*, 126(1), p. 109836.
- Sgaravatti, G. S. T. C. T. a. G. Z., 2023. *Bruegel Datasets*. [Online] Available at: <https://www.bruegel.org/dataset/national-policies-shield-consumers-rising-energy-prices> [Accessed 26 2 2024].
- IMF, 2022. *World Economic Outlook database*, Washington, DC: International Monetary Fund.
- CMS, 2015. *Electricity Law and Regulation in Italy*, Frankfurt : CMS.
- Rotondi , F. & Salzano, G., 2021. *Italy Is Lagging Its European Union Peers on Energy Autonomy*, London : Bloomberg.
- IEA, 2020. *Energy statistics, Italy*, Paris: IEA.
- Brown, S., 2021. *Italy's deployment of wind and solar has stagnated*, London: Ember Global Electricity Review.
- International Trade Administration, 2020. *Italy - Country Commercial Guide*, Milan: International Trade Administration.

Speak, C., 2022. *Italy announces plan to end reliance on Russian gas by 2025*, Stockholm: The Local.

Eurostat, 2020. *Energy imports dependency*, Luxembourg: Eurostat.

Andreolli, F. et al., 2023. *The Consequences of the Ukraine war and the EU Sanctions on the Energy Sector in Europe*. 1 ed. Berlin: Friedrich-Ebert-Stiftung.

Bianchi, M. & Raimondi, P. P., 2022. *Russian Energy Exports and the Conflict in Ukraine: What Options for Italy and the EU?*, Rome: Istituto Affari Internazionali .

Balsalobre-Lorente, D., Sinha, A. & Murshed, M., 2023. Russia-Ukraine conflict sentiments and energy market returns in G7 countries: Discovering the unexplored dynamics. *Energy Economics*, 125(1), p. 106847.

European Commission, 2022. *Questions and Answers on REPowerEU: Joint European action for more affordable, secure and sustainable energy*, Strasbourg: European Union.

Brown, S., 2021. *Gas-reliant Italy lags behind in Europe's race to renewables*, London: Ember.

Bersano, A. et al., 2020. Evaluation of a potential reintroduction of nuclear energy in Italy to accelerate the energy transition. *The Electricity Journal*, 33(7), p. 106813.

Frilingou, N. et al., 2023. Navigating through an energy crisis: Challenges and progress towards electricity decarbonisation, reliability, and affordability in Italy. *Energy Research & Social Science*, 96(1), p. 102934.

Magazzino, C. & Giolli, . L., 2024. Analyzing the relationship between oil prices and renewable energy sources in Italy during the first COVID-19 wave through quantile and wavelet analyses. *Renewable Energy Focus*, 48(1), p. 100544.

Arslan, O. & Er, I. D., 2008. SWOT analysis for safer carriage of bulk liquid chemicals in tankers. *Journal of Hazardous Materials*, 154(1), pp. 901-913.

Kuzemko, C., Blondeel, . M., Dupont, C. & Brisbois, . M. C., 2022. Russia's war on Ukraine, European energy policy responses & implications for sustainable transformations. *Energy Research & Social Science*, 92(1), p. 102842.

Colgan, J. D., Gard-Murray, A. S. & Hinthorn, . M., 2023. Quantifying the value of energy security: How Russia's invasion of Ukraine exploded Europe's fossil fuel costs. *Energy Research & Social Science*, 103(1), p. 103201.

Hasan, Y., 2022. Russia-Ukraine Crisis and Energy Insecurity: Is energy transition a sustainable alternate?. *Journal of Peace and Diplomacy*, 3(1), p. 30–46.

Borasio, M. & Moret, S., 2022. Deep decarbonisation of regional energy systems: A novel modelling approach and its application to the Italian energy transition. *Renewable and Sustainable Energy Reviews*, 153(1), p. 111730.

Esposito, L. & Romagnoli, G., 2023. Overview of policy and market dynamics for the deployment of renewable energy sources in Italy: Current status and future prospects. *Heliyon*, 9(7), p. e17406.

Bigerna, S., Ceccacci, . F., Micheli, . S. & Polinori, P., 2023. Between saying and doing for ensuring energy resources supply: The case of Italy in time of crisis. *Resources Policy*, 25(A), p. 103782.

Figini, G. & Moreno, R. S., 2023. 2023/2 The Russian Disruption and its Repercussions on Italy's Energy System. *Europe in Formation*, 2(397), pp. 139-151.

Ntanos, S. et al., 2018. Public Perceptions and Willingness to Pay for Renewable Energy: A Case Study from Greece. *Sustainability*, 10(3), p. 687.

