Politecnico di Torino

Master's Engineering and Management

Academic Year 2024/2025

A Hybrid MCDM and GIS Framework for Offshore Wind Development: A Case Study of Site Selection and Roadmap for Chile

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ABSTRACT

”A Hybrid MCDM and GIS Framework for Offshore Wind Development: A Case Study of Site Selection and Roadmap for Chile”

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As the global energy sector shifts toward cleaner and more sustainable sources, offshore wind is emerging as a crucial component for achieving sustainable development and reducing carbon emissions. Against this background, this thesis presents a hybrid multi-criteria decision-making (MCDM) and GIS framework that aims to identify optimal sites for offshore wind by integrating spatial planning analysis with MCDM techniques. Using GIS, key environmental, technical, and social criteria are mapped and analyzed. The Analytic Hierarchy Process (AHP) is applied to weight these criteria, and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is then used to rank the identified potential sites based on their suitability. The resulting spatial suitability map then classifies sites into Zones A, B, and C, which, along with MDCM, are used again to benchmark the country. The qualitative analysis informs a phased roadmap with short-, medium-, and long-term milestones tailored for Chile’s institutional maturity and infrastructure readiness. This approach supports adaptive management, enabling scalable development aligned with technological advances and policy evolution. Results indicate that the highest suitability is concentrated in the southern regions, characterized by sufficient availability of wind resource and strategic proximity to incipient port infrastructures. This zone is a prime candidate, particularly because of its synergy with green hydrogen production. Notably, floating wind technology dominates approximately 73% of the total suitable areas, reflecting Chile’s predominantly deep coastal waters. However, diverse challenges are identified, including limited grid infrastructure and the Southern Macrozone conflict. The results provide data-driven input for developing a phased development roadmap and actionable novel insights for policymakers, investors, and stakeholders seeking to accelerate Chile’s transition to sustainable energy.

ACKNOWLEDGEMENTS

No puedo sino sentirme en deuda e infinitamente agradecida con un sinfín de personas cuyo apoyo incondicional logró que llegara al culmine de esta importante etapa de mi vida y, después de un largo y sinuoso camino, pueda escribir la tesis que acá presento.

En primer lugar, quiero agradecer a mis guías, Emiliano Nelon Gorr y Claudio Moscoloni, cuyas mentes brillantes me ayudaron a dilucidar y crear el camino que posteriormente formó los resultados plasmados en este documento. Gracias por su compromiso e invaluable tiempo dedicado al desarrollo de esta investigación.

A mi familia, a Catalina, a mi abuelita, pero especialmente a mi mamá, quien es mi fuente de inspiración y modelo a seguir. Su apoyo y frases de aliento me han ayudado a salir adelante aún en los momentos más difíciles. Y, aunque estemos a más de diez mil kilómetros de distancia, ha estado para mí cuando la necesito, siendo mi pilar fundamental desde siempre. Gracias por hacer posible que todos mis sueños se vuelvan realidad.

A mis amigas/os, aquellos que confiaron en mí y apoyaron para irme a lo desconocido, y quienes hicieron de este lugar desconocido un hogar. Gracias por llenar de historias mis días universitarios, haciéndolos más llevaderos, y por estar conmigo en mis éxitos y fracasos.

Finalmente, a mí misma, por tener la valentía de irme de casa a los dieciocho años y del país a los veintidós. Por permitirme crecer, disfrutar y cambiar en el proceso. Este logro no es solo el fin de una etapa, pero el comienzo de nuevos desafíos. Me quedo con todo lo aprendido, las historias, alegrías y presencia de aquellos que estuvieron a mi lado en este viaje.

Gracias.

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Chapter 1

Introduction

1.1 Background

Today, the global energy landscape is changing rapidly as countries move away from fossil fuels and look to cleaner, more sustainable energy sources [1]. This transition is primarily driven by the urgent need to combat climate change, improve energy security, and promote economic growth through green technologies [2]. Between the different renewable options, offshore wind power has emerged as a promising solution due to its enormous potential, strong performance, and steadily falling costs [3].

During the last 20 years, offshore wind energy has made impressive progress, especially in Europe. Several countries like Denmark, the UK, the Netherlands, and Germany have led the way, mainly supported by strong policies, cutting-edge innovation, and solid infrastructure [4]. Denmark, in particular, built the world's first offshore wind farm in 1991 and has since become a global leader, thanks to clear regulations, effective marine planning, and close cooperation among stakeholders [5].

Beyond Europe, offshore wind is also expanding rapidly across countries as China, Japan, South Korea, and Taiwan, investing heavily, and it's beginning to take off in the Americas [4]. Yet in Latin America, even though the vast technical potential of the zone exists, the technology remains underdeveloped [6].

Chile, however, presents a unique opportunity. With over 6,000 kilometers of coastline, strong offshore winds, and favorable sea conditions, it has huge capacity for offshore wind development, reaching 957 GW of technical potential. While the country has made great strides in onshore renewables, especially solar and wind, the offshore segment is still in its early stages. The government has shown a strong commitment to decarbonization, with ambitious climate goals and initiatives like the National Green Hydrogen Strategy. But offshore wind remains mostly untapped [7] [8].

Unlocking this potential in an emerging market like it is Chile case, will require a strategic and coordinated approach. It needs to be carefully balanced among technical, environmental, and social factors. Effective spatial planning is critical to select the best sites while avoiding conflicts with other ocean uses like fishing or conservation. In addition, decision-making tools that can weigh multiple factors are essential for guiding smart and sustainable development [9].

That's where the combination of Geographic Information Systems (GIS) and Multi-Criteria Decision-Making (MCDM) methods like the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) comes in. GIS helps analyze spatial data, while MCDM techniques offer a structured way to evaluate and prioritize options. Together, they create a powerful framework for evidence-based planning [10].

This integrated approach has already demonstrated its effectiveness in energy planning across various international contexts. In the case of Chile, it can inform strategic decisions on site selection, infrastructure investment, and policy design in alignment with national sustainability goals. Benchmarking against frontrunners like Denmark also highlights critical gaps and actionable reforms needed to accelerate offshore wind deployment.

Ultimately, offshore wind is not only a technical and logistical undertaking; it's also a strategic opportunity for Chile to transform its energy system, reduce carbon emissions, and position itself as a regional leader in renewable energy.

1.2 Problem Statement

Despite Chile's achievements in onshore renewable energy, offshore wind remains underdeveloped, which is paradoxical given its vast coastline and favorable wind resources, as it was mentioned before. Therefore, the gap is not due to a lack of potential but stems from a combination of systemic and institutional barriers.

There are several challenges identified that limit this technology development: limited data, a lack of clear regulations, underdeveloped marine spatial planning, and insufficient infrastructure [7]. On top of that, the high upfront costs of offshore wind highlight the need for strong policies and ways to reduce investment risk [11].

Offshore wind site selection is inherently complex, requiring the integration of environmental, technical, regulatory, and socio-economic criteria [12]. In Chile, this complexity is heightened by a lack of structured, spatially energy planning policy [7]. As a result, there is no clear pathway to identify priority areas or guide strategic development.

From a methodological standpoint, in Chile there is still room to adopt proven tools like GIS and MCDM for offshore wind planning, aligning with international best practices that demonstrated successful application of them in other countries. Furthermore, there is a lack of benchmarking against global best practices, which could inform local development, planning, and help avoid missteps [7, 10, 13].

To move forward, Chile needs an integrated, scalable framework that supports both transparent spatial site selection and strategic planning. One must be adaptable to evolving policy and market conditions while offering practical guidance for long-term development.

1.3 Research Aim and Objectives

This thesis aims to develop a hybrid GIS–MCDM framework to support the spatial planning and strategic deployment of offshore wind energy in Chile. By combining geospatial analysis with decision-making tools such as AHP and TOPSIS, the study seeks to identify suitable sites, evaluate Chile's readiness compared to global leaders and other Latin American countries, and propose a novel phased roadmap for development.

To achieve this research aim, the thesis pursues the following specific objectives:

1. **Develop a GIS–MCDM framework for offshore wind site selection in Chile.**
   Integrate GIS with MCDM techniques to evaluate spatial suitability based on environmental, technical, and infrastructural criteria.

2. **Identify and rank optimal offshore wind sites using GIS, AHP, and TOPSIS.**
   Apply AHP to assign weights to the selected criteria, apply TOPSIS to rank the most promising locations for offshore wind development, and use GIS to visualize the suitability map.

3. **Benchmark Chile's offshore wind readiness**

   Assess Chile's performance using AHP and TOPSIS-based indicators, comparing it to mature offshore wind markets to highlight gaps and inform policy recommendations, as well as other emerging markets like South American countries.

4. **Identify key barriers, policy gaps, and enabling conditions.**

   Analyze the main technical, regulatory, and economic challenges limiting offshore wind development in Chile and propose targeted reforms to foster investment and implementation.

5. **Incorporate regional and social considerations into spatial planning.**

   Analyze challenges related to marine spatial planning, territorial conflicts (e.g., in the Southern macrozone), and stakeholder engagement to ensure context-sensitive site selection.

6. **Classify suitable areas into development zones**

   Rank areas into Zones A, B, and C based on development feasibility by percentile.

7. **Propose a phased roadmap.**

   Design a phased roadmap to guide offshore wind deployment in alignment with national energy goals based on social, environmental, and suitability factors.

1.4 Significance of the Study

This study, which focuses on offshore wind development in emerging economies, significantly contributes to academic research and practical policy-making in the renewable energy sector. It offers a hybrid framework that blends MCDM methods like AHP and TOPSIS with GIS-based analysis, providing a flexible and useful method for determining the best sites for offshore wind farms. This approach is beneficial in nations like Chile, where data constraints and governance issues can make planning more difficult. The framework assists in identifying priority areas for growth by combining expert input with quantitative and spatial research. It also offers a helpful model for comparable situations worldwide.

Moreover, the research takes a broader look at Chile's overall readiness to embrace offshore wind energy. It goes beyond technical mapping by incorporating policy benchmarking, institutional analysis, and strategic tools like SWOT, PESTEL, and stakeholder mapping. It also addresses regional complexities, such as the Southern Macrozone conflict, to ensure the proposed roadmap reflects on-the-ground realities. Altogether, the study delivers grounded, evidence-based recommendations that aim to support thoughtful, phased development of offshore wind—helping Chile move toward a more sustainable and inclusive energy future.

1.5 Method Summary

To achieve the research objectives, and as it was already stated, this study adopts a hybrid methodological framework that combines MCDM techniques with GIS election in Chile. The methodological process unfolds in several key stages:

1. **Criteria Selection & Data Processing.**

   Relevant spatial and non-spatial criteria are identified through literature and international best practices. GIS layers—such as wind speed and power, bathymetry, port distance and capacity, marine protected areas, fishing grounds, and distance to grid are processed and standardized in QGIS and MATLAB, using a unified coordinate reference system (EPSG:32718 – WGS 84 / UTM zone 18S).

2. **Weighting & Suitability Mapping.**

   AHP is applied to derive weights from expert input. These weights are combined with TOPSIS to rank the most favorable offshore wind sites and composite a suitability map..

3. **Zone Classification.**

   Suitable areas identified in the GIS model are categorized into three development zones (A, B, and C), based on percentile thresholds and TOPSIS scores, to guide phased implementation.

4. **International Benchmarking.**

   AHP and TOPSIS are applied a second time to compare Chile's offshore wind readiness with that of global leaders. The assessment covers six key categories: policy and regulatory environment, technological development, economic and financial conditions, environmental and social considerations, grid infrastructure, and energy mix.

5. **Managerial Analysis:**

   A qualitative evaluation includes SWOT and PESTEL analyses, stakeholder mapping, and a case study of the Southern Macrozone conflict to contextualize barriers and opportunities.

6. **Roadmap Development.**

   The spatial, benchmarking, and managerial findings are synthesized into a strategic roadmap tailored to Chile's needs, with phased recommendations for policy, investment, and infrastructure development.

1.6 Thesis Structure

This thesis is divided into six chapters, each one building on the previous to tackle the research problem, meet the objectives, and provide a thorough analysis of offshore wind development in Chile:

Chapter 1: Introduction – Sets the scene by providing background information, defining the research problem, outlining the goals and scope, and explaining how the thesis is structured.

Chapter 2: Literature Review – Looks at the global progress of offshore wind energy, discusses technical and socio-political challenges, reviews spatial and multi-criteria decision-making methods used in energy planning, and explores Chile's current energy context.

Chapter 3: Methodology – Explains the combined approach used, including MCDM (AHP and TOPSIS) for different sets of criteria, GIS-based spatial analysis, and how results are integrated using MATLAB. It also covers the methods used for comparing Chile internationally and roadmap development.

Chapter 4: Results – Shows the outcomes of the site suitability analysis and international benchmarking, highlighting Chile's offshore wind potential as well as key strengths and challenges.

Chapter 5: Discussion – Interprets the findings within the framework of Chile's regulatory, technical, and environmental issues, drawing comparisons with best practices from leading offshore wind markets.

Chapter 6: Conclusions and Strategic Roadmap – Wraps up the study by summarizing main findings, contributions, and limitations, and offers a step-by-step roadmap along with strategic recommendations for advancing offshore wind in Chile. It also suggests areas for future research and policy development.

This structure gradually moves from broad background information to concrete, actionable insights, ensuring a clear connection between technical analysis and strategic planning for Chile's offshore wind energy future.

Chapter 2

Literature Review

2.1 Offshore Wind Energy: Global Overview

The offshore wind energy sector has emerged over the past two decades as a crucial pillar in the global transition towards a more environmentally friendly alternative to conventional electricity generation. Its increasing importance is mainly due to the growing market and the limited space available offshore [14]. In addition, compared to onshore wind technologies, offshore installations can benefit from higher and more consistent wind speeds due to the absence of obstacles such as hills, valleys, forests, and rugged terrain. This allows offshore turbines to achieve significantly higher production per installed unit [15]. Locating offshore wind farms several miles from shore can reduce conflicts with nearshore wildlife and human use activities, which causes fewer land use conflicts. It also enables large-scale utility generation near populated areas where there is insufficient area on the land for wind farms, [16]. These advantages have led to rapid global growth, with total installed offshore wind capacity reaching over 64 GW by the end of 2022. Although these significant strides have been made, achieving the 1.5 °C increase limit climate target will require scaling to 494 GW by 2030 and 2,465 GW by 2050, [17].

This technology can be broadly classified into two categories: fixed-bottom and floating systems. Although fixed-bottom turbines dominate the current market due to economic viability primarily in waters under 60 meters, floating wind technologies are gaining traction as a solution for deeper waters where the first ones are no longer feasible. The adoption of floating offshore wind technology presents a significant opportunity to unlock vast, untapped wind resources located in deepwater areas, thereby overcoming geographical limitations associated with conventional fixed-bottom installations. However, the primary challenges in implementing floating foundations involve maintaining stability, limiting displacements to acceptable levels, ensuring efficient mooring, and avoiding expensive designs, installation, and maintenance [18].

Countries like the United Kingdom, China, and Denmark have emerged as major players in offshore wind, thanks to a mix of strong government support, well-developed supply chains, and continuous investment in new technologies, for example, floating wind [19]. By the end of 2023, the UK had nearly 15 GW of offshore wind capacity installed, which is more than any other country except for China, and is aiming for an ambitious 50 GW by 2030, with 5 GW planned from floating projects [20]. As illustrated in Figure 2.1, global annual offshore wind installations witnessed a significant surge, particularly from 2021 onwards, largely driven by rapid expansion in China. The figure demonstrates the country's accelerated pace, contributing the vast majority of new installations in 2021 and maintaining a dominant share in subsequent years, while Europe has also consistently added substantial capacity. China has quickly taken the lead, commissioning 6.3 GW of new capacity in 2023 alone, which made up 58% of global additions that year [19]. Its rapid growth is fueled by national goals to shift towards cleaner energy and to have non-fossil sources cover more than 80% of energy consumption by 2060. Meanwhile, Denmark, although on a much smaller scale, continues to punch above its weight. It's among the top five countries in total offshore installations and is pushing the boundaries of offshore innovation with projects like its Energy Islands, which are large-scale artificial or existing islands that act as hubs for collecting and distributing electricity from surrounding offshore wind farms. Denmark's regulatory approach is often praised for encouraging efficiency and new ideas in the sector [21].

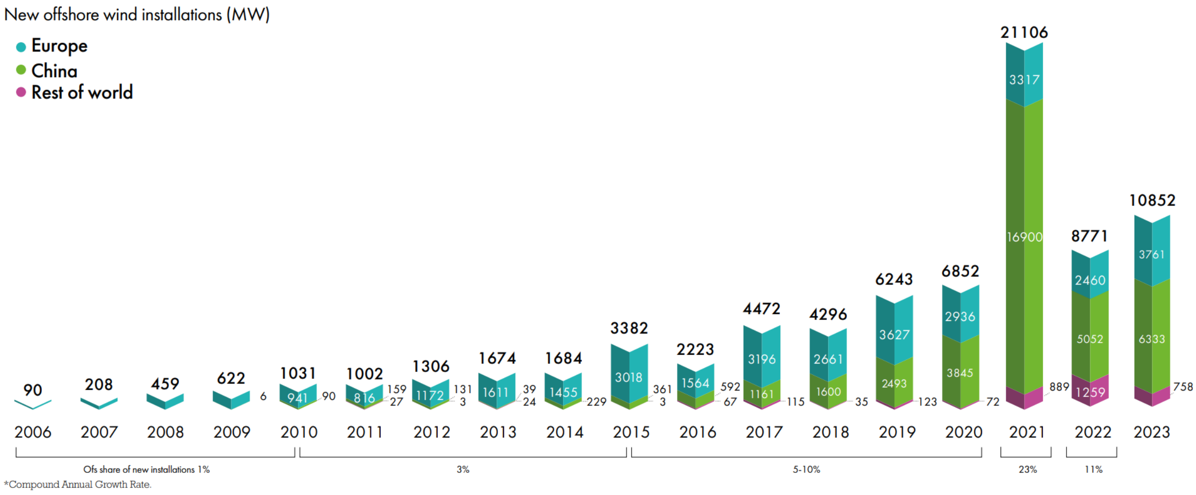

Figure 2.1: New offshore wind installations (MW) by region, 2006-2023. Source: Adapted from GWEC (2024).