Colasante, A., D'Adamo, I. & Morone, P., 2021. Nudging for the increased adoption of solar energy? Evidence from a survey in Italy. *Energy Research & Social Science*, 74(1), p. 101978.

Solarin, S. A., Bello, M. O. & Bekun, F. . V., 2021. Sustainable electricity generation: the possibility of substituting fossil fuels for hydropower and solar energy in Italy. *International Journal of Sustainable Development & World Ecology*, 28(5), pp. 429-439.

Cergibozan, R., 2022. Renewable energy sources as a solution for energy security risk: Empirical evidence from OECD countries. *Renewable Energy*, 183(1), pp. 617-626.

Gastaldi, F. C. M. & Trosini, M., 2017. Investments and cleaner energy production: A portfolio analysis in the Italian electricity market. *Journal of Cleaner Production*, 142(1), pp. 121-132.

Wang, Y., Xu, L. & Solangi, Y. A., 2020. Strategic renewable energy resources selection for Pakistan: Based on SWOT-Fuzzy AHP approach. *Sustainable Cities and Society*, 52(1), p. 101861.

Shadman, S. et al., 2021. The role of current and future renewable energy policies in fortifying Malaysia's energy security: PESTLE and SWOT analysis through stakeholder engagement. *Progress in Energy and Environment*, 16(1), pp. 1-17.

Pramanik, D., Mondal, S. C. & Haldar, A., 2020. A framework for managing uncertainty in information system project selection: an intelligent fuzzy approach. *International Journal of Management Science and Engineering Management*, 15(1), pp. 70-78.

Safder, U., Hai, T. N., Loy-Benitez, J. & Yoo, C., 2022. Nationwide policymaking strategies to prevent future electricity crises in developing countries using data-driven forecasting and fuzzy-SWOT analyses. *Energy*, 259(1), p. 124962.

Vyas, V., Singh, A. P. & Srivastava, A., 2021. Entropy-based fuzzy SWOT decision-making for condition assessment of airfield pavements. *International Journal of Pavement Engineering*, 22(10), pp. 1226-1237.

- Srinivas, R. et al., 2018. Sustainable management of a river basin by integrating an improved fuzzy based hybridized SWOT model and geo-statistical weighted thematic overlay analysis. *Journal of Hydrology*, 563(1), pp. 92-105.
- Karimi, M., Niknamfar, A. H. & Niaki, S. T. A., 2019. An application of fuzzy-logic and grey-relational ANP-based SWOT in the ceramic and tile industry. *Knowledge-Based Systems*, 163(1), pp. 581-594.
- Karatop, B. & Taşkan, B., 2021. A New Integrated Approach for Determination of Turkey's Solar Energy Production Strategies: The Fuzzy Expanded SWOT. *Gazi Üniversitesi Fen Bilimleri Dergisi Part: C Tasarım ve Teknoloji*, 9(4), pp. 621-644.
- Amin, S. . H., 2011. Supplier selection and order allocation based on fuzzy SWOT analysis and fuzzy linear programming. *Expert Systems with Applications*, 38(1), pp. 334-342.
- Babar, A. H. K., Ali, Y. & Khan , A. . U., 2020. Moving toward green mobility: overview and analysis of electric vehicle selection, Pakistan a case in point. *Environment, Development and Sustainability*.
- Khan, F. & Ali, Y., 2022. Moving towards a sustainable circular bio-economy in the agriculture sector of a developing country. *Ecological Economics*, 196(1), p. 107402.
- Touazi, I., 2023. Energy Security and Gas Pipeline Diplomacy: Italy's Mediterranean Foreign Policy Post Russia-Ukraine War between Security Threats and Geostrategic Competition. *ITSS Verona Magazine*, 2(1).
- Khan, F., Ali, Y. & Khan, A. U., 2020. Sustainable hybrid electric vehicle selection in the context of a developing country. *Air Quality, Atmosphere & Health volume*, 13(1), p. 489–499.
- Zadeh, L., 1965. Fuzzy sets. *Information and Control*, 8(3), pp. 338-353.
- Chou, S.-Y. & Chang, Y.-H., 2008. A decision support system for supplier selection based on a strategy-aligned fuzzy SMART approach. *Expert Systems with Applications*, 34(4), pp. 2241-2253.
- Ruiz, H. et al., 2020. GIS-AHP Multi Criteria Decision Analysis for the optimal location of solar energy plants at Indonesia. *Energy Reports*, 6(1), pp. 3249-3263.
- Rediske, G. et al., 2021. Wind power plant site selection: A systematic review. *Renewable and Sustainable Energy Reviews*, 148(1), p. 111293.
- Meeus, L. & Saguan, M., 2011. Innovating grid regulation to regulate grid innovation: From the Orkney Isles to Kriegers Flak via Italy. *Renewable Energy*, 36(6), pp. 1761-1765.
- Laurentis, C. D. & Pearson, P. J. G., 2021. Policy-relevant insights for regional renewable energy deployment. *Energy, Sustainability and Society volume*, 11(1), p. 19.
- IEA, 2023. *Italy - countries & regions*, Paris: International Energy Agency (IEA).

Fava, F. et al., 2021. The bioeconomy in Italy and the new national strategy for a more competitive and sustainable country. *New Biotechnology*, 61(1), pp. 124-136.

European Commission, 2022. *BIOENERGY IN THE EUROPEAN UNION*, Ispra: European Commission.

Jain, A. et al., 2022. Bioenergy and bio-products from bio-waste and its associated modern circular economy: Current research trends, challenges, and future outlooks. *Fuel*, 307(1), p. 121859.

IEA, 2021. *Implementation of bioenergy in Italy – 2021 update*, Paris: IEA Bioenergy.

Global Data, 2022. *Italy Biopower Market Size and Trends by Installed Capacity, Generation and Technology, Regulations, Power Plants, Key Players and Forecast, 2022-2035*, s.l.: Global Data.

Moliner, C., Arato, E. & Marchelli, F., 2021. Current Status of Energy Production from Solid Biomass in Southern Italy. *Energies*, 14(9), p. 2576.

IEA, 2023. *International Energy Association*. [Online] Available at: <https://www.iea.org/countries/italy/renewables> [Accessed 28 2 2024].

Global Data, 2023. *Global Data*. [Online] Available at: https://www.globaldata.com/store/report/italy-hydropower-market-analysis/?utm_source=lgp5-power-generation&utm_medium=21-210274&utm_campaign=thematic-report-hyperlink&_gl=1*1qmkmnd*_ga*MTE5Mjk5NzY4OS4xNzA5MTM1MDI3*_ga_1WM9T40P2F*MTcwOTEzNTAyOS4xLjEuMTcwOT [Accessed 28 2 2024].

Enel, 2021. *How much hydroelectric energy is produced in Italy and where*. [Online] Available at: <https://www.enelgreenpower.com/learning-hub/renewable-energies/hydroelectric-energy/italy> [Accessed 12 January 2023].

Algieri, A., Zema, D. . A., Nicotra, A. & Zimbone, S. M., 2020. Potential energy exploitation in collective irrigation systems using pumps as turbines: A case study in Calabria (Southern Italy). *Journal of Cleaner Production*, 257(1), p. 120538.

Hive Power, 2021. *Renewable Energy In Italy: What You Should Know*. [Online] Available at: <https://www.hivepower.tech/blog/renewable-energy-in-italy-what-you-should-know> [Accessed 13 January 2023].

IEA , 2021. *Implementation of bioenergy in Italy – 2021 update*, Paris: IEA Bioenergy.

Enel, 2021. *Renewable energy in Italy: what kinds are out there, how much is produced, and how widespread is it*, Rome: Enel Green Power.

Electricity Future, 2021. *Electricity Future*. [Online]
Available at: https://www.elettricitafutura.it/News-/Comunicati-Stampa/Europe-calls-for-the-energy-transition-in-Italy-Simplification-Decree-has-to-speed-up-the-renewables_3574.html
[Accessed 13 January 2023].

Ford, N., 2021. *Italy set for solar surge that could uncouple markets*, London: Reuters.

Reve, 22. *Messy permitting leads to yet another undersubscribed wind energy auction in Italy*. [Online]
Available at: <https://www.evwind.es/2022/02/01/messy-permitting-leads-to-yet-another-undersubscribed-wind-energy-auction-in-italy/84451>
[Accessed 14 January 2023].

Yzquierdo, J. H. & Sánchez-Bayón, A., 2020. The European transition to a green energy production model: Italian feed-in tariffs scheme & Trentino Alto Adige mini wind farms case study. *Small Business in International Review*, 4(2), pp. 39-52.

Caporale, D. & Lucia, C. D., 2015. Social acceptance of on-shore wind energy in Apulia Region (Southern Italy). *Renewable and Sustainable Energy Reviews*, 52(1), pp. 1378-1390.

Barooni, M. et al., 2023. Floating Offshore Wind Turbines: Current Status and Future Prospects. *Energies*, 16(1), p. 2.

Carlini, E. M. et al., 2022. *Integration of Wind Offshore Generation into the Italian Transmission Network: connection solutions and case study*. Rome, IEEE, pp. 1-6.