Despite its significant potential, offshore wind development faces several challenges, including high capital costs and complex permitting processes, and sometimes the need for substantial upgrades to grid infrastructure. The high upfront costs stem from investments in specialized equipment, technology, and infrastructure, as well as manufacturing, transportation, and maintenance expenses [22]. Permitting processes are also lengthy and complicated, often taking up to nine years from lease award to project commissioning, and can involve navigating through multiple layers of government and potential legal challenges. Furthermore, the integration of offshore wind into the grid requires significant transmission network upgrades [12]. However, these challenges have been partially mitigated by substantial cost reductions, driven by factors such as economies of scale, technological innovations, and increased competition in the sector. Advances in floating wind turbine designs, structural optimization, and turbine efficiency have all contributed a lowering costs. As a result, the levelized cost of electricity (LCOE) for offshore wind has dropped by nearly 60% over the past decade, making it increasingly competitive and attractive in new markets worldwide [23].

2.2 Offshore Wind in Latin America

While offshore wind energy is expanding rapidly in mature markets such as Europe and Asia, its deployment in Latin America remains in its early stages. The region has traditionally focused on more cost-competitive renewable sources, particularly solar PV and onshore wind, due to lower upfront capital requirements, shorter development timelines, and well-established regulatory environments [9]. However, offshore wind interest is beginning to gain attention as countries seek to diversify their energy portfolios, meet growing electricity demand, and align with climate commitments like the Paris Climate Agreement's common goals. The recognition of vast untapped offshore wind potential, particularly along the Atlantic and Pacific coasts, is gradually shifting the narrative in favor of offshore development [6].

Brazil stands out as one of the most advanced countries in Latin America when it comes to offshore wind energy development. With an impressive technical potential of over 1200 GW, Brazil's northeast coastline is particularly well-suited for offshore wind projects [6]. These regions benefit from high wind capacity factors, which make them ideal for harnessing renewable energy efficiently, and the relatively shallow waters along the coast are ideal for fixed-bottom turbines, which are currently the most widely used technology [24]. The Brazilian government has been proactive in supporting the development of this sector by introducing draft legislation that aims to regulate the use of maritime space for energy generation. This regulatory framework is designed to streamline the licensing process, which is often a significant barrier to timely project development. Additionally, Brazil's efforts to create a clear and consistent policy landscape for offshore wind projects have been supported by strategic public-private partnerships, which are crucial for attracting investment and ensuring the success of large-scale projects [25]. Despite these advancements, there are still significant challenges to overcome. One of them is grid integration, as it may require upgrades to ports and logistics, along with the expansion of the transmission network and the implementation of solutions to accommodate large capacity additions. Investment risks, as well, including financing and regulatory uncertainties, continue to pose challenges for developers and investors. However, Brazil's ongoing efforts to build a stable and attractive offshore wind energy market, through innovative regulatory mechanisms and the collaboration of the public and private sectors, are laying the foundation for a scalable and sustainable offshore wind industry that could play a crucial role in meeting the country's renewable energy targets [24].

Colombia is emerging as another key player, motivated by its need to decarbonize a hydro-dependent energy mix that supplies around 67% of the country's electricity and is increasingly grid vulnerable to climate variability [6]. Therefore, in collaboration with the World Bank and ESMAP, the government launched its first Offshore Wind Roadmap, identifying a total technical potential of approximately 110 GW along the Caribbean coast, of which over 50 GW is considered viable after accounting for constraints. The country has already begun key steps like preliminary zoning, marine spatial planning, environmental scoping, and coordination across multiple agencies such as DIMAR, ANLA, and the Ministry of Mines and Energy. Although the offshore supply chain is still in early stages, the country is advancing a regulatory framework, launching the first round of Temporary Occupation Permits, and engaging a wide range of ministries to ensure a just and inclusive transition, especially in high-resource but underserved regions like La Guajira. These efforts show strong political will and a clear recognition of offshore wind's potential to improve energy security, attract investment, boost regional economies, and support the country's path to decarbonization [26, 27].

Uruguay, despite its smaller geographic size and electricity market, offers a unique case. Having nearly fully decarbonized its electricity sector through major investments in wind, solar, and biomass, positioning itself as a renewable energy leader in Latin America. The country is now exploring offshore wind as a key enabler of its green hydrogen strategy, targeting both domestic use and exports [28]. The National Administration of Fuels, Alcohols and Portland (ANCAP) has been authorized to prepare four offshore wind blocks dedicated to hydrogen production, and initial studies have identified two promising regions with a combined technical potential of over 120 GW. These areas were selected with attention to environmental and maritime constraints. Uruguay is also collaborating with international partners like IRENA, Germany, and Japan to attract investment, share knowledge, and support technology transfer. While still in the planning phase, these efforts demonstrate Uruguay's strategic approach to expanding its clean energy leadership into offshore wind and hydrogen [29].

In Mexico, offshore wind has a vast untapped technical potential that has been estimated to be approximately 869 GW [30]. Specifically in regions such as the Gulf of Mexico and the Isthmus of Tehuantepec, conditions have been recognized as favorable, with shallow waters and strong wind conditions that could support fixed-bottom installations [31]. These characteristics make these areas prime candidates for initial offshore wind projects. In terms of policy frameworks, despite the fact that the traditional federal government has had dominance over energy matters, state governments in Mexico have increasingly explored avenues to facilitate growth in renewable energy development, including offshore wind. This, driven by a range of key motivations like fighting climate change, economic growth, creating green jobs, community development, and improved energy access. The growing involvement of state entities may offer a potential pathway for advancing renewable energy projects, particularly in handling social licensing complexities. However, despite initial evaluations of offshore wind potential, there's still no national strategy or detailed analysis of the country's Exclusive Economic Zone (EEZ), raising questions about the competitiveness of this resource. Therefore, Mexico needs a thorough assessment of its offshore wind potential to identify the best locations, support effective policy-making, and plan for grid integration, which will help ensure the sector's growth and contribute to broader clean energy and blue economy goals [32, 33].

While Argentina boasts a well-established onshore wind energy sector, particularly in Patagonia, and a substantial estimated offshore wind potential of 1,870 GW [34], the development of offshore wind farms remains nascent. Currently, offshore activities are limited to oil and gas exploration. The primary impediments to the advancement of offshore wind energy include the considerable upfront capital expenditure required and the lack of a specific regulatory framework governing these projects. Nevertheless, the increasing national and international focus on green hydrogen production in the South region and the imperative to mitigate climate change are anticipated to be significant motivators for future development in this sector. Recognizing its considerable offshore wind resources, which rank favorably on a global scale, the establishment of a targeted and supportive regulatory regime may be necessary to fully unlock Argentina's substantial capacity and contribute to its broader energy transition goals [35].

In summary, while Latin America is still in the early stages of offshore wind development, growing political interest, ambitious climate targets, and abundant offshore wind resource availability indicate a promising trajectory. Countries like Brazil and Colombia are leading the way with policy frameworks and technical assessments, while others, such as Uruguay, Mexico, and Argentina, are gradually exploring the sector's potential in alignment with broader energy transition and green hydrogen goals. However, challenges remain, including regulatory uncertainty, high capital costs, and limited offshore infrastructure. To accelerate offshore wind deployment, Latin American countries will need to leverage international cooperation, invest in capacity building, and design tailored policy instruments that reflect regional specificities. By doing so, the region can unlock offshore wind's potential as a key driver of clean, secure, and sustainable energy systems.

2.3 Offshore Wind Development in Chile

Chile presents a very promising, though largely untapped, opportunity for offshore wind development in Latin America. With over 6,000 km of Pacific coastline, the country offers abundant and stable wind resources, particularly in the southern regions between 45° and 56° South [7]. This area exhibits exceptional wind power density that reaches approximately 3190 W/m² and high capacity factors around 70%, making it particularly attractive [36]. The World Bank [37] estimates Chile's technical offshore wind potential to exceed 957 GW, predominantly situated in deeper waters where floating wind technology is essential due to the country's steep bathymetry and limited continental shelf, especially in the northern zone. Consequently, a significant majority, specifically 86%, of Chile's estimated offshore wind potential lies in these deeper waters, necessitating the deployment of floating wind solutions. Although the continental shelf extends further south from Valparaiso, suitable areas for bottom-fixed platforms remain limited [7]. The spatial distribution of this potential is illustrated in Figure 2.2, which highlights the dominance of floating wind areas along the coast and the regional variations in wind speeds.

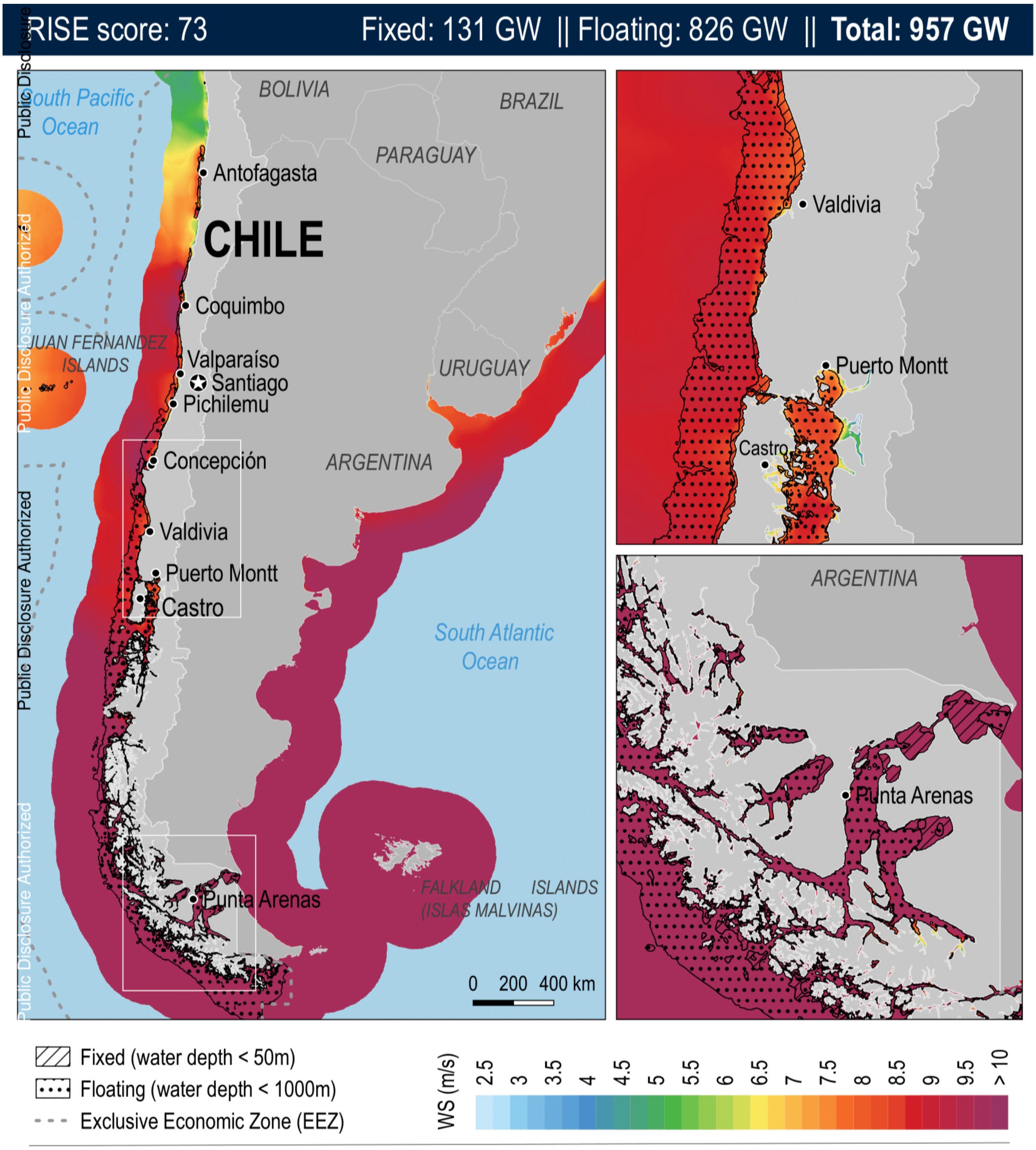

Figure 2.2: Estimated offshore wind technical potential in Chile, indicating fixed and floating wind suitability zones and wind speed distribution. Source: Adapted from World Bank (2020).

The significant demand for clean energy in Chile is further stressed by its ambitious national targets. The nation has committed to achieving greenhouse gas emission and carbon neutrality by 2050, alongside a strategic objective to achieve 80% renewable electricity in its power mix by 2030. This commitment is reinforced by the intended phasing out of coal-fired power plants by 2040, a crucial step in reducing its reliance on coal [8]. Notably, offshore wind energy can also be strategically integrated within Chile's broader energy vision through its connection to the National Green Hydrogen Strategy, which was unveiled by the Ministry of Energy in late 2020 [38]. Consequently, this alignment with ambitious decarbonization objectives, the projected growth in electricity demand, the planned coal phase-out, and the pivotal National Green Hydrogen Strategy firmly positions offshore wind energy as a substantial contributor.

Despite its considerable potential to contribute significantly to the nation's energy mix, the offshore wind sector in this region faces notable challenges. A comprehensive and dedicated regulatory framework has yet to be established to provide clear guidelines and incentives. Marine spatial planning, as well, remains in early development stages that could lead to conflicts with other maritime activities and delay project permits. Additionally, limited transmission infrastructure near optimal coastal zones and underprepared port facilities for turbine assembly and transport pose logistical hurdles. Although preliminary studies and resource assessments have been launched to evaluate the technical and economic feasibility, high initial capital costs and regulatory uncertainty continue to act as a significant deterrent to attracting large-scale private investment [6, 36].

The nation's successful track record in scaling up solar and onshore wind demonstrates a strong capacity to attract investment and build necessary infrastructure under favorable policy conditions [39]. Drawing on international best practices, particularly in regulatory design, grid integration, and cross-sector coordination, can forge a tailored approach that responds and considers local energy, social, and environmental contexts. This strategy could support the development of a robust and competitive offshore wind sector.

2.4 Multi-Criteria Decision-Making in Offshore Wind

Decision-making in the offshore wind sector is inherently complex due to the need to balance a wide range of technical, economic, environmental, and social criteria [40]. This complexity is amplified by the spatial constraints of marine areas, resource variability, evolving policy landscapes, and the need to avoid conflicts with other maritime activities such as shipping, fisheries, and conservation zones [41]. In this context, Multi-Criteria Decision-Making (MCDM) methods have emerged as essential tools to support structured, transparent, and replicable planning processes for offshore wind development [42].

MCDM techniques allow for the systematic evaluation of site alternatives by quantifying trade-offs between multiple, often conflicting, criteria. They are particularly valuable in situations characterized by uncertainty, limited data availability, and the necessity of integrating expert judgment or stakeholder perspectives [43]. In the offshore wind domain, MCDM has been widely applied for site suitability assessment, where it enables a comprehensive and balanced comparison of spatial alternatives under diverse constraints.

Among the most widely used MCDM methods in offshore wind planning are the Analytic Hierarchy Process (AHP) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). AHP, developed by Saaty in the 1980s, structures decision problems hierarchically and relies on pairwise comparisons to derive weights for each criterion [44]. Its transparency and ease of use make it especially suitable for early-stage planning processes and stakeholder engagement. In the renewable energy sector, AHP has been extensively applied to site selection, technology ranking, and policy evaluation [45]. More broadly, it is also the most commonly used MCDM method in sustainable development, due to its ability to address complex decisions involving environmental, economic, and social dimensions [46].

Several studies have demonstrated the effectiveness of AHP in offshore wind site selection. This method has been used to assess locations based on criteria such as wind resources, water depth, seabed conditions, and the presence of environmental or socio-political constraints. For example, Sánchez-Lozano et al. (2016) [47] applied the AHP to identify optimal offshore wind sites in Southeastern Spain, balancing technical and environmental considerations. Similarly, AHP was used to evaluate offshore wind farm sites in Northwest Turkey. They identified over 17 criteria, categorized as decision and exclusion factors, and conducted expert surveys to determine the relative importance of each [48].

TOPSIS, in contrast, ranks alternatives based on their geometric distance from an ideal (best) and anti-ideal (worst) solution. This method evaluates how close each option is to the optimal scenario while also considering how far it is from the least desirable outcome, making it particularly suited for assessing alternatives with quantitative and diverse performance data [49]. In renewable energy planning, TOPSIS has been widely applied to regional suitability analyses, technology assessments, and investment prioritization, where it helps to objectively rank complex alternatives under multiple conflicting criteria [50, 51]. In the context of offshore wind, TOPSIS was used to identify the best region possible for offshore wind farms in the Black Sea Region in Turkey [52].