Doukas, H. et al., 2022. Wind repowering: Unveiling a hidden asset. *Renewable and Sustainable Energy Reviews*, 162(1), p. 112457.

International Trade Administration, 2022. *Natural Gas & Renewable Energy*, Washington, D.C: International Trade Administration.

Profili, F. et al., 2018. Health effects among a cohort exposed to low-level arsenic in a geothermal area of Tuscany, Italy. *International Archives of Occupational and Environmental Health* volume, 91(1), p. 971–979.

Kabeyi, M. J. B., 2019. Geothermal Electricity Generation, Challenges, Opportunities and Recommendations. *International Journal of Advances in Scientific Research and Engineering (IJASRE)*, 5(8), p. 53–95.

Meredith, S., 2022. *Russia is squeezing Europe’s gas supplies, sparking a bitter and reluctant return to coal*, Englewood Cliffs: Sustainable energy (CNBC).

Thimet, P. & Mavromatidis, v., 2022. Review of model-based electricity system transition scenarios: An analysis for Switzerland, Germany, France, and Italy. *Renewable and Sustainable Energy Reviews*, 159(1), p. 112102.

Ghilès, F., 2022. *As North African energy links are redrawn, Italy becomes Europe's southern gas hub*, Barcelona: Notes Internacionals CIDOB.

Malinauskaite, J. et al., 2019. Energy efficiency in industry: EU and national policies in Italy and the UK. *Energy*, 172(1), pp. 255-269.

Monforti, F. et al., 2014. Assessing complementarity of wind and solar resources for energy production in Italy. A Monte Carlo approach. *Renewable Energy*, 63(1), pp. 576-586.

Khan, F., Ali, Y. & Pamucar, D., 2022. A new fuzzy FUCOM-QFD approach for evaluating strategies to enhance the resilience of the healthcare sector to combat the COVID-19 pandemic. *Kybernetes*, 51(4), pp. 1429-1451.

Nucci, M. R. D. & Prontera, A., 2023. The Italian energy transition in a multilevel system: between reinforcing dynamics and institutional constraints. *Zeitschrift für Politikwissenschaft*, 33(1), p. 181–204.

European Council, 2024. *Fit for 55*, Brussels: European Council: Council of the European Union.

NS Energy, 2023. *Med Wind Floating Offshore Wind Park*, London: NS Energy.

Terna, 2023. *Terna: By the end of 2022 connection solutions will be provided for 95 GW of new offshore wind power*, Rome: Terna.

Serri, L., Colle, L., Vitali, B. & Bonomi, T., 2020. Floating Offshore Wind Farms in Italy beyond 2030 and beyond 2060: Preliminary Results of a Techno-Economic Assessment. *Applied Sciences*, 10(24), p. 8899.

Al-Anbar, M. A., Thamee, M. Y. & Al-Ansari, N., 2018. Landfill Site Selection by Weighted Overlay Technique: Case Study of Al-Kufa, Iraq. *Sustainability*, 10(4), p. 999.

Astrald, M., Gasparini, G. P., Gervasio, L. & Salusti, E., 2001. Dense Water Dynamics along the Strait of Sicily (Mediterranean Sea). *Journal of Physical Oceanography*, 31(12), p. 3457–3475.

Hexicon, 2022. *Hexicon*. [Online] Available at: https://www.hexicongroup.com/mfn_news/strong-development-for-hexicon-in-italy-concession-applications-filed-for-several-floating-wind-farms/#:~:text=The%20offshore%20wind%20farm%20in,Sardinia%2C%20Sicily%2C%20and%20Puglia. [Accessed 15 November 2023].

- Yap, J. Y. L., Ho, C. . C. & Ting , C.-Y., 2019. A systematic review of the applications of multi-criteria decision-making methods in site selection problems. *Built Environment Project and Asset Management*, 9(4), pp. 548-563.
- Shao, M. et al., 2024. A novel framework for wave power plant site selection and wave forecasting based on GIS, MCDM, and ANN methods: A case study in Hainan Island, Southern China. *Energy Conversion and Management*, 299(1), p. 117816.
- Shao, M. et al., 2020. A review of multi-criteria decision making applications for renewable energy site selection. *Renewable Energy*, 157(1), pp. 377-403.
- Peters, J. . L. et al., 2020. A systematic review and meta-analysis of GIS use to reveal trends in offshore wind energy research and offer insights on best practices. *Renewable and Sustainable Energy Reviews*, 128(1), p. 109916.
- Martinez, A. & Iglesias, . G., 2021. Multi-parameter analysis and mapping of the levelised cost of energy from floating offshore wind in the Mediterranean Sea. *Energy Conversion and Management*, 243(1), p. 114416.
- Martinez, A. & Iglesias, . G., 2022. Mapping of the levelised cost of energy for floating offshore wind in the European Atlantic. *Renewable and Sustainable Energy Reviews*, 154(1), p. 111889.
- ANEV, 2021. *OFFSHORE WIND POWER*, Rome: ANEV.
- Taoufik, M. & Fekri, A., 2021. GIS-based multi-criteria analysis of offshore wind farm development in Morocco. *Energy Conversion and Management: X*, 11(1), p. 100103.
- Tercan, E. et al., 2020. A GIS-based multi-criteria model for offshore wind energy power plants site selection in both sides of the Aegean Sea. *Environmental Monitoring and Assessment*, 192(1), p. 652.
- Sánchez-Lozano, J. M. et al., 2022. A GIS-based offshore wind site selection model using fuzzy multi-criteria decision-making with application to the case of the Gulf of Maine. *Expert Systems with Applications*, 210(1), p. 118371.
- Feizi, F., Karbalaee-Ramezanali, . A. A. & Farhadi , S., 2021. FUCOM-MOORA and FUCOM-MOOSRA: new MCDM-based knowledge-driven procedures for mineral potential mapping in greenfields. *SN Applied Sciences*, 3(1), p. 358.
- Khan, F. & Ali, Y., 2022. Implementation of the circular supply chain management in the pharmaceutical industry. *Environment, Development and Sustainability volume*, 24(1), p. 13705–13731.

- Everest, T., Savaşkan, G. S., Or, A. & Özcan, H., 2022. Suitable site selection by using full consistency method (FUCOM): a case study for maize cultivation in northwest Turkey. *Environment, Development and Sustainability*, 26(1), p. 1831–1850.
- Ulutas, A. & Karakus, C. B., 2021. Location selection for a textile manufacturing facility with GIS based on hybrid MCDM approach. *INDUSTRIA TEXTILA*, 72(2), pp. 126-132.
- Tulun, Ş., Arsu, T. & Gürbüz, E., 2023. Selection of the most suitable biogas facility location with the geographical information system and multi-criteria decision-making methods: a case study of Konya Closed Basin, Turkey. *Biomass Conversion and Biorefinery volume*, 13(1), p. 3439–3461.
- Sadegh, H. et al., 2023. Assessing the vulnerability of Iran to subsidence hazard using a hierarchical FUCOM-GIS framework. *Remote Sensing Applications: Society and Environment*, 31(1), p. 100989.
- Khan, A., Ali, Y. & Pamucar, D., 2023. Solar PV power plant site selection using a GIS-based non-linear multi-criteria optimization technique. *Environmental Science and Pollution Research volume*, 30(1), p. 57378–57397.
- Deveci, M. et al., 2022. Hybrid q-Rung Orthopair Fuzzy Sets Based CoCoSo Model for Floating Offshore Wind Farm Site Selection in Norway. *CSEE Journal of Power and Energy Systems*, 8(5), pp. 1261-1280.
- Gil-García, I. C., Ramos-Escudero, A., Dagher, H. & Molina-García, A., 2022. Fuzzy GIS-based MCDM solution for the optimal offshore wind site selection: The Gulf of Maine case. *Renewable Energy*, 183(1), pp. 130-147.
- Li, Z., Tian, G. & El-Shafay, A., 2022. Statistical-analytical study on world development trend in offshore wind energy production capacity focusing on Great Britain with the aim of MCDA based offshore wind farm siting. *Journal of Cleaner Production*, 363(1), p. 132326.
- Ifkirne, M. et al., 2022. Multi-Criteria GIS-Based Analysis for Mapping Suitable Sites for Onshore Wind Farms in Southeast France. *Land*, 11(10), p. 1839.
- Vagiona, D. G. & Kamilakis, M., 2018. Sustainable Site Selection for Offshore Wind Farms in the South Aegean—Greece. *Sustainability*, 10(3), p. 749.
- Gkeka-Serpetsidaki, P. & Tsoutsos, T., 2021. Sustainable site selection of offshore wind farms using GIS-based multi-criteria decision analysis and analytical hierarchy process. Case study: Island of Crete (Greece). *Low Carbon Energy Technologies in Sustainable Energy Systems*, pp. 329-342.

Konurhan, Z., Yücesan, . M. & Gül, . M., 2023. An integrated Bayesian Best-Worst Method and GIS-based approach for offshore wind power plant site selection: A case study in North Aegean and Marmara Sea (Türkiye). *Turkish Geographical Review*, 82(1), pp. 7 - 22.