More recently, hybrid approaches that combine AHP and TOPSIS have gained popularity to complement their strengths: AHP is typically used to derive criteria weights, while TOPSIS handles the ranking of alternatives. The combination of different MCDM methods enhances the robustness and consistency of the decision-making process, and can provide a decision framework that can gather, order, and analyse relevant information [53]. Within the energy sector, numerous studies have demonstrated the effectiveness of the integrated MCDM methods, which can include AHP-TOPSIS or similar hybrid approaches. For example, this integration was successfully utilised for problems in offshore wind farm site selection and spatial planning in Eastern Macedonia and Thrace region, Greece [10]. A similar case was observed in the Canary Islands, where a hybrid MCDM-GIS approach supported the identification of optimal offshore wind zones for floating structures [54]

Therefore, MCDM methods provide a robust and flexible framework for addressing the complexity of renewable energy planning, particularly in offshore wind site selection. The integration of AHP and TOPSIS techniques allows the balanced evaluation of diverse criteria, combining expert judgment with objective data analysis. These tools are especially valuable in emerging markets such as Chile, where regulatory frameworks are still evolving, data may be limited, and stakeholder interests must be carefully navigated. By incorporating both qualitative and quantitative dimensions, MCDM methods enhance the transparency, reproducibility, and stakeholder legitimacy of decision processes.

2.5 GIS Applications in Offshore Wind

Choosing the right location is one of the most important steps when planning an offshore wind farm [55]. The success of the project depends on many local factors, like how strong and consistent the wind is, how far the site is from ports or grid connections, the bathymetry, and whether there are any environmental or social restrictions. If the site isn't chosen carefully, the wind farm might produce less energy, cost more to build and maintain, or face conflicts with other marine activities. That's why a thorough and well-structured site assessment is key to reducing risks and making sure the project delivers strong, long-term results [56, 57].

In this context, Geographic Information Systems (GIS) have become an indispensable tool in renewable energy planning. GIS enables the integration, visualization, and spatial analysis of diverse datasets, allowing planners to evaluate a wide range of criteria within a georeferenced framework [58]. This is especially relevant for offshore wind projects, where marine space is limited, and multiple users such as fisheries, shipping, conservation, and military zones must be considered [57].

Numerous studies have demonstrated the effectiveness of GIS-based frameworks for offshore wind site selection. For example, a GIS-MCDM model was developed to evaluate offshore wind potential along the Spanish coast, integrating factors such as water depth, distance to shore, and exclusion zones [47]. Similarly, in Abu Dhabi, UAE, a GIS-based weighted overlay model was applied to assess offshore wind potential. Their framework incorporated criteria such as wind speed, ocean currents, seabed topography, and exclusion zones like marine protected areas and oil infrastructure. The research also included an environmental impact screening to minimize ecological disruption, underscoring the need for integrated spatial and environmental planning in offshore wind development [59].

In the context of floating offshore wind, a GIS-based methodology for site selection in Galicia (Northwest Spain) was developed, considering high wind resource areas alongside environmental, navigational, and infrastructural constraints such as depth, ports, and shipyards. Their tool allows for the flexible inclusion of additional restrictions as needed, enabling more refined site suitability analysis for floating wind projects [60].

Building on this, a spatial marine optimization method was proposed for floating offshore wind farm planning across the Atlantic coasts of Portugal, Spain, and France. Their GIS-based tool, developed in Python, involves a three-stage process: compiling marine spatial planning and regulatory data, excluding non-viable zones, and evaluating the remaining areas based on metocean, logistical, environmental, and techno-economic criteria. Their findings show that only 0.22% of the studied Atlantic EEZ is suitable for floating wind deployment, highlighting the value of GIS in narrowing down complex spatial decisions [61].

Beyond identifying suitable areas, GIS also plays a key role in constraint mapping. Zones with significant limitations, such as military areas or ecologically sensitive regions, can be excluded based on planning objectives. This helps ensure that selected sites align with regulatory frameworks and are more likely to receive public and institutional support. Additionally, GIS allows for clear visual communication of results, which is valuable for stakeholder engagement and policy advocacy [62].

In summary, GIS-based analysis can provide a rigorous and adaptable framework for offshore wind site selection. As marine spatial planning becomes increasingly complex due to competing uses and environmental pressures, this integrated approach offers a structured way to evaluate multiple criteria, support stakeholder dialogue, and enable informed decision-making. For emerging offshore wind markets such as Chile, it presents a robust foundation to guide sustainable development aligned with national energy and climate objectives.

2.6 Policy and International Best Practices for Offshore Wind

The global success of offshore wind energy has been driven by more than just strong winds and advanced technology — it's also the result of solid policies, strategic planning, and long-term government support. Countries like the UK, Denmark, Germany, and the Netherlands have become leaders in the field by putting in place well-coordinated policies that encourage innovation, reduce risks for investors, and ensure offshore wind is smoothly integrated into the national energy system [63, 64].

One of the most important elements of effective offshore wind policy is setting clear, long-term targets. These targets give investors the confidence they need to commit and help guide infrastructure planning, grid expansion, and supply chain development. For instance, the UK's Offshore Wind Sector Deal includes ambitious goals backed by collaboration between the government and industry, while Denmark's Energy Agreement provides clear auction timelines and a transparent permitting process [63, 64].

Another key strategy is centralized marine spatial planning. Tools like Marine Spatial Plans (MSPs) help avoid conflicts with other ocean users, such as fisheries, shipping, or marine conservation areas, by designating specific zones for offshore wind deployment. Countries like the

Netherlands and Germany have successfully included wind development areas in their MSPs, which has helped speed up approvals and improve coordination among stakeholders [65, 66].

Integrating offshore wind into Europe's energy system requires both strategic grid planning and strong port infrastructure. The "hub-and-spoke" model, developed by the North Sea Wind Power Hub, offers a coordinated way to collect and distribute offshore wind power across countries, improving efficiency and enabling future technologies like hydrogen production. Germany, the Netherlands, and Denmark are adopting hub-based systems using shared cables, converter stations, and planned energy islands to streamline connections [67]. At the same time, ports are essential to the success of offshore wind, supporting construction, logistics, and maintenance. Key hubs like Esbjerg in Denmark and the Humber in the UK have already enabled major expansions. Esbjerg alone has supported over 23 GW across 59 projects. These ports are now working together to meet future demand, but an estimated €8.5 billion investment is still needed by 2030 to upgrade Europe's port infrastructure [25].

Another important success factor has been early and ongoing collaboration. Engaging local communities, environmental organizations, and industry stakeholders from the beginning has helped increase public acceptance and avoid delays [68]. Environmental Impact Assessments (EIAs) and strategic reviews are typically part of the permitting process, making sure development aligns with marine protection goals [69, 70].

In short, countries that have successfully scaled offshore wind show that it's not just about technology, but also about having the right policy environment. For emerging markets like Chile, these international lessons offer a clear path forward: regulatory clarity, investment in infrastructure, and strong coordination across sectors will be key to unlocking the full potential of offshore wind.

2.7 Integrated Approaches in Offshore Wind Planning

As was already discussed, planning offshore wind energy projects is a complex task that goes far beyond just analyzing wind conditions or environmental impacts. It requires a truly multidisciplinary approach and one that brings together technical, environmental, regulatory, economic, and social factors. To deal with this complexity, many recent studies and policy initiatives have turned to integrated methods that combine spatial analysis, decision-support tools, and input from stakeholders to guide smarter, evidence-based planning [71].

At the heart of these integrated approaches is the use of GIS and MCDM methods. GIS helps visualize and layer spatial data like wind resources, water depth, marine protected areas, and other constraints, while MCDM tools, such as AHP and TOPSIS, allow decision-makers to prioritize these criteria in a structured and transparent way. Together, they make it possible to evaluate not only where offshore wind can be developed, but also different trade-offs and priorities that should influence those decisions [10].

This combined approach has proven effective in several studies. For example, in the South Aegean region of Greece, GIS, AHP, and TOPSIS were used to identify optimal offshore wind locations by integrating technical, spatial, economic, social, and environmental criteria [72]. A similar hybrid methodology was also applied in the Eastern Macedonia and Thrace region, further demonstrating its suitability for offshore wind planning [10].

Another key aspect of integrated planning is linking site selection to broader strategic planning. Identifying technically suitable locations is only the first step; these sites must also align with policy timelines, grid infrastructure development, and investment. To address this, recent studies and projects incorporate scenario analysis and cost-benefit assessments into their frameworks. This ensures that offshore wind deployment is not only spatially optimized but also feasible in terms of timing, infrastructure, and financing [72].

For example, the Seagreen Offshore Wind Farm in Scotland, despite its excellent wind resources, faced major curtailment in 2024 due to inadequate grid infrastructure, resulting in significant operational and financial losses [73]. In contrast, the East Anglia Array in the UK integrated site development with grid planning and financial mechanisms like Contracts for Difference (CfDs), allowing for more efficient and timely deployment [74]. These cases highlight that effective offshore wind planning must go beyond identifying where to develop and also consider when and how deployment should occur within a coordinated strategic framework.

In the end, integrated planning represents the best-practice approach for offshore wind: it's holistic, transparent, and flexible. For emerging markets like Chile, adopting this approach offers a solid foundation for aligning technical possibilities with long-term policy goals, community needs, and sustainable development priorities.

2.8 Research Gap

The current literature on offshore wind planning shows significant progress in spatial analysis methods, decision-support frameworks, and policy development, especially in countries with mature renewable energy sectors across Europe and parts of Asia. Many studies have successfully applied GIS and MCDM techniques, such as AHP and TOPSIS, to support offshore wind site selection. These integrated approaches allow for more systematic, transparent, and multidimensional evaluations of site suitability and deployment strategies [10, 72].

Despite its long coastline and strong offshore wind potential, Chile remains largely underrepresented in this growing field. Few studies have explored the spatial feasibility of offshore wind in Chile, and those that do often lack depth in their methodology or fail to fully integrate economic, environmental, and infrastructure-related considerations. Notably, there is a lack of national-scale GIS-based site selection studies that use a structured weighting of criteria grounded in stakeholder or policy relevance [7, 36, 6].

Furthermore, while MCDM tools are commonly used in international energy planning [10], there is still room to apply a hybrid GIS–AHP approach to offshore wind site selection in the Chilean context. Additionally, such approaches have not yet been combined with comparative assessments using MCDM methods to evaluate Chile's readiness against global leaders. This limits the ability to identify critical performance gaps and to adapt successful international strategies to the Chilean context.

Another key shortcoming in the literature is the disconnect between spatial analysis and actionable policy guidance. While suitability maps provide valuable technical insights, they are often not linked to broader development strategies that consider regulatory, infrastructural, and socio-political readiness. For a country like Chile, where offshore wind is still an emerging sector, such a roadmap is essential to guide phased development, infrastructure investment, and policy reform [6, 7, 37].

This thesis addresses these gaps by introducing, for the first time, a novel GIS–MCDM framework tailored to Chile, using AHP for site selection and TOPSIS for international benchmarking. It also bridges the gap between spatial analysis and strategic planning by linking results to a development roadmap informed by global best practices. In doing so, it offers both a methodological contribution and practical value for advancing offshore wind energy in Chile.

Chapter 3

Methodology

3.1 Methodology Overview and Research Design

As it was already hinted before, this study employs a hybrid methodological framework combining GIS with MCDM techniques to identify optimal offshore wind farm locations and subsequently develop a benchmark and strategic managerial analysis as background for an implementation roadmap to support Chile's successful adoption of the technology.

Therefore, to comply with the research objectives, this study is divided into two main stages that align with them:

1. **Spatial Site Selection Analysis:** A GIS-MCDM analysis using AHP and TOPSIS that evaluates geospatial, infrastructure, and social factors to generate a suitability map for favorable areas.

2. **Strategic Assessment and Roadmap Development:** Benchmarking using MCDM, percentile-zoning, managerial, and qualitative tools to develop the offshore wind implementation roadmap.

The general methodological workflow of this study is illustrated in **Figure 3.1**.

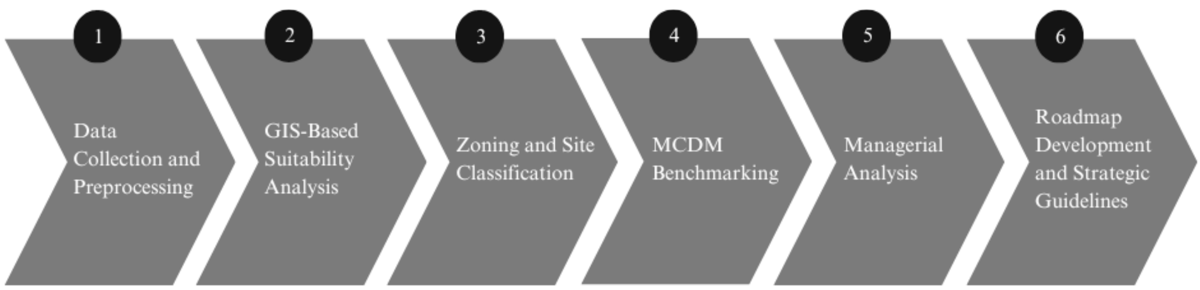

Figure 3.1: Hybrid GIS-MCDM Methodological Workflow for Offshore Wind Site Selection and Strategic Roadmap Development.

The full process consists of six sequential steps, each of which is described in detail below:

1. **Data Collection and Preprocessing:** Spatial and non-spatial data were collected to support both stages of the research. Official global and national sources were used, and the datasets were then processed, standardized, and projected when necessary to ensure spatial consistency for Chile's EEZ.

2. **GIS-Based Suitability Analysis:** A spatial suitability model was performed, which integrated multiple raster criteria that were weighted afterwards using AHP and combined via TOPSIS to generate a suitability map.

3. **Zoning and Site Classification:** The suitability map was then categorized into percentile-based zones to identify priority areas for planning and policy.

    - **Zone A:** High suitability
    - **Zone B:** Moderate suitability
    - **Zone C:** Low suitability

4. **MCDM Benchmarking:** AHP and TOPSIS techniques were used for a second time to set weights of different criteria that determine offshore wind development in different countries, to afterwards create a benchmark.

5. **Managerial Analysis:** To complement quantitative benchmarking, qualitative analyses were conducted.

    - **SWOT:** To identify internal strengths and weaknesses as well as external opportunities and threats specific to Chile's offshore wind sector.
    - **PESTEL:** Performed to examine the broader political, economic, social, technological, environmental, and legal context affecting this technology adoption.
    - **Stakeholder Mapping:** Used to understand the key actors, their interests, influence, and interactions within the sector.

- **Southern Macrozone Conflict Case:** To contextualize the socio-political challenges of offshore wind development in Chile, a case analysis was conducted in the southern part of the country.

6. **Roadmap Development:** A strategic and novel roadmap was subsequently constructed based on the zone classification and managerial analysis results. This included a three-phase series of recommendations that were aligned with practices from leading offshore wind nations.

This combined approach and design effectively ensures both geospatial and strategic policy insights, allowing site-specific recommendations, as well as providing high-level strategic guidance that follows international best practices, considering national priorities. Overall, this makes the results actionable for decision-makers and stakeholders in Chile's renewable energy transition.

3.2 Data Collection

3.2.1 Spatial Data

The site selection process for offshore wind in Chile utilized diverse spatial and environmental datasets to evaluate the suitability of potential locations. Key criteria included wind resource assessment, marine environmental constraints, infrastructural accessibility, and social constraints. Specifically, the data layers comprised:

- **Wind Speed, Wind Mean Power Density, Bathymetry**: Obtained from the Global Wind Atlas[1], providing high-resolution climatological wind data as well as depth measurements critical for estimating the energy potential and suitable areas for different structures.

- **Marine Protected Areas (MPAs)**: Spatial proximity from boundaries and ecologically sensitive zones was also considered. This data was collected from the Protected Planet initiative by UNEP-WCMC[2]

[1] `https://globalwindatlas.info/`
[2] `https://www.protectedplanet.net/country/CHL`

- **Distance to Ports**: Proximity to existing ports was assessed to facilitate logistics, installation, and maintenance operations through Global Fishing Watch[3].
- **Port Availability and Capacity**: Information on port infrastructure to accommodate offshore wind activities was collected on Maritime Safety Information[4].
- **Grid Proximity**: Main power lines were extracted using the QuickOSM plugin in QGIS, based on OpenStreetMap data[5].
- **Fishing Grounds**: Areas with significant fishing activity were mapped to reduce socio-economic conflicts through Global Fishing Watch[6].
- **Land**: A land mask was also used in order to avoid onshore suitability miscalculations, information extracted from Biblioteca del Congreso Nacional de Chile[7].

Also, for the southern macrozone conflict case, data on violent incidents related to this from the years 2020 to 2025 were collected from Campo Seguro [8].

All these layers can be visualized in Figures C.1 and C.1 in Appendix C. They show the different spatial data used to help with the site selection.

3.2.2 Non-Spatial Data

A non-spatial dataset was compiled to assess the criteria among the benchmark countries using a hybrid AHP-TOPSIS framework for the roadmap development. This data was:

- **Policy and Regulatory Environment**: Includes national offshore wind strategies, renewable energy targets, permitting procedures, and incentive mechanisms.
- **Economic and Financial Factors**: Covers investment costs, levelized cost of energy (LCOE), market structures, and support schemes.

[3] https://globalfishingwatch.org/
[4] https://msi.nga.mil/Publications/WPI
[5] Data from OpenStreetMap, accessed via QuickOSM (QGIS). https://www.openstreetmap.org
[6] https://globalfishingwatch.org/
[7] https://www.bcn.cl/siit/mapas_vectoriales
[8] https://www.camposeguro.cl/mapas

- **Environmental and Social Considerations**: Includes environmental impact assessment practices, stakeholder engagement processes, and public acceptance.
- **Grid Infrastructure and Energy Mix**: Encompasses grid integration capacity, renewable energy penetration, and the flexibility of the energy system.

Data for these indicators were collected from a wide range of sources, including reports by IRENA [75], IEA [76], the World Bank [77], BloombergNEF [78]. Additionally, key insights into policy frameworks, market development strategies, and lessons learned were extracted from offshore wind roadmaps and best practice guidelines published by leading benchmark countries.

Additionally, qualitative data and insights from SWOT and PESTEL analyses were integrated to complement the MCDM evaluation and inform the roadmap development. These analyses incorporated political, economic, social, technological, environmental, and legal factors, drawn from various authoritative and relevant documents:

- **Governmental Reports and National Strategies**: To understand Chile's energy goals and policy landscape, were reviewed key documents from the Chilean government. These included commitments to decarbonization, specific strategies for renewable energy and green hydrogen, social and political reports, as well as environmental assessment guidelines. Data obtained from: Chilean Ministry of Energy [79], Long-Term Climate Strategy [8], INDH Annual Reports on Human Rights [80], Environmental Assessment Service (SEA) [81], Ministry of Environment [82], Ministry of National Assets [83], Superintendence of the Environment [84], National Electricity Coordinator [85], Ministry of Interior and Regional Governments [86], Ministry of Public Works [87], Ministry of Finance [88], SUBPESCA [89], InvestChile [13].
- **International Organization Publications**: Covers insights into global context, technical potential assessments, economic insights, and regulatory comparisons were drawn from reports and analyses Obtained from: International Energy Agency (IEA) reports[76], World Bank publications [77], ESMAP guides [90], International Renewable Energy Agency (IRENA) [75], OECD Environmental Performance Reviews [91], UNFCCC documents [92], International Labour Organization (ILO) conventions [93].

- **Industry Publications and Market Analyses**: Data on industry-specific capabilities, supply chain dynamics, capital costs, market pricing, and global deployment trends. Obtained from: Global Wind Energy Council (GWEC) [94], analyses from consultancies or law firms [95, 96, 97], US Department of State investment climate [98], MERIC [7].

- **Academic Studies and Research Papers**: Encompasses peer-reviewed scientific literature that contributed to understanding specific technical aspects, environmental impacts, and socio-economic considerations [36, 99, 100].

The combined use of quantitative criteria and qualitative frameworks enabled a comprehensive strategic assessment to support offshore wind deployment planning in Chile and benchmarking against leading countries.

3.3 Software and Tools

A variety of specialized software tools were used throughout the study to handle different tasks such as spatial data processing, MCDM techniques, decision-making analysis, and visualization. The choice of tools was made carefully, considering factors like how well they worked with geospatial data, their reliability in producing accurate results, the ability to reproduce the analysis, and their overall suitability for supporting decision-making in offshore wind site selection.

3.3.1 QGIS

QGIS (Version 3.40) [101], an open-source Geographic Information System, served as the primary platform for spatial data processing and visualization in this research. Its key functions in this study included:

- Clipping, projecting, and aligning raster and vector datasets.

- Conducting proximity analyses for ports, grid infrastructure, and MPAs.

- Rasterization of vector layers and standardization to a 1 km spatial resolution.

- Transforming the data in each layer into categories that show how suitable each area is for offshore wind development.
- Facilitating visual inspection and validation of spatial data.

QGIS was primarily selected due to its flexibility in handling diverse geospatial formats and its robust tools for spatial analysis, which facilitated efficient data processing and visualization.

3.3.2 MATLAB

MATLAB was used to execute the final integration and analysis of GIS criteria using the AHP-based weighted overlay method and TOPSIS. It also supported advanced classification and zoning. MATLAB's role included:

- Applying AHP-derived weights to raster layers.
- Calculating the final suitability index for each grid cell.
- Performing percentile classification to create Zones A, B, and C.
- Automating normalization and map matrix operations.
- Producing high-resolution suitability and zoning maps for export.

MATLAB was chosen for its matrix computation efficiency, reproducibility of classification logic, and easy integration with exported GIS raster data.

3.3.3 Microsoft Excel

Microsoft Excel was used for organizing and analyzing non-spatial datasets, particularly those related to the strategic benchmarking phase. Its functions included:

- Constructing pairwise comparison matrices for AHP for site selection and benchmarking.
- Implementing the TOPSIS ranking method.
- Conducting normalization, correlation, and consistency checks.

Excel offered a transparent and auditable platform for documenting and verifying each step of the MCDM procedures.

3.4 Multi-Criteria Decision-Making Methods

To address the complex and multi-criteria nature of this research, MCMD is presented as a core component of this framework. The two different techniques used (AHP and TOPSIS) allow the evaluation of alternatives incorporating qualitative data, expert judgment, and ranking based on the best possible solutions. Therefore, this section outlines the methodological steps followed to apply these techniques within the framework of offshore wind planning. AHP is used to derive the weights of evaluation criteria through expert-based pairwise comparisons. TOPSIS is employed to select the best suitability areas and rank selected countries based on their relative performance across weighted criteria. The following subsections detail the mathematical procedures, including matrix construction, normalization, consistency verification, weight extraction (AHP), and distance-based ranking (TOPSIS). These calculations form the backbone of the decision-support framework, grounded in a transparent, replicable, and systematic process.

3.4.1 AHP

To determine the relative importance of the decision criteria used in this study, AHP was implemented through a structured process. The method enabled the construction of a pairwise comparison matrix based on expert judgment, from which a consistent and justifiable set of weights was derived. The following steps and equations describe the full AHP procedure applied in this work.

1. **Pairwise Comparison Matrix**

   For this step, to create the pairwise comparison matrix, each pair of criteria was compared using Saaty's Fundamental Scale [44], which assigns a value from 1 to 9 as shown in Table 3.1. Thus, a higher number indicates a stronger preference for one criterion over the other, while the reciprocal values reflect the inverse comparison.

   Then, the values assigned to a pair of criteria are put in a reciprocal matrix $\mathbf{A} = [a_{ij}]$, where:

$$a_{ij} = \frac{1}{a_{ji}}, \quad a_{ii} = 1, \quad i, j = 1, 2, \ldots, n \tag{3.1}$$

Table 3.1: Saaty's Fundamental Scale

Scale	Numerical Rating	Reciprocal
Extreme Importance	9	1/9
Very Strong to Extreme	8	1/8
Very Strong Importance	7	1/7
Strong to Very Strong	6	1/6
Strong Importance	5	1/5
Moderate to Strong	4	1/4
Moderate Importance	3	1/3
Equal to Moderate	2	1/2
Equal Importance	1	1

Source: Adapted from Saaty (1980).

Here, a_{ij} the importance of the criterion i relative to the criterion j. The value comparing criterion i j is the reciprocal of the comparison j to i. Also, every criterion is equally important to itself (the diagonal elements are 1).

2. **Matrix Normalization**

Each entry in the matrix was normalized by dividing it by the sum of its column:

$$n_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{3.2}$$

3. **Weight Calculation**

The average of each row in the normalized matrix gives the weight of each criterion:

$$w_i = \frac{1}{n} \sum_{j=1}^{n} n_{ij} \tag{3.3}$$

4. **Consistency**

To validate logical consistency, the consistency index (CI) and consistency ratio (CR) were calculated. First, the weighted sum vector Aw is computed:

$$(Aw)_i = \sum_{j=1}^{n} a_{ij} w_j \tag{3.4}$$

Then, the maximum eigenvalue is estimated as:

$$\lambda_{\max} = \frac{\sum_{i=1}^{n} \frac{(Aw)_i}{w_i}}{n} \tag{3.5}$$

The consistency index (CI) is:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1} \tag{3.6}$$

Finally, the consistency ratio is:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{3.7}$$

and *RI* is the random index dependent on matrix size n [44]. A CR less than 0.1 indicates acceptable consistency.

3.4.2 TOPSIS

To evaluate and rank the alternatives considered in this study, TOPSIS was applied using the weights previously derived through AHP. This method facilitated a systematic comparison of both offshore wind site selection and countries by measuring their relative proximity to ideal and anti-ideal solutions. The following steps and equations describe the full TOPSIS procedure [49].

1. **Normalization**

   The decision matrix $\mathbf{X} = [x_{ij}]$, where $i = 1, \ldots, m$ alternatives and $j = 1, \ldots, n$ criteria are normalized as:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{3.8}$$

Weighted Normalized Matrix

The normalized matrix is weighted by the criteria weights w_j from AHP:

$$v_{ij} = w_j \cdot r_{ij} \tag{3.9}$$

2. **Ideal and Negative-Ideal Solutions**

   The ideal solution $\mathbf{v}^+$ and negative-ideal solution $\mathbf{v}^-$ are defined as:

$$v_j^+ = \max_i v_{ij} \quad \text{for benefit criteria,} \quad v_j^- = \min_i v_{ij} \tag{3.10}$$

$$v_j^+ = \min_i v_{ij} \quad \text{for cost criteria,} \quad v_j^- = \max_i v_{ij} \tag{3.11}$$

3. **Distance Measures**

   The separation of each alternative from the ideal and negative-ideal solutions is computed by Euclidean distance:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2}, \quad S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \tag{3.12}$$

4. **Relative Closeness**

   The relative closeness to the ideal solution is given by:

$$C_i^* = \frac{S_i^-}{S_i^+ + S_i^-}, \quad 0 \leq C_i^* \leq 1 \tag{3.13}$$

   Alternatives are ranked in descending order C_i^*, with higher values indicating better performance.

3.4.3 Application in this Study

AHP was first used to determine the weights of spatial criteria for offshore wind site suitability and later for strategic criteria in the benchmarking analysis. TOPSIS then integrated the weighted criteria to generate ranked suitability maps and country performance scores, respectively.

3.5 GIS-Based Suitability Analysis

The first major component of this study focuses on the geospatial identification of suitable areas for offshore wind development within Chile's maritime territory. A GIS-based MCDM framework was applied to integrate spatial datasets representing technical, environmental, and infrastructural conditions relevant to offshore wind siting.

3.5.1 Study Area and Coordinate System

The analysis was conducted over the Chilean Exclusive Economic Zone (EEZ) on the continental shelf, excluding restricted zones such as marine protected areas, insular territories, and the Chilean Antarctic Territory. All spatial data were standardized and aligned to the EPSG:32718 – WGS 84 / UTM Zone 18S coordinate reference system, which provides accurate area and distance calculations suitable for Chile's geographic location.

3.5.2 Selection of GIS Criteria

The criteria for assessing spatial suitability were selected by drawing on international offshore wind siting guidelines, the availability of reliable data, and Chile's unique coastal characteristics. Each one captures a key factor that can either support or limit offshore wind development.

These factors were translated into spatial layers, as explained in the data section, reflecting both global best practices and Chile's local conditions. Together, they offer a well-rounded view that considers physical, environmental, and logistical aspects to accurately evaluate where offshore wind projects can be most effectively developed.

Visual Impact Consideration

In this study, visual impact was not considered. This decision is based on evidence from previous studies showing that visual impact is a complex and inherently subjective factor that varies depending on individual perception, weather conditions, and landscape context. Because of this variability, accurately measuring visual impact is challenging. Additionally, studies show that offshore wind farms generally wind turbines becomes negligible beyond a 10 km distance from the shore [102]. For these reasons, this study focuses instead on other spatial and environmental criteria that can be more objectively assessed.

3.5.3 GIS Data Processing

Apart from aligning and clipping, each spatial dataset underwent processing to prepare it for the site suitability analysis:

- **Wind Speed, Power Density, Bathymetry**: Raster layers were projected to EPSG:32718 – WGS 84 / UTM Zone 18S.
- **Marine Protected Areas (MPAs)**: MPAs were projected and buffered to establish exclusion and proximity zones. Since there are no restrictions in Chile associated with offshore wind development near MPAs, a precautionary distance-based proximity scoring system was applied to reflect the varying degrees of ecological risks:

Table 3.2: Marine Protected Areas Proximity Scoring

Distance	Score	Justification
0 km	0.0	Inside MPA — prohibited to protect critical habitats and meet conservation obligations.
>0 – 0.5 km	0.1	High biodiversity risk due to edge effects; construction noise and turbidity can disrupt sensitive species.
>0.5 – 1.5 km	0.2	Mobile species may transit between MPA and surrounding areas; operational noise may affect.
>1.5 – 5 km	0.4	Impacts like light and sediment dispersion can affect broader ecological dynamics.
>5 – 10 km	0.7	Reduced direct impact, but indirect effects still possible. Aligns with buffer zones proposed in literature.
>10 km	1.0	Safe distance and minimal ecological concern. Often used as precautionary threshold in environmental impact assessments.

Avoiding Marine Protected Areas (MPAs) is widely recommended to safeguard biodiversity and ensure compliance with conservation objectives. During construction, noise and other disturbances may affect marine mammals. In Chile, a significant portion of the maritime territory is designated as protected, but many MPAs are located far from the mainland, in less industrialized zones. However, there are currently no official guidelines in Chile defining how close offshore wind projects can be to these areas, highlighting the importance of adopting a precautionary approach in spatial planning.

- **Distance to Ports**: Reprojected and maximum distance set at 150 km from the nearest port.
- **Grid Infrastructure**: Power lines were processed using the GIS proximity tool to generate distance rasters, which were then used to assess the feasibility of grid connection based on spatial proximity, no further than 150 km.
- **Fishing Grounds**: Fishing activity density maps were buffered around 0.5 km from the zones and also rasterized.
- **Land Mask**: This layer was converted into a binary raster and projected.
- **Port Capacity**: A port influence raster was generated based on suitability scores calculated through a multi-criteria evaluation framework. Using AHP five criteria were weighted: Water Depth & , Vessel Capacity, Cargo Handling & Infrastructure, Shelter & Environmental Protection, Logistics Support & Connectivity, and Safety & Management. The scores were computed in MATLAB from a cleaned port dataset and normalized across criteria. Final suitability scores were exported and used in QGIS to create a scored raster, where higher values indicate stronger logistical support for offshore wind development A maximum distance of 150 km was set. Detailed criteria weights, the AHP consistency check, and full MATLAB code are provided in Appendix A and Appendix B.

3.5.4 AHP for GIS Criteria Weighting

After the criteria selection, AHP was used to assign weights to each of them. A pairwise comparison matrix was developed based on literature values and expert consultation. As a result of all the steps followed, the consistency ratio (CR) was calculated to ensure logical coherence (CR < 0.1 was achieved). The final weights reflect the relative importance of each factor in offshore wind site selection.

3.5.5 Exclusion criteria and masking

Before the TOPSIS method, exclusionary constraints were applied to mask areas unsuitable for offshore wind development. Specifically, raster cells were excluded (set to `NaN`) if they met any of the following conditions:

- Bathymetry shallower than -50 m for bottom-fixed structures.
- Bathymetry deeper than -1000 m for floating structures.
- Wind speeds below 7 m/s.
- Distance to ports exceeding 150 km.
- Distance to grid infrastructure exceeding 150 km.
- Port capacity score equal to zero.
- Distance to fishing grounds closer than 0.5 km.

Also, a binary exclusion mask was applied to eliminate land areas from the analysis and ensure that only marine zones were evaluated for offshore wind suitability. This mask was generated from the land boundary shapefile. All land pixels were assigned `NaN` values, effectively removing them from the analysis.

3.5.6 TOPSIS Continuous Suitability Map

The final output of the GIS-based site selection framework is a continuous suitability map generated using the TOPSIS method implemented in MATLAB. This map aggregates the standardized spatial layers based on the AHP-derived weights and evaluates each location's relative performance by calculating its closeness to the ideal and anti-ideal conditions.

Each raster cell represents a potential site for offshore wind development and is assigned a suitability score C_i ranging from 0 (least suitable) to 1 (most suitable). These scores are computed by applying the TOPSIS procedure using the weighted criteria values at each location as inputs. As a result, a surface is developed that offers a spatial view of offshore wind suitability across the country.

The continuous suitability map was later used as the basis for identifying priority areas and formulating the strategic development roadmap, and the complete code from all the steps in Appendix B.

3.6 Zoning

To help translate the spatial suitability results into more actionable policy and development strategies, this study also uses a zoning framework that classifies the Chilean offshore area into suitability classifications by percentile. This zoning serves as a bridge between the technical feasibility derived from GIS analysis and the strategic planning necessary for a phased and coordinated offshore wind deployment roadmap.

Based on the continuous suitability scores (ranging from 0 to 1) obtained from the GIS weighted overlay, the study applies a classification approach to define three zones of development priority as shown in Table 3.3:

Table 3.3: Suitability Classification by Percentile Range

Zone	**Percentile Range**	**Suitability Level**
Zone A	$> 66.67\%$	High Suitability
Zone B	33.33% – 66.67%	Medium Suitability
Zone C	$< 33.33\%$	Low Suitability

3.7 Strategic Benchmarking Using MCDM

Benchmarking involved applying MCDM methods to assess and rank countries based on several offshore wind-related dimensions. AHP was used to weigh the importance of each criterion, while TOPSIS helped rank the countries by their overall performance related to those criteria. Together, these tools provide a clear and systematic way to benchmark Chile against global leaders and other Latin American countries. The results highlight where Chile is doing well and where improvements are needed—to better guide policy, investment, and technology strategies.

3.7.1 Criteria for Strategic Assessment

To evaluate Chile's national readiness and identify key areas for improvement, a set of high-level criteria was defined based on international best practices and previous offshore wind benchmarking studies. These are shown in Table 3.4 below.