Ecer, F. & Pamucar, D., 2020. Prioritizing the weights of the evaluation criteria under fuzziness: the fuzzy full consistency method – FUCOM-F. *Facta Universitatis Series Mechanical Engineering*, 18(3), pp. 419-437.

Astraldi, M. et al., 1999. The role of straits and channels in understanding the characteristics of Mediterranean circulation. *Progress in Oceanography*, 44(1), pp. 65-108.

4C Offshore , 2023. *Global Offshore Map*. [Online] Available at:

<https://map.4coffshore.com/offshorewind/index.aspx?lat=37.957&lon=11.447&wfid=IT48>

Global Wind Atlas, 2023. *Global Wind Atlas 3.0*. [Online] Available at:

<https://globalwindatlas.info/en/>

[Accessed 23 11 2023].

AEOLIAN, 2023. *AEOLIAN*. [Online] Available at:

<https://atlanteecolico.rse-web.it>

[Accessed 23 11 2023].

European Commission, 2023. *EMODnet Map Viewer*. [Online] Available at:

<https://emodnet.ec.europa.eu/geoviewer/#>

[Accessed 23 11 2023].

GEBCO, 2023. *Gridded Bathymetric Data*. [Online] Available at:

https://www.gebco.net/data_and_products/gridded_bathymetry_data/

[Accessed 23 11 2023].

Straume, E. et al., 2019. *National Ocean and Atmospheric Administration*. [Online] Available at:

<https://www.ngdc.noaa.gov/mgg/sedthick/>

[Accessed 4 12 2023].

Open Street Map, 2023. *OpenStreetMap data*. [Online] Available at:

<https://www.openstreetmap.org/copyright>

[Accessed 6 12 2023].

ZES Sicilia Orientale, 2023. *ZES Sicilia Orientale*. [Online] Available at:

<https://www.sitr.regione.sicilia.it/portal/apps/webappviewer/index.html?id=38480aa2dac24f3f8c0039a95378eaae>

[Accessed 6 12 2023].

EMODnet Map Viewer, 2023. *EMODnet Human Activities*. [Online]
Available at: <https://emodnet.ec.europa.eu/geoviewer/>
[Accessed 6 12 2023].

EMODnet Map Viewer, 2023. *EMODnet Human Activities*. [Online]
Available at: <https://emodnet.ec.europa.eu/geoviewer/>
[Accessed 6 12 2023].

EMODnet Map Viewer, 2023. *EMODnet Human Activities*. [Online]
Available at: <https://emodnet.ec.europa.eu/geoviewer/>
[Accessed 6 12 2023].

Emodnet Map Viewer, 2023. *Administrative units*. [Online]
Available at: <https://emodnet.ec.europa.eu/geoviewer/>
[Accessed 5 12 2023].

EMODnet Map Viewer, 2023. *Administrative units*. [Online]
Available at: <https://emodnet.ec.europa.eu/geoviewer/>
[Accessed 6 12 2023].

Wessel, P. & Smith, W. . H. F., 1996. A global, self-consistent, hierarchical, high-resolution shoreline database. *Journal of Geophysical Research*, 101(B4), pp. 8741-8743.

Terna, 2023. *Terna and the Sicilian Region: 2023-2032 2023-2032 National Electricity Grid Development Plan Meeting*, Rome: Terna.

Entsoe, 2023. *Entsoe*. [Online]
Available at: <https://www.entsoe.eu/data/map/downloads/>
[Accessed 5 12 2023].

Sicilian Region, 2023. *Department of the Territory and the Environment*. [Online]
Available at: [Department of the Territory and the Environment](#)
[Accessed 6 12 2023].

Blue Flag , 2023. *Blue Flag Beaches*. [Online]
Available at: <https://www.blueflag.global/all-bf-sites>
[Accessed 5 12 2023].

European Environmental Agency, 2020. *European Environmental Agency*. [Online]
Available at: [European Environmental Agency](#)
[Accessed 5 12 2023].

ArcGIS online, 2023. *World Database of Protected Areas*. [Online]
Available at: <https://www.arcgis.com/apps/mapviewer/index.html?layers=ae78aeb913a343d69e950b53e29>

076f7

[Accessed 5 12 2023].

United Nations, 2023. *UN Environment Programme World Conservation Monitoring*. [Online] Available at:

<https://data-gis.unep-wcmc.org/portal/apps/mapviewer/index.html?layers=1919c32890074ce5a589a1a99b48994b>

[Accessed 5 12 2023].

Bird Life International, 2023. *Bird Life International*. [Online] Available at:

<https://migrationatlas.org/node/1678>

[Accessed 5 12 2023].

Movebank, 2023. *Move Bank for animal tracking data*. [Online] Available at:

https://www.movebank.org/cms/webapp?gwt_fragment=page%3Dsearch_map_linked%2CsensorTypeId%3D653%2CstudyIds%3D173641633%2Clat%3D42.30653582280873%2Clon%3D10.69938000000054%2Cz%3D6

[Accessed 5 12 2023].

Kays, R. et al., 2022. The Movebank system for studying global animal movement and demography. *Methods in Ecology and Evolution*, 13(2), pp. 419-431.

Spanoghe, G. et al., 2023. *BOP_RODENT - Rodent specialized birds of prey (Circus, Asio, Buteo) in Flanders (Belgium)*, Belgium: Research Institute for Nature and Forest (INBO).

Brønnvik, H. et al., 2022. Experience does not change the importance of wind support for migratory route selection by a soaring bird. *The Royal Society*, 9(12), p. 220746.

Bilgili, M., Alphan, . H. & Ilhan , A., 2023. Potential visibility, growth, and technological innovation in offshore wind turbines installed in Europe. *Environmental Science and Pollution Research*, 30(1), p. 27208–27226.

Gigović, L., Pamučar, . D., Božanić, . D. & Ljubojević , S., 2017. Application of the GIS-DANP-MABAC multi-criteria model for selecting the location of wind farms: A case study of Vojvodina, Serbia. *Renewable Energy*, 103(1), pp. 501-521.

SEANSE, 2020. *Planning Criteria for Offshore Wind Energy*, Netherlands: SEANSE.

The Ministry of Infrastructure and the Environment, 2014. *White paper on Offshore Wind Energy*, The Hague: The Ministry of Infrastructure and the Environment.

Serri, L., Colle, L., Vitali, B. & Bonomi, T., 2020. Floating Offshore Wind Farms in Italy beyond 2030 and beyond 2060: Preliminary Results of a Techno-Economic Assessment. *Applied Sciences*, 10(24), p. 8899.

- Terna, 2023. *Terna and the Sicilian Region: 2023-2032 2023-2032 National Electricity Grid Development Plan Meeting*, Rome: Terna.
- Vagion, D. G. & Kamilakis, M., 2018. Sustainable Site Selection for Offshore Wind Farms in the South Aegean—Greece. *Sustainability*, 10(3), p. 749.
- Santos, C. D. et al., 2022. Factors influencing wind turbine avoidance behaviour of a migrating soaring bird. *Scientific Reports*, 12(1), p. 6441.
- Zadeh, L., 1965. Fuzzy sets. *Information and Control*, 8(3), pp. 338-353.
- Pamučar, D., Stević, Ž. & Sremac, S., 2018. A New Model for Determining Weight Coefficients of Criteria in MCDM Models: Full Consistency Method (FUCOM). *Symmetry*, 10(9), p. 393.
- Sheridan, B. et al., 2012. Calculating the offshore wind power resource: Robust assessment methods applied to the U.S. Atlantic Coast. *Renewable Energy*, 43(1), pp. 224-233.
- European Commission, 2023. *Hydrogen*, Brussels: European Commission.
- Marco, G., 2022. *Italy in the international hydrogen economy*, Rome: Istituto Affari Internazionali.
- Vogl, V., Åhman, M. & Nilsson, L. J., 2018. Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production*, 203(1), pp. 736-745.
- Gérard, F. et al., 2020. *Opportunities for hydrogen energy technologies considering the climate energy and actions*, Rotterdam: Fuel cells and hydrogen joint undertaking.
- ITA, 2024. *Italy Energy Storage*, Washington, D.C.: International Trade Administration.
- Ministry of Economic Development, 2020. *Piano Nazionale Integrato Per PIANO L'Energia e il Clima*, Rome: Ministero dello Sviluppo Economico.
- IEA, 2021. *National Hydrogen Strategy Preliminary Guidelines*, Paris: International Energy Agency.
- Gandiglio, M. & Marocco, P., 2024. Mapping Hydrogen Initiatives in Italy: An Overview of Funding and Projects. *Energies*, 17(11), p. 2614.
- Eniscoula, 2022. *Wind power in Italy: where do we stand?*, Rome: Eniscoula.
- Man, J., Ma, T., Yu, Y. & Ren, H., 2024. Levelized costs and potential production of green hydrogen with wind and solar power in different provinces of mainland China. *Journal of Renewable Sustainable Energy*, 16(1), p. 025902.
- Vidas, L., Castro, R., Bosisio, A. & Pires, A., 2024. Optimal sizing of renewables-to-hydrogen systems in a suitable-site-selection geospatial framework: The case study of Italy and Portugal. *Renewable and Sustainable Energy Reviews*, 202(1), p. 114620.