Table 3.4: Criteria List and Scales for Offshore Wind Evaluation

Criterion Code	Criteria Name	Scale
1. Policy & Regulatory Environment		
CR 1.1	Offshore Wind Legislation	1–5
CR 1.2	Permitting Efficiency	1–5
CR 1.3	Renewable Energy Targets	1–5
CR 1.4	Renewable Energy Support	1–5
2. Technological & Industrial Development		
CR 2.1	Installed Offshore Wind Capacity	MW
CR 2.2	Technological Innovation	1–5
CR 2.3	Port Infrastructure	1–5
3. Economic & Financial Factors		
CR 3.1	Capex	€/MW
CR 3.2	Investment Climate	1–5
CR 3.3	LCOE	€/MWh
4. Environmental & Social Considerations		
CR 4.1	EIA	1–5
CR 4.2	Community Engagement	1–5
5. Grid Infrastructure & Integration		
CR 5.1	Grid Maturity	1–5
6. Energy Mix		
CR 6.1	Offshore Wind Production	GWh
CR 6.2	Offshore Wind / Total Renewable	%

3.7.2 AHP for Strategic Criteria

The AHP technique was applied again to derive the relative weights of strategic criteria used in the benchmarking analysis. This facilitated a consistent, transparent, and replicable weighting scheme that reflects stakeholder priorities and expert knowledge. The resulting weights were integrated into the TOPSIS technique to rank the countries.

3.7.3 TOPSIS for Country Ranking

The TOPSIS method was employed to rank Chile's offshore wind readiness relative to selected benchmark countries. By calculating the geometric distance of each alternative to both the ideal (best-case) and anti-ideal (worst-case) solutions, TOPSIS identifies the most favorable option among the evaluated countries. This approach enables assessment of Chile's position about global leaders and Latin American countries in offshore wind development.

3.8 Managerial and Qualitative Analysis

3.8.1 SWOT

The SWOT framework is widely recognized for the ability to provided a high-level overview [103]. This assesses Chile's internal strengths and weaknesses, with external opportunities and threats associated with offshore wind development. This analysis contextualizes the quantitative findings within managerial and strategic perspectives, guiding policy decisions, identifying key focus areas for improvement, and helping define the roadmap.

3.8.2 PESTEL

The PESTEL analysis explores the broader Political, Economic, Social, Technological, Environmental, and Legal factors influencing offshore wind deployment in Chile. This holistic perspective is crucial for understanding the external environment and anticipating future trends and risks [104].

3.8.3 Stakeholder Mapping

Stakeholder mapping identifies and categorizes key actors involved in or affected by offshore wind projects. Understanding stakeholder interests, influence, and potential conflicts facilitates effective engagement strategies and promotes collaborative governance [105].

3.8.4 Detailed Case Study: Southern Macrozone Conflict

This case study provides an examination of a socio-environmental conflict in Chile's Southern Macrozone that can affect offshore wind development. Insights from this case highlight challenges in balancing development with community interests, offering valuable lessons and restrictions for future projects.

3.9 Roadmap Development and Strategic Guidelines

3.9.1 Integration of Spatial Zoning Benchmarking and Managerial Results

This step involves the methodological integration of outputs from two core components: the GIS-based percentile-zoning analysis and the international benchmarking conducted via MCDM. The GIS analysis identifies zones of high suitability for offshore wind development based on geospatial and environmental criteria, while the benchmarking highlights Chile's relative performance against other countries across strategic dimensions. The managerial results inform external and internal factors related to the country environment to adopt this technology. The integration of these results provides a multidimensional basis for a contextual roadmap, ensuring spatial prioritization based on local site potential and strategic preparedness.

3.9.2 Phased Roadmap Development

To turn the analysis into practical plans, we create a phased rollout framework. This breaks down Chile's development into short, medium, and long-term goals. Each phase is guided by how suitable different areas are (using Zones A, B, and C), how ready institutions are, and examples from other countries. This step-by-step approach makes it easier to adapt along the way, allowing progress to scale up as infrastructure improves, technology advances, and policies evolve.

3.9.3 Alignment with International Best Practices

This step involves a systematic review, and how the roadmap developed prior aligns with international best practices to guide Chile's offshore wind strategy and fill the gaps identified prior. Case studies from mature offshore wind markets are analyzed to identify successful policies, regulatory frameworks, and technological solutions. These are then evaluated for relevance and applicability to Chile's roadmap, ensuring that the strategic guidance is both evidence-based and context-sensitive.

3.10 Summary

This research developed a comprehensive framework combining GIS-MCDM-based spatial analysis, MCDM benchmarking, and qualitative managerial tools to inform offshore wind development in Chile. The integrated approach offers robust insights into site suitability, strategic positioning, and phased planning, while addressing socio-environmental considerations through detailed case studies and stakeholder analysis. Findings highlight critical areas for policy intervention and strategic investment, providing a foundation for advancing Chile's offshore wind sector in alignment with international standards and local realities.

Chapter 4

Results

4.1 AHP GIS Criteria Outcome

This section presents the results of the AHP applied to the GIS-based site selection criteria for offshore wind suitability.

The pairwise comparison matrix was constructed considering the relevance of each factor, such as Wind Speed, Wind Mean Power Density, Bathymetry, Port Capacity, Marine Protected Areas, Fishing Grounds, Distance to Grid, and Distance to Ports in influencing the technical and social feasibility of offshore wind farms. Consistency of the judgments was verified using the Consistency Ratio (CR), which was found to be below the acceptable threshold of 0.1; specifically was found a CR of 0.0457 indicating reliable comparisons.

Table 4.1 displays the final normalized weights assigned to each criterion already mentioned in Table 3.4. As expected, Wind Speed and Wind Mean Power Density received the highest weights, reflecting their critical influence on energy production potential and technical viability of offshore wind structures. Conversely, criteria such as Marine Protected Areas and Fishing Grounds were assigned lower weights due to their role as constraints rather than enabling factors.

Table 4.1: AHP Weights for Offshore Wind Site Selection Criteria

Criterion	**Name**	**Weight**
CR 1	Wind Speed	0.2437
CR 2	Wind Mean Power Density	0.2489
CR 3	Bathymetry	0.0711
CR 4	Marine Protected Areas	0.0411
CR 5	Distance to Ports	0.1010
CR 6	Port Capacity	0.1424
CR 7	Distance to Grid	0.1005
CR 8	Fishing Grounds	0.0513

4.2 GIS Suitability Map Results

4.2.1 Bottom-Fixed Offshore Wind Structures

This subsection presents the results of the GIS-based suitability analysis for bottom-fixed offshore wind structures along the Chilean coastline. The suitability map was generated by integrating multiple spatial criteria, using the TOPSIS method with AHP-derived weights.

The resulting map highlights the spatial distribution of areas categorized by their suitability values, ranging from low to high. Overall, the most suitable areas for bottom-fixed offshore wind were found in regions with high wind resources, moderate bathymetry (less than 50 meters), and proximity to major port infrastructure and transmission networks. Specifically, high-suitability zones were identified along the Far South regions where a suitability area of 9583.7 km^2 was found and also a technical potential of 38.33 GW.

Areas with low suitability were primarily located in zones with lower wind speed and power, and mainly on steep bathymetric profiles that exceed the technical feasibility limits for bottom-fixed foundations.

To visualize the final site suitability results, Figures 4.1 to 4.5 present the spatial distribution of offshore wind zones across Chile. The country has been divided into five macro-zones (Far North, Near North, Central Chile, South, and Far South) to better capture regional variation in technical and spatial conditions.

Table 4.2 summarizes the area coverage that is suitable for Bottom-Fixed structures, and Table 4.3 shows the technical potential for this technology in the country, which was calculated using a 4MW/km^2 density.

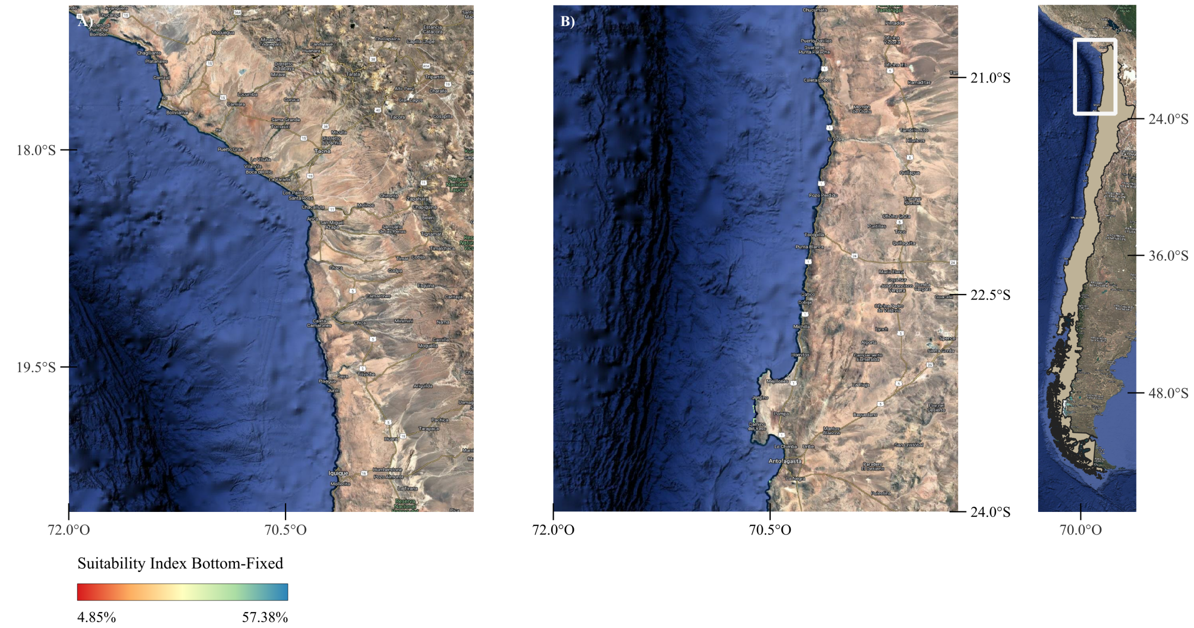

Figure 4.1: Suitability Index for Bottom-Fixed Structures in Norte Grande (Far North). Panel A) shows the northern portion and Panel B) the southern portion.

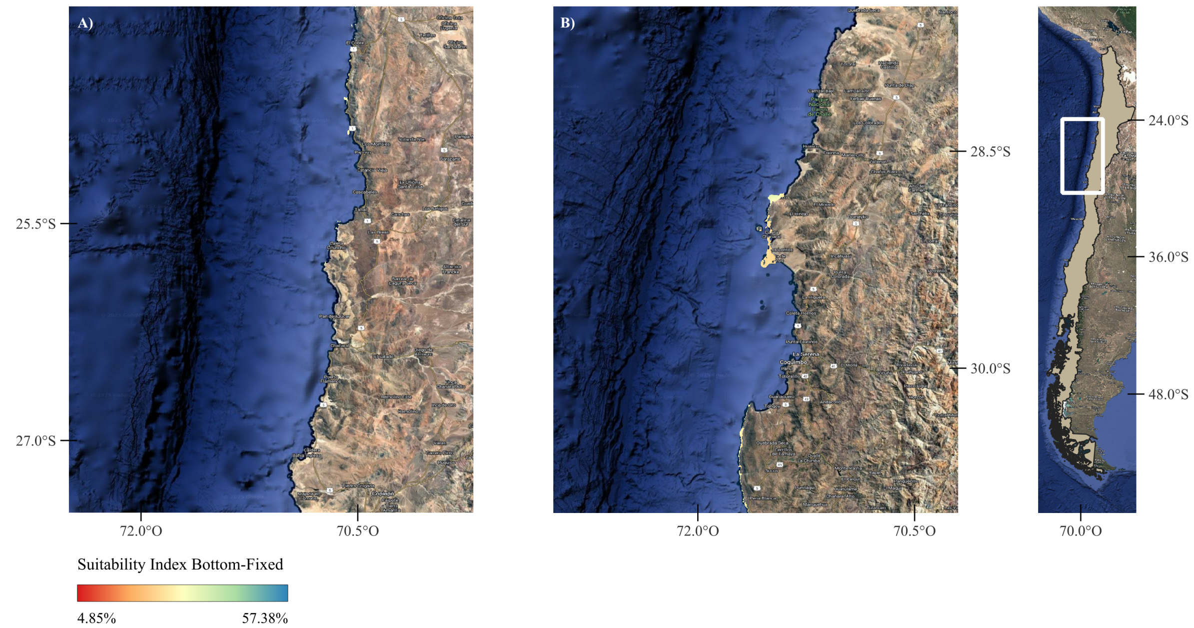

Figure 4.2: Suitability Index for Bottom-Fixed Structures in Norte Chico (Near North). Panel A) shows the northern portion and Panel B) the southern portion.

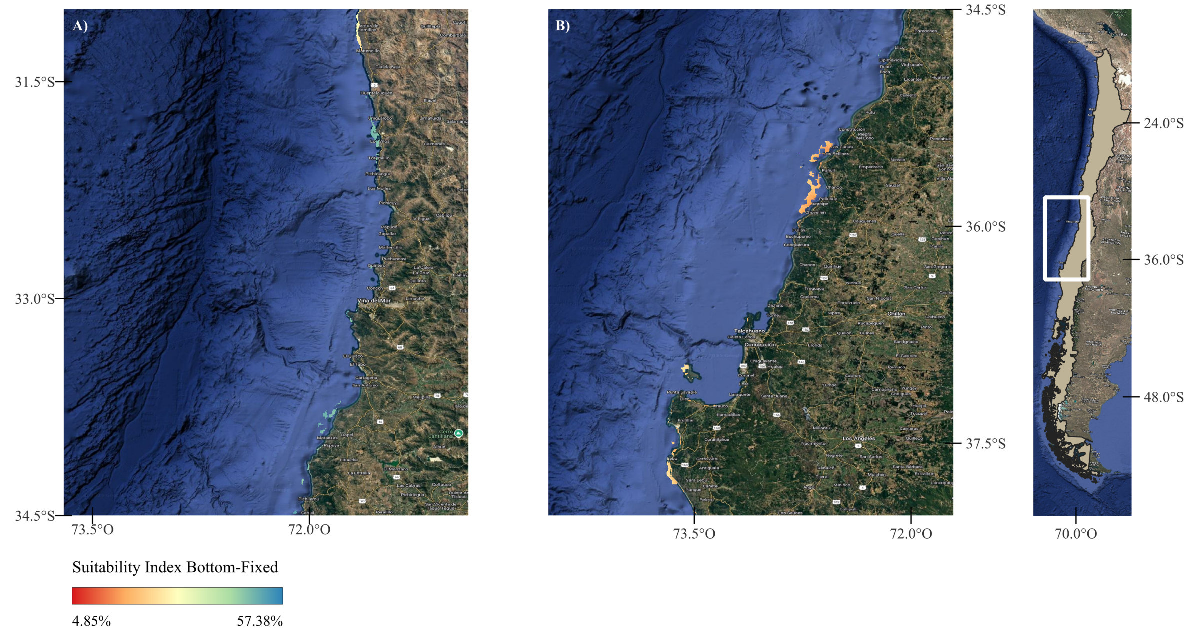

Figure 4.3: Suitability Index for Bottom-Fixed Structures in Zona Centro (Central Chile). Panel A) Shows the northern portion, and Panel B) southern portion.

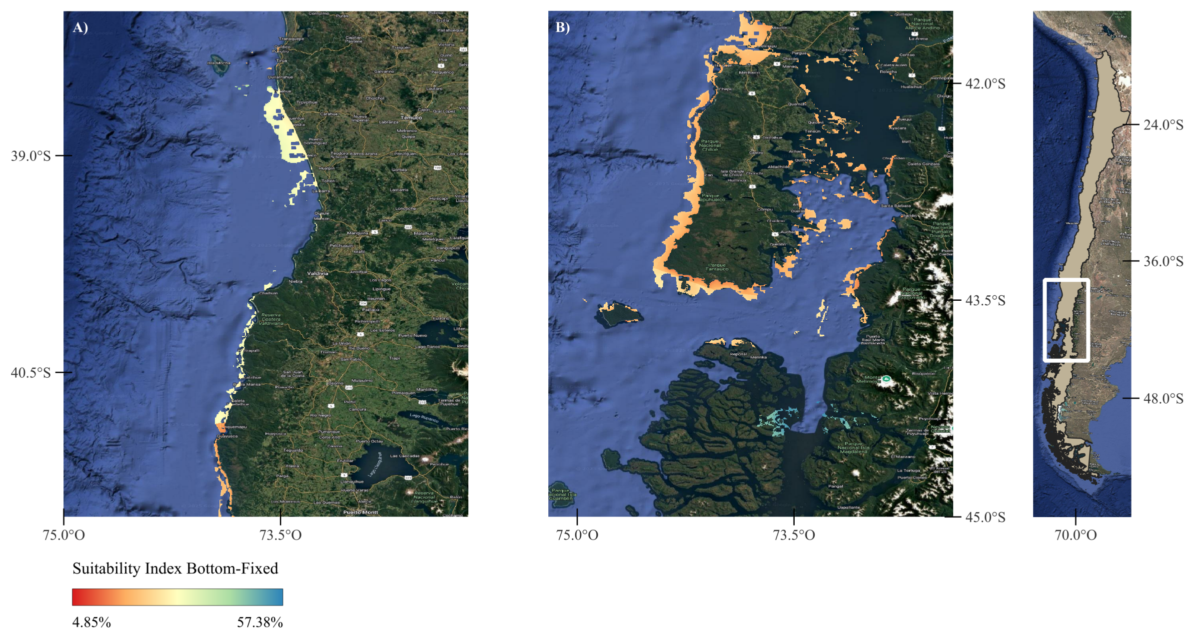

Figure 4.4: Suitability Index for Bottom-Fixed Structures in Zona Sur (South). Panel A) shows the northern portion and Panel B) southern portion.

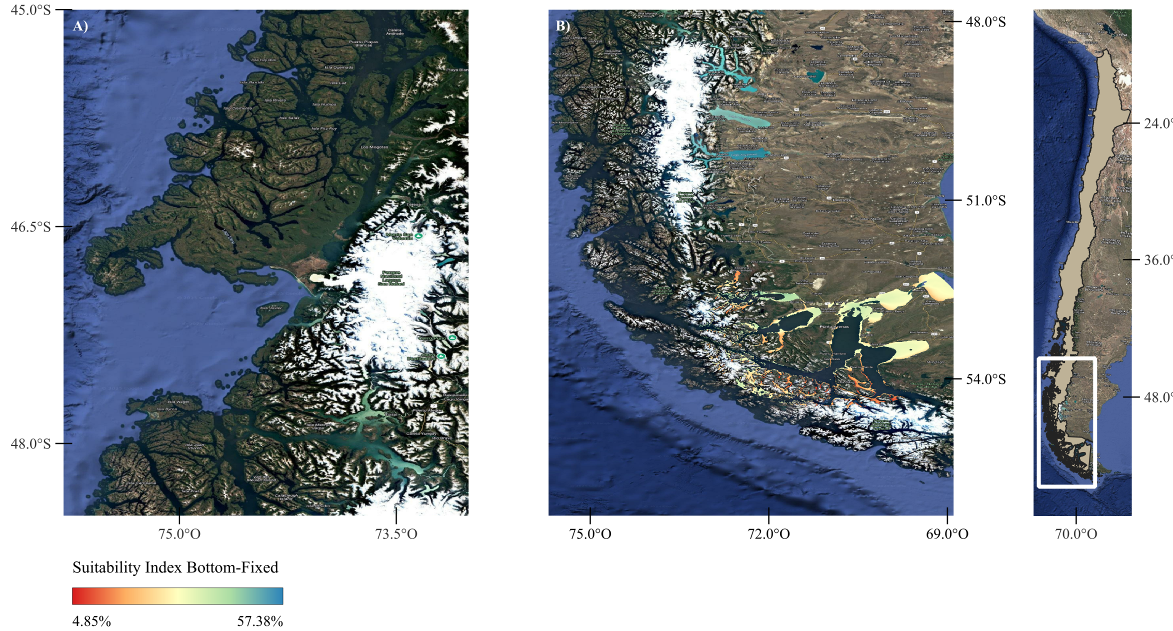

Figure 4.5: Suitability Index for Bottom-Fixed Structures in Sur Austral (Far South). Panel A) shows the northern portion, and Panel B) southern portion.

Table 4.2: Bottom-Fixed Offshore Wind Suitable Area by Zone

Zone	Area (km^2)
Norte Grande (Far North)	16.65
Norte Chico (Near North	219.02
Zona Centro (Central Chile)	386.86
Zona Sur (South)	3958.16
Sur Austral (Far South)	9583.70
Total	**14164.40**

Table 4.3: Technical Potential of Bottom-Fixed Offshore Wind by Zone

Zone	Technical Potential (GW)
Norte Grande (Far North)	0.07
Norte Chico (Near North)	0.88
Zona Centro (Central Chile)	1.55
Zona Sur (South)	15.83
Sur Austral (Far South)	38.33
Total	**56.66**

4.2.2 Floating Offshore Wind Structures

This subsection presents the results of the GIS-based suitability analysis for floating offshore wind structures using the same dynamics as prior.

In contrast to bottom-fixed systems, floating offshore wind enables development in deeper waters, allowing for a broader range of suitable locations, especially in Chile. The most suitable areas for floating wind were found in regions with strong and consistent wind resources, deeper and technically accessible bathymetric conditions (between 50 and 1000 meters). The most suitable zones were particularly identified in the South and Far South regions, where wind availability aligns with sufficient proximity to ports and lower spatial conflicts. In the South zone was found the largest suitable area (24293.32 km^2) with a technical potential of 97.17 GW. Meanwhile, the Far South shows the highest suitability index.

Areas with low suitability were mostly found in zones characterized by the worst wind conditions, such as the northern part of the country, which can restrict deployment feasibility.

To visualize the final site suitability results for floating structures, Figures 4.6 to 4.10 present the spatial distribution of suitability zones across Chile. As with the bottom-fixed analysis, the country is divided into five macro-zones (Far North, Near North, Central Chile, South, and Far South) to reflect regional variability in technical and spatial factors relevant to floating wind deployment.

Table 4.4 summarizes the area coverage of suitability for floating offshore wind development, while Table 4.5 presents the corresponding technical potential, calculated using a 4 MW/km^2 density assumption as well.

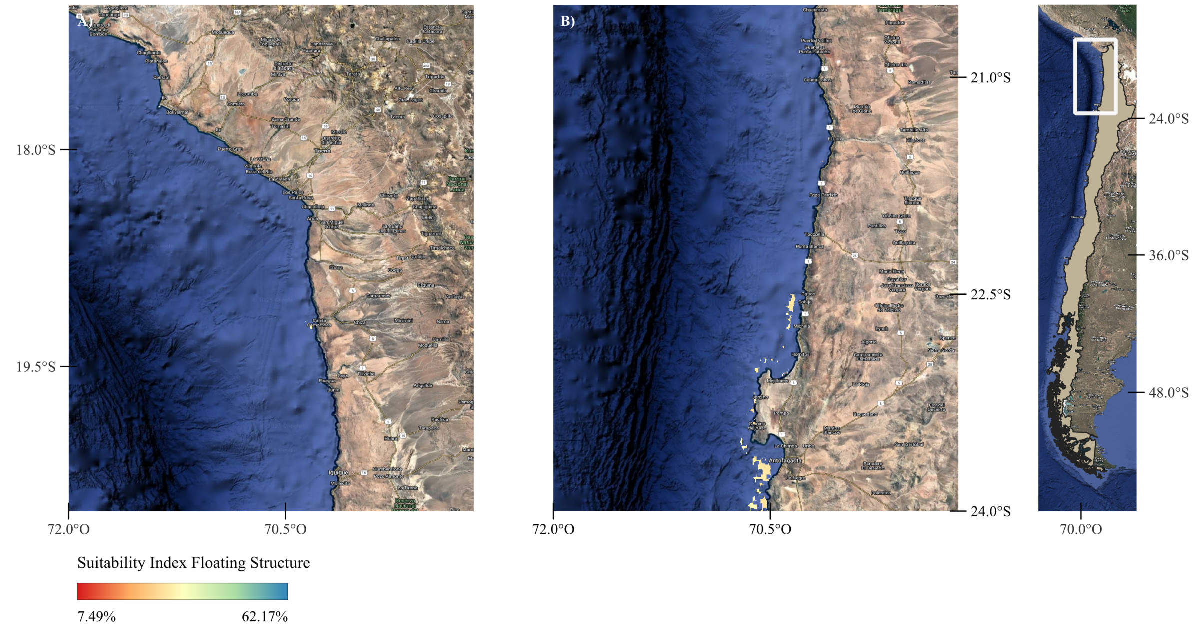

Figure 4.6: Suitability Index for Floating Structures in Norte Grande (Far North). Panel A) shows the northern portion and Panel B) the southern portion.

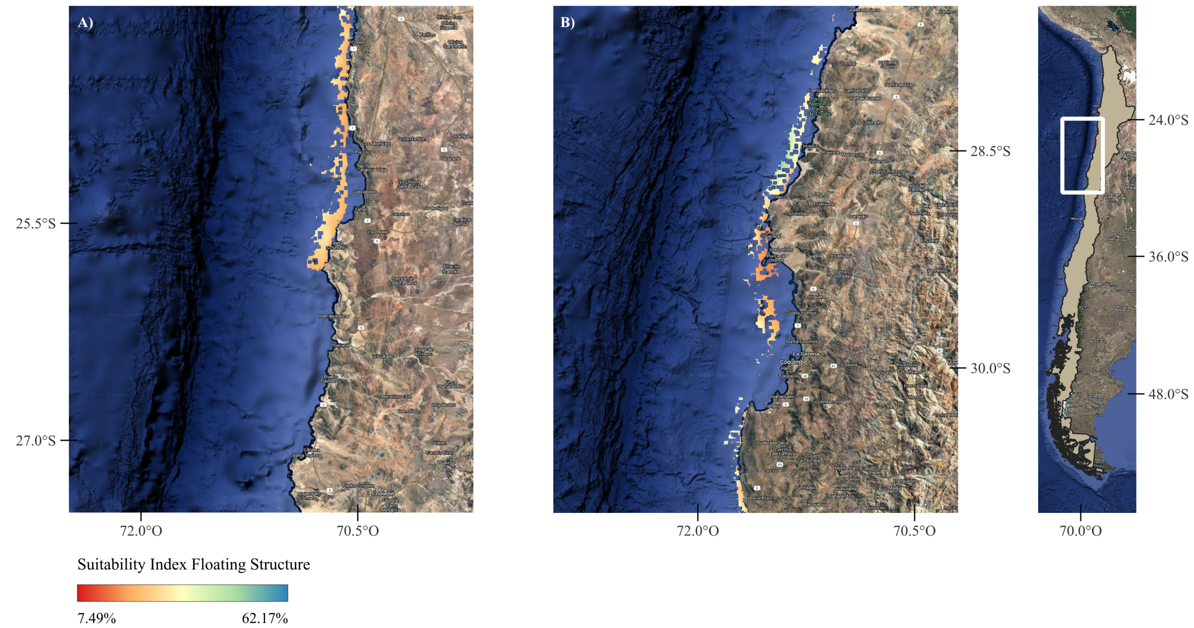

Figure 4.7: Suitability Index for Floating Structures in Norte Chico (Near North). Panel A) shows the northern portion and Panel B) the southern portion.

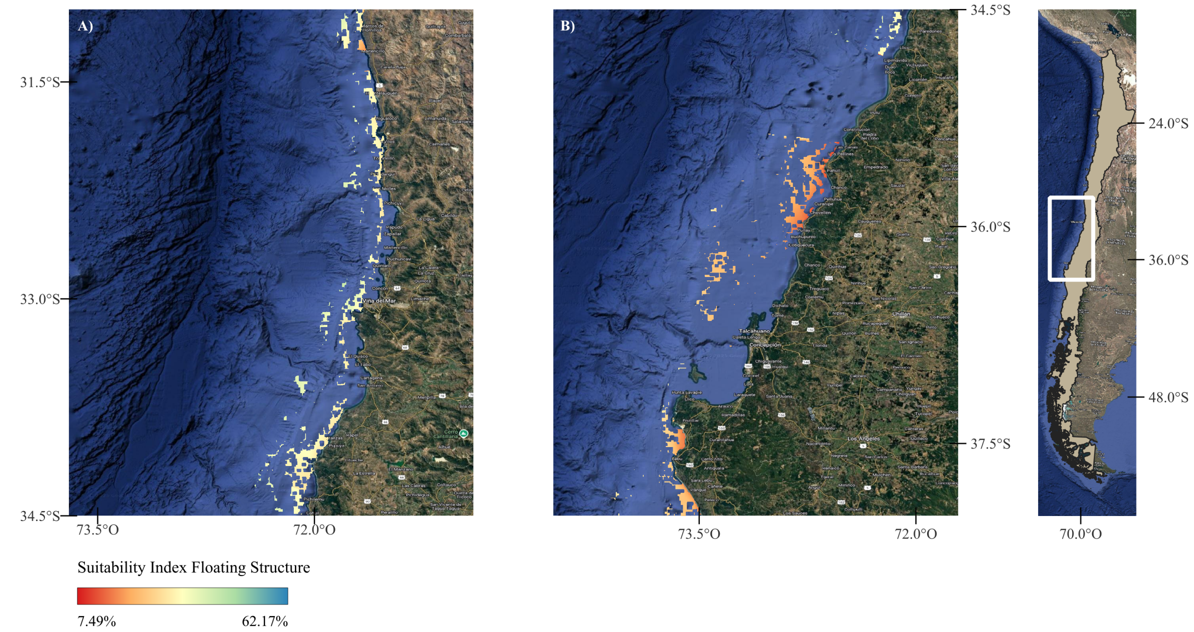

Figure 4.8: Suitability Index for Floating Structures in Zona Centro (Central Chile). Panel A) shows the northern portion and Panel B) the southern portion.

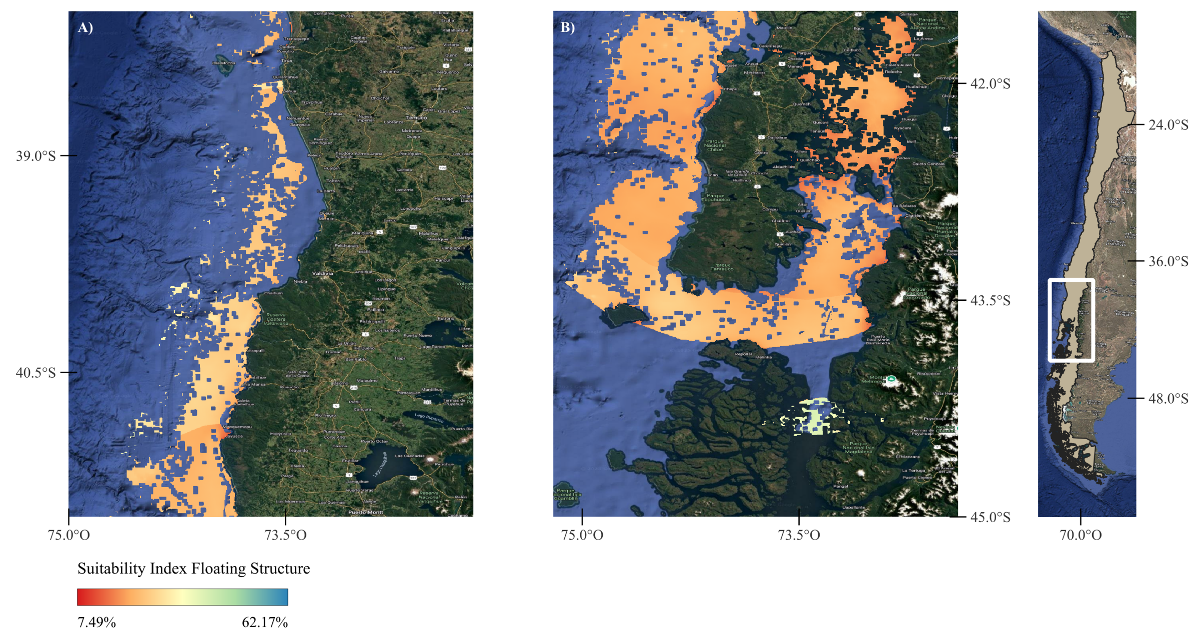

Figure 4.9: Suitability Index for Floating Structures in Zona Sur (South). Panel A) shows the northern portion and Panel B) the southern portion.

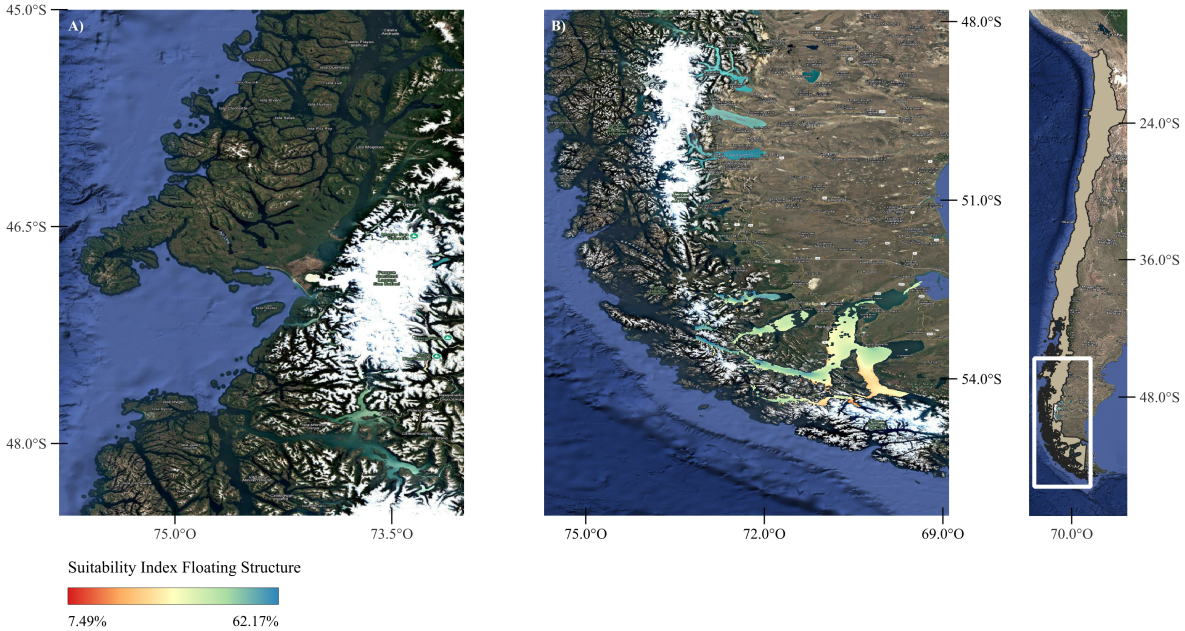

Figure 4.10: Suitability Index for Floating Structures in Sur Austral (Far South). Panel A) shows the northern portion and Panel B) the southern portion.