Correa , G. et al., 2022. Evaluation of levelized cost of hydrogen produced by wind electrolysis: Argentine and Italian production scenarios. *Journal of Energy Storage*, 52(B), p. 105014.

Pastore, L. M., Basso, G. L., Sforzini , M. & Santoli, L. d., 2022. Technical, economic and environmental issues related to electrolyzers capacity targets according to the Italian Hydrogen Strategy: A critical analysis. *Renewable and Sustainable Energy Reviews*, 166(1), p. 112685.

Superchi , F., Mati, . A., Carcasci , C. & Bianchini, . A., 2023. Techno-economic analysis of wind-powered green hydrogen production to facilitate the decarbonization of hard-to-abate sectors: A case study on steelmaking. *Applied Energy*, 342(1), p. Applied Energy.

Frangiaco , P. & Genovese, . M., 2020. Technical-economic analysis of a hydrogen production facility for power-to-gas and hydrogen mobility under different renewable sources in Southern Italy. *Energy Conversion and Management*, 223(1), p. 113332.

Marocco, P. et al., 2024. Design of hydrogen production systems powered by solar and wind energy: An insight into the optimal size ratios. *Energy Conversion and Management*, 314(1), p. 118646.

Superchi, F. et al., 2023. Development of a reliable simulation framework for techno-economic analyses on green hydrogen production from wind farms using alkaline electrolyzers. *Renewable Energy*, 207(1), pp. 731-742.

Colangelo, G., Spirito, . G., Milanese, . M. & Risi, A. d., 2024. Hydrogen production from renewable energy resources: A case study. *Energy Conversion and Management*, 311(1), p. 118532.

Correa, G. et al., 2022. Pressurized PEM water electrolysis: Dynamic modelling focusing on the cathode side. *International Journal of Hydrogen Energy*, 47(7), pp. 4315-4327.

Siemens Gamesa, 2025. *Siemens Gamesa*. [Online] Available at: <https://www.siemensgamesa.com/global/en/home/products-and-services/onshore/wind-turbine-sg-3-4-132.html> [Accessed 7 1 2025].

Climate Action Programme, 2025. *"New 'Renewables ninja' calculates solar and wind power availability*. [Online] Available at: <https://www.renewables.ninja> [Accessed 7 1 2025].

Marocco, P. et al., 2024. Design of hydrogen production systems powered by solar and wind energy: An insight into the optimal size ratios. *Energy Conversion and Management*, 314(1), p. 118646.

- Yates, J. et al., 2020. Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis. *Cell Reports Physical Science*, 1(10), p. 100209.
- Travaglini, R. et al., 2024. Towards the development of offshore wind farms in the Mediterranean Sea: A techno-economic analysis including green hydrogen production during curtailments. *IET Renewable Power Generation*, 18(15), pp. 3112-3126.
- U.S. Department of Energy, 2014. *Proceedings from the Electrolytic Hydrogen Production Workshop*, Golden, Colorado: National Renewable Energy Laboratory.
- Hancke, R., Bujlo, . P., Holm, . T. & Ulleberg, Ø., 2024. High-pressure PEM water electrolyser performance up to 180 bar differential pressure. *Journal of Power Sources*, 601(1), p. 234271.
- Hodges, A. et al., 2022. A high-performance capillary-fed electrolysis cell promises more cost-competitive renewable hydrogen. *Nature Communications* , 22(1), p. 1304.
- Aricò, A. S., 2015. *Enhanced performance and cost-effective materials for long-term operation of PEM water electrolyzers coupled to renewable power sources*, Messina: European Commission.
- Böhm, H., Zauner, . A., Rosenfeld, D. C. & Tichler, R., 2020. Projecting cost development for future large-scale power-to-gas implementations by scaling effects. *Applied Energy*, 264(1), p. 114780.
- Böhm, H., Zauner, . A., Rosenfeld, . D. C. & Tichler, R., 2020. Projecting cost development for future large-scale power-to-gas implementations by scaling effects. *Applied Energy*, 264(1), p. 114780.
- Galparsoro, I. et al., 2022. Reviewing the ecological impacts of offshore wind farms. *npj Ocean Sustainability volume*, 1(1).
- Bergström, L., Sundqvist, F. & Bergström, U., 2013. Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. *Marine Ecology Progress Series*, 485(1), pp. 199-210.
- Vázquez, A. et al., 2022. A macroscale optimal substructure selection for Europe's offshore wind farms. *Sustainable Energy Technologies and Assessments*, 53(D), p. 102768.