Table 4.4: Floating Offshore Wind Suitable Area by Zone

Zone	**Area (km^2)**
Norte Grande (Far North)	225.53
Norte Chico (Near North	2353.80
Zona Centro (Central Chile)	2356.16
Zona Sur (South)	24293.32
Sur Austral (Far South)	9724.59
Total	**38953.40**

Table 4.5: Technical Potential of Floating Offshore Wind by Zone

Zone	**Technical Potential (GW)**
Norte Grande (Far North)	0.90
Norte Chico (Near North)	9.42
Zona Centro (Central Chile)	9.42
Zona Sur (South)	97.17
Sur Austral (Far South)	38.90
Total	**155.81**

4.2.3 Maximum Suitability Index

The Maximum Suitability Index refers to the area that achieved the highest score in the GIS-based MCDM analysis, indicating optimal conditions for offshore wind development as shown in 4.11. This metric reflects a convergence of favorable spatial criteria, including high wind resources, technically feasible bathymetry, proximity to port and grid infrastructure, and low environmental or socio-economic conflicts.

For bottom-fixed structures, maximum suitability values were observed in coastal regions where bathymetric depths remain below 50 meters and infrastructure accessibility is high, specifically in the southern part, with a maximum index of 57.18%.

In the case of floating structures, the broader technical range for water depth allows high suitability scores to be achieved in deeper offshore areas. Notably, maximum suitability zones for floating wind were identified in the Far South Zone, where wind speeds are consistently strong, and this reached a suitability index of 62.17%.

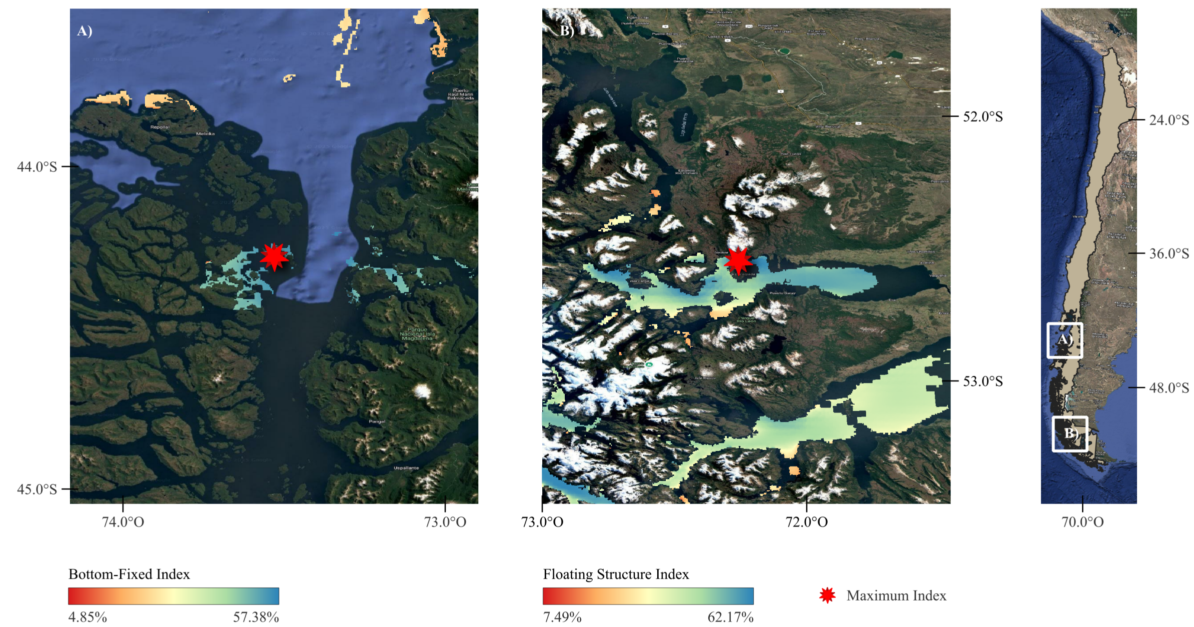

Figure 4.11: Maximum Suitability Index for Offshore Wind. Panel A) shows Bottom-Fixed Structures, and Panel B) Floating Structures.

4.3 GIS Percentile-Zoning Results

4.3.1 Percentile-Zoning Bottom-Fixed Offshore Wind Structures

This subsection presents the spatial classification of the bottom-fixed offshore wind suitability map into percentile-based zones. The continuous suitability index was divided into three zones using percentile thresholds: Zone A (high suitability), Zone B (moderate suitability), and Zone

C (low suitability). This zoning approach facilitates clearer interpretation for planning purposes and supports the strategic roadmap development, as previously stated.

Figures 4.12 to 4.16 show the spatial distribution of these zones across Chile, divided into the five macro-zones of the country. The maps highlight the most promising areas for bottom-fixed offshore wind deployment based on technical feasibility and spatial constraints.

Zone A areas for bottom-fixed structures are primarily located in the South and Far South. Zone B areas may be considered for development if supported by regulatory improvements or infrastructure upgrades, still beign the most relevant ones the same as Zone A. Zone C areas typically face significant limitations due to steep bathymetric gradients, environmental protections, or high levels of conflicting maritime activity, being the South Zone the one with larger area.

Table 4.6 summarizes the total area covered by each zone within each macro-region.

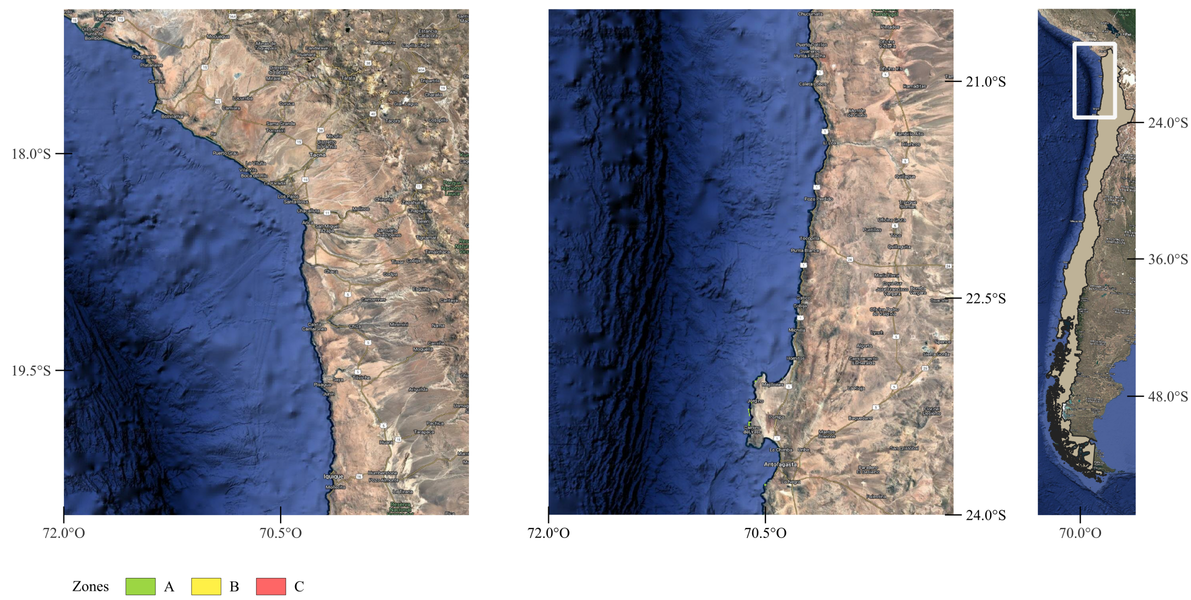

Figure 4.12: Percentile-Zoning for Bottom-Fixed Structures in Norte Grande (Far North). Panel A) shows the northern portion and Panel B) the southern portion.

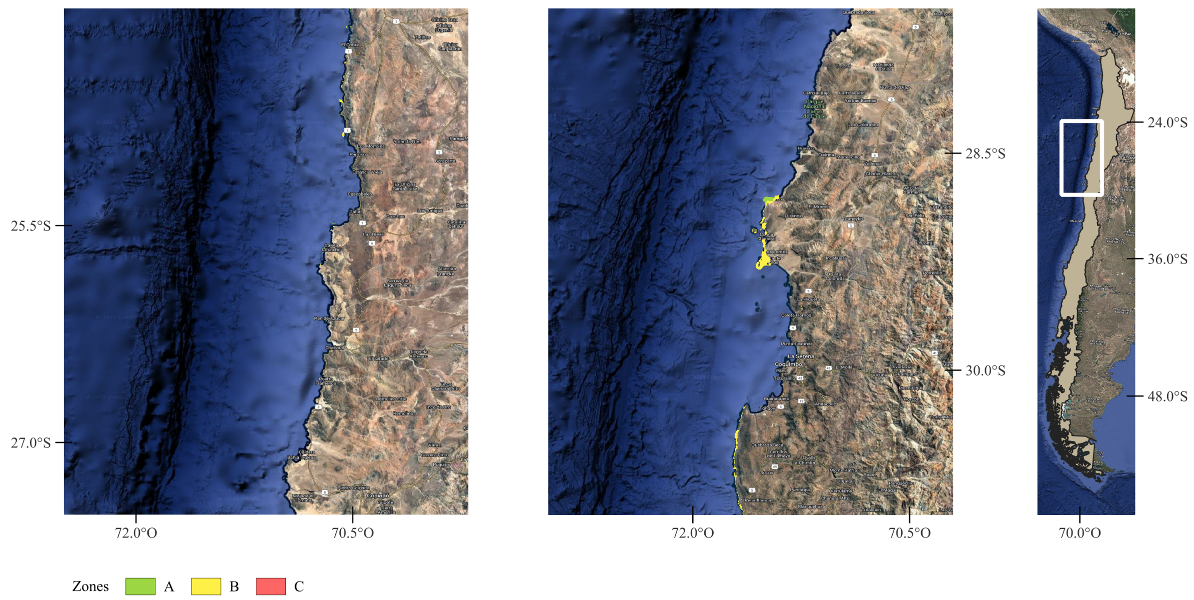

Figure 4.13: Percentile-Zoning for Bottom-Fixed Structures in Norte Chico (Near North). Panel A) shows the northern portion and Panel B) the southern portion.

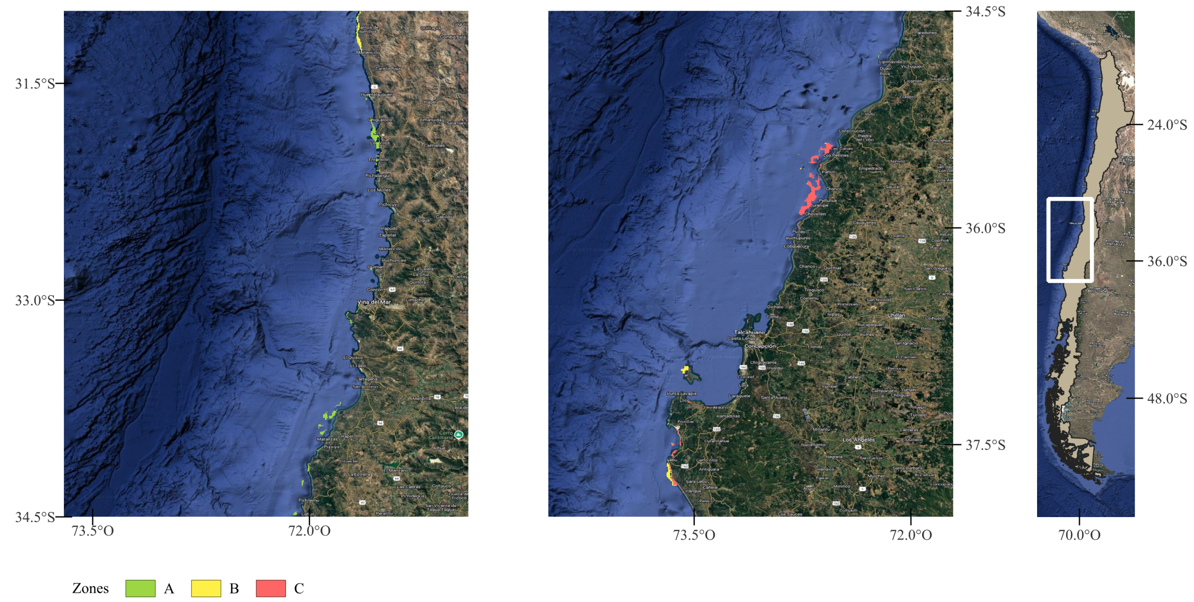

Figure 4.14: Percentile-Zoning for Bottom-Fixed Structures in Zona Centro (Central Chile). Panel A) shows the northern portion and Panel B) the southern portion.

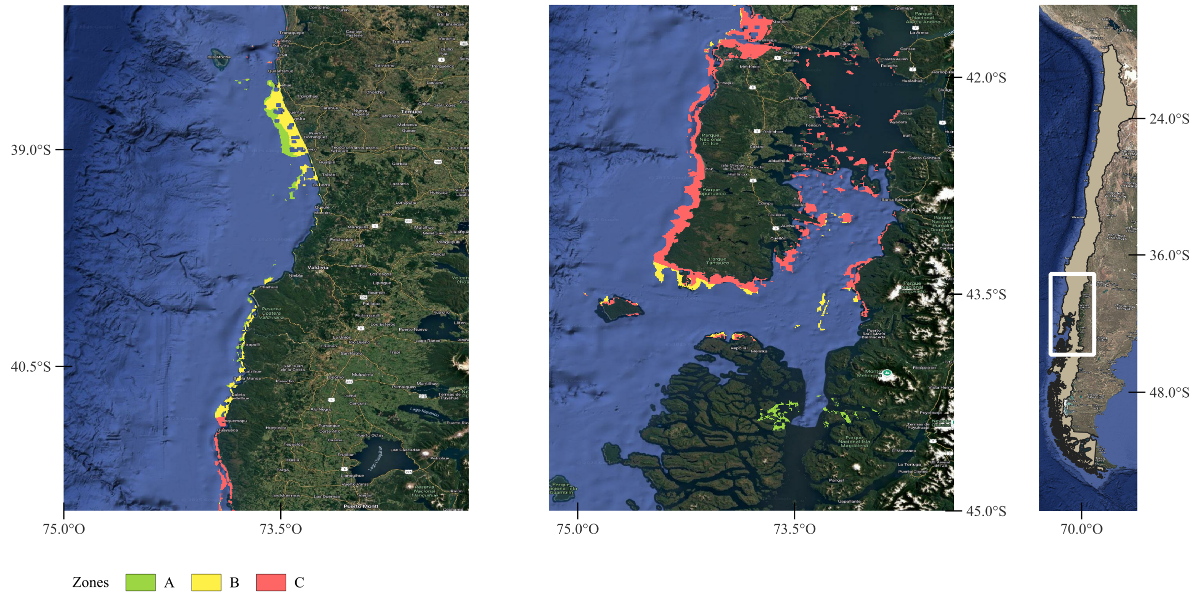

Figure 4.15: Percentile-Zoning for Bottom-Fixed Structures in Zona Sur (South). Panel A) shows the northern portion and Panel B) the southern portion.

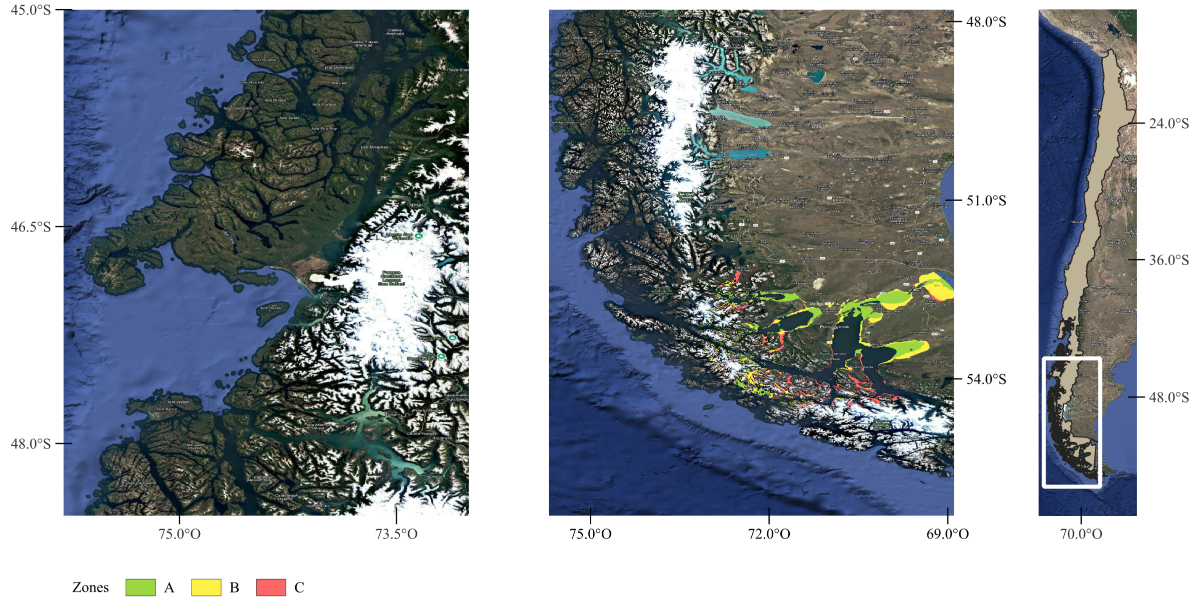

Figure 4.16: Percentile-Zoning for Bottom-Fixed Structures in Sur Austral (Far South). Panel A) shows the northern portion and Panel B) the southern portion.

Table 4.6: Bottom-Fixed Offshore Wind Suitable Area by Zone and Percentile Classification

Zone	**Area Zone A (km^2)**	**Area Zone B (km^2)**	**Area Zone C (km^2)**
Norte Grande (Far North)	16.65	0	0
Norte Chico (Near North)	32.28	186.74	0
Zona Centro (Central Chile)	132.03	61.58	193.25
Zona Sur (South)	299.46	892.22	2766.48
Sur Austral (Far South)	4240.51	3581.96	1761.24

4.3.2 Percentile-Zoning Floating Offshore Wind Structures

Same procedure with bottom-fixed structures, this time Figures 4.17 to 4.21 show the spatial distribution of the suitability zones across Chile for floating structures, divided into the five macro-zones.

Zone A areas for floating structures are mostly concentrated in the Far South, with 9317.85 km^2 of area. Zone B areas that are more widespread and could be considered for development under improved regulatory or technological conditions show that in the South of Chile is located the biggest portion of area for this suitability being 11368.66 km^2. Zone C areas generally exhibit unfavorable bathymetric profiles or significant environmental or socio-economic constraints, being also the southern portion the one with the most significant area of 11990.37 km^2.

Table 4.7 summarizes the total area covered by each zone within each macro-region.

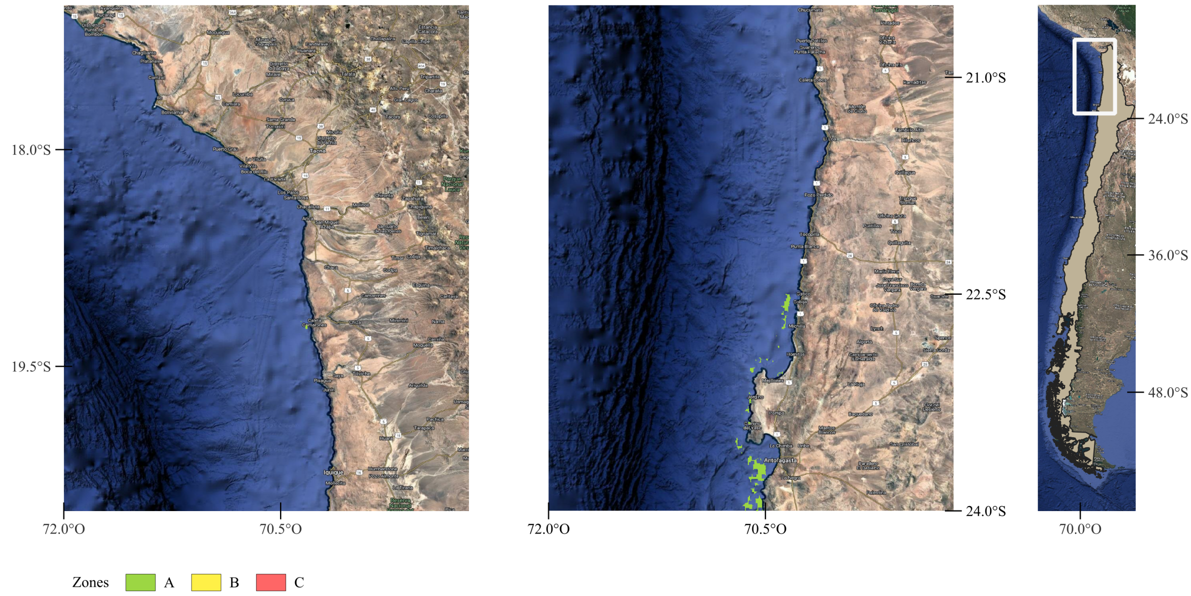

Figure 4.17: Percentile-Zoning for Floating Structures in Norte Grande (Far North). Panel A) shows the northern portion and Panel B) the southern portion.

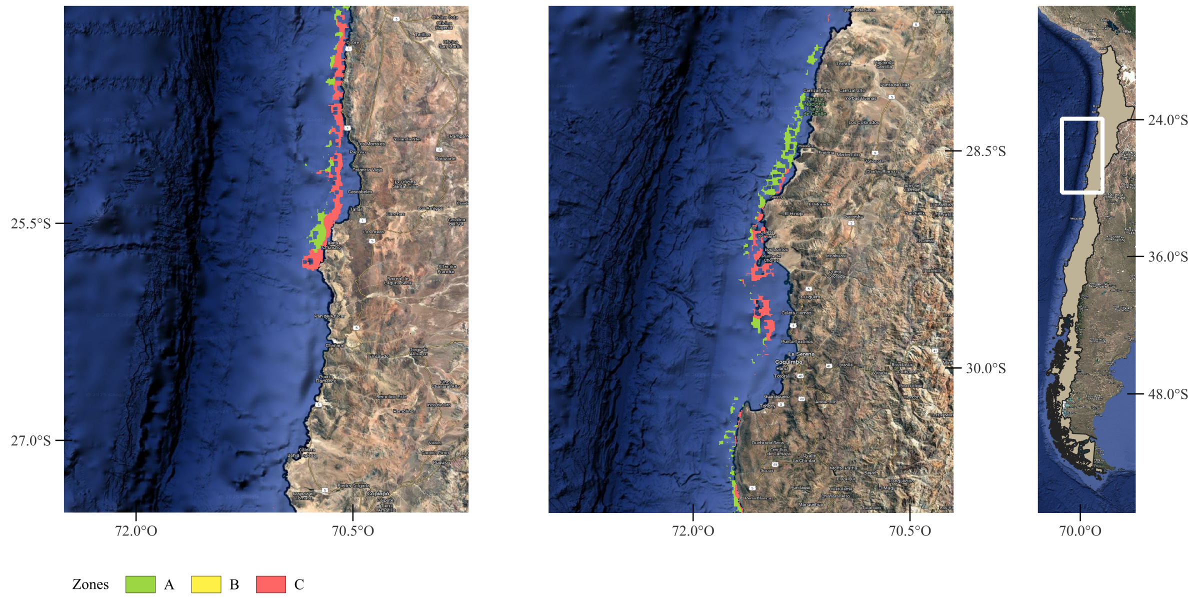

Figure 4.18: Percentile-Zoning for Floating Structures in Norte Chico (Near North). Panel A) shows the northern portion and Panel B) the southern portion.

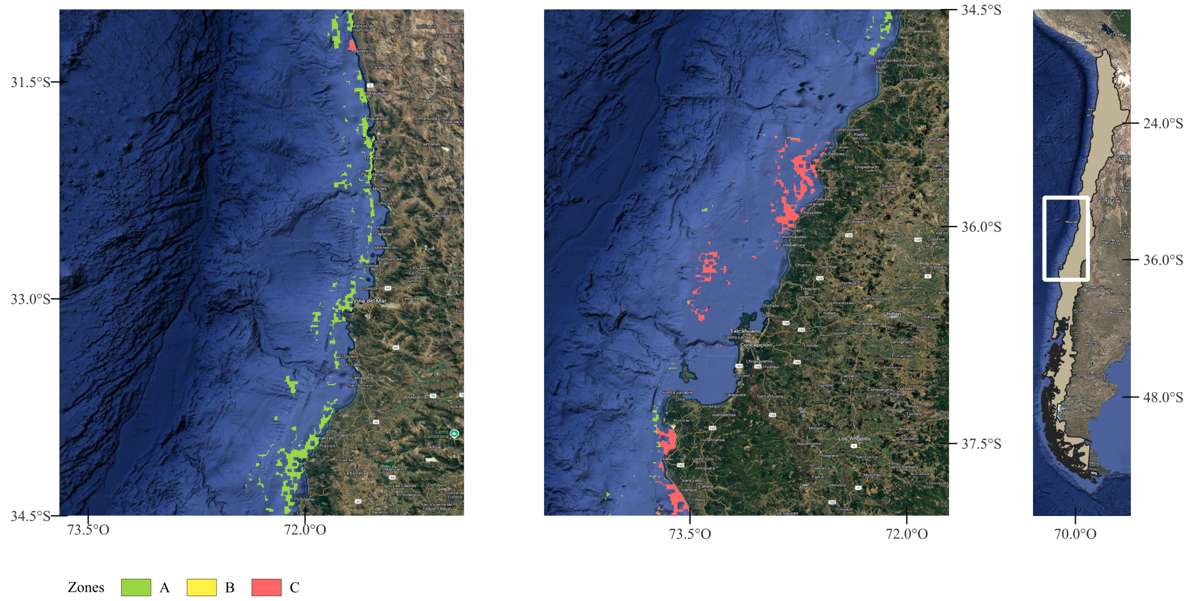

Figure 4.19: Percentile-Zoning for Floating Structures in Zona Centro (Central Chile). Panel A) shows the northern portion and Panel B) the southern portion.

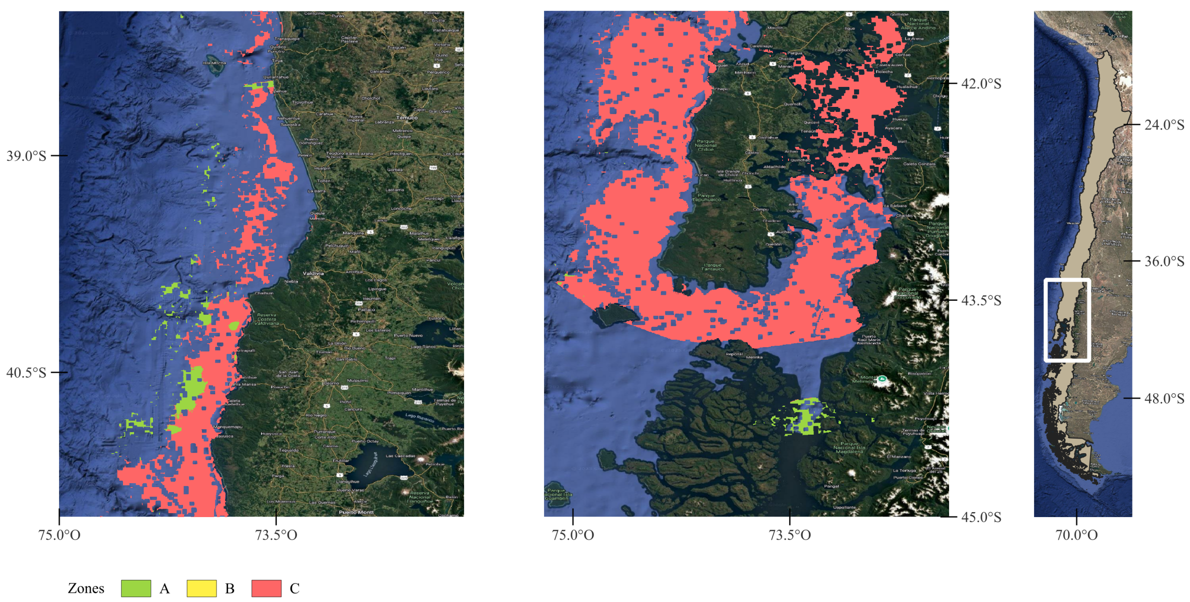

Figure 4.20: Percentile-Zoning for Floating Structures in Zona Sur (South). Panel A) shows the northern portion and Panel B) the southern portion.

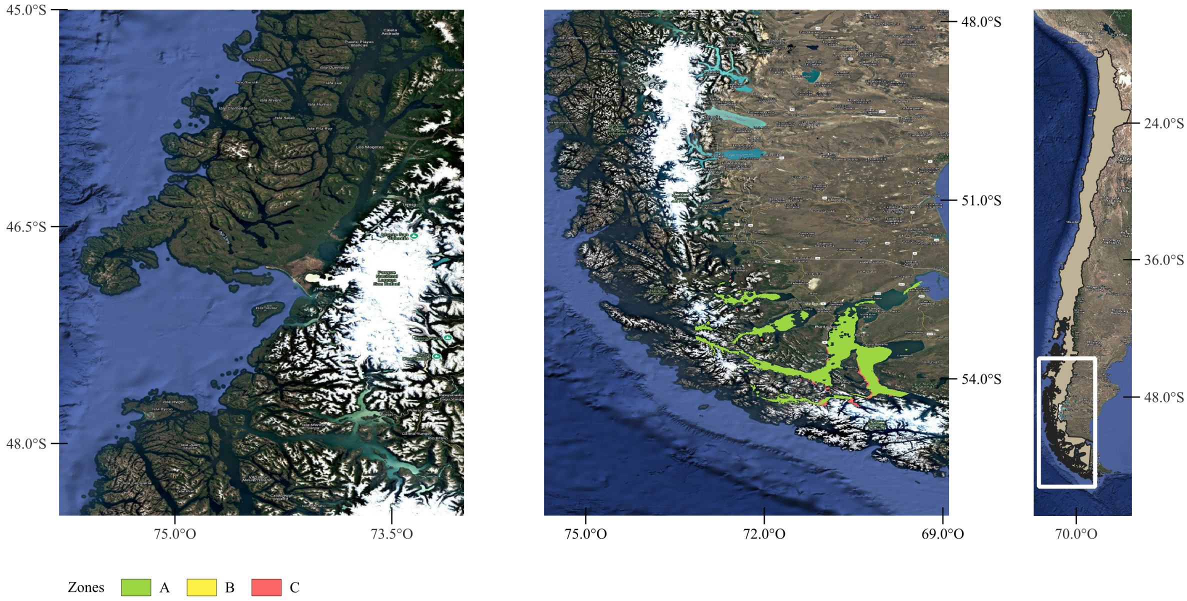

Figure 4.21: Percentile-Zoning for Floating Structures in Sur Austral (Far South). Panel A) Shows northern portion and panel B) southern portion.

Table 4.7: Floating Offshore Wind Suitable Area by Zone and Percentile Classification

Zone	Area Zone A (km^2)	Area Zone B (km^2)	Area Zone C (km^2)
Norte Grande (Far North)	225.22	0	0.31
Norte Chico (Near North)	981.47	949.50	422.83
Zona Centro (Central Chile)	1524.34	389.58	442.24
Zona Sur (South)	934.29	11368.66	11990.37
Sur Austral (Far South)	9317.85	279.32	127.42

4.4 AHP and TOPSIS Country Benchmark

This section presents the results of AHP and TOPSIS analysis, which were conducted to benchmark Chile's offshore wind readiness against a selection of comparator countries located in Europe and South America.

First, the AHP was applied to determine the relative importance of various criteria influencing offshore wind development. The detailed criteria, identified through a comprehensive literature review, were grouped into higher-level categories such as regulatory framework, resource assessment, grid infrastructure, and supply chain readiness. Consistency was verified using the Consistency Ratio (CR), which was found to be 0.0898, indicating reliable comparisons. Table 4.8 presents the calculated weights for each sub-criterion already mentioned.

Table 4.8: Weights for Offshore Wind Evaluation Criteria

Criterion Code	**Weight**
CR 1.1	0.1078
CR 1.2	0.0252
CR 1.3	0.1078
CR 1.4	0.0252
CR 2.1	0.0358
CR 2.2	0.0358
CR 2.3	0.0439
CR 3.1	0.1049
CR 3.2	0.1709
CR 3.3	0.1440
CR 4.1	0.0102
CR 4.2	0.0102
CR 5.1	0.0687
CR 6.1	0.0548
CR 6.2	0.0548

Following the determination of criterion weights, the TOPSIS method was employed to rank the selected countries based on their performance across these criteria. The ”Closeness to Ideal Solution” metric derived from TOPSIS reflects a country’s overall readiness for offshore wind development, with higher values indicating a more favorable position.

Table 4.9 presents the calculated closeness to the ideal solution for each benchmarked country, ordered from highest to lowest.

The results clearly show that Denmark holds the top position with a closeness score of 0.912, underscoring its leading role and maturity in offshore wind. It is closely followed by the Netherlands (0.724) and the United Kingdom (0.697), both highly active and experienced markets. These top-tier countries benefit from robust regulatory frameworks, advanced grid infrastructure, strong financial incentives, and established supply chains.

In contrast, Chile is positioned in the lower tier of the benchmarked countries, with a closeness score of 0.149. This places Chile 14th out of the 17 countries assessed. Its ranking suggests significant room for development across various criteria when compared to the leading nations. Other emerging markets such as Mexico, Colombia, and Argentina also rank in similar lower positions, indicating common challenges faced by countries initiating in this subject.

It’s also important to notice that the criteria in which Chile ranked lower and the main gaps identified were in permitting efficiency and renewable energy support, which are critical for

Table 4.9: TOPSIS Ranking Outcome

Country	Closeness to Ideal Solution
Denmark	0.912
Netherlands	0.724
United Kingdom	0.697
Germany	0.646
Belgium	0.521
Norway	0.370
France	0.347
Spain	0.333
Ireland	0.279
Portugal	0.258
Italy	0.237
Brazil	0.170
Uruguay	0.163
Chile	0.149
Mexico	0.105
Colombia	0.079
Argentina	0.070

accelerating offshore wind deployment. This is Chile's biggest area of weakness — lack of existing OW infrastructure, innovation, and port readiness. Technological & Industrial Development No investment framework No investment framework

It is also important to note which of the criteria Chile ranked the lowest and where the main gaps were. One of the identified areas includes permitting efficiency, which is critical for accelerating offshore wind deployment. The major weakness found was the lack of existing offshore wind infrastructure, limited technological innovation, and insufficient port readiness, all of them regarding the technological and industrial development dimension. Also, the absence of a dedicated investment framework further slows progress and private sector engagement.

4.5 Managerial and Qualitative Analysis Outcomes

4.5.1 PESTEL

This section is dedicated to showing the PESTEL analysis results to explore the different external factors influencing offshore wind development in Chile that shape the environment of this emerging industry.

1. Political

- **Government Commitment to Decarbonization:** Chile has set ambitious renewable energy goals, including carbon neutrality by 2050 [8]. This strong political commitment supports the development of new renewable sources like offshore wind.

- **Policy and Regulatory Framework:** While there is a general framework for onshore renewables, specific legislation for offshore wind is still underdeveloped, creating uncertainty for investors [7].

- **Political Stability:** Chile is generally regarded as a stable democracy in Latin America. However, recent social unrest and an ongoing constitutional process have introduced political uncertainty and potential policy shifts, which may affect long-term investments [98].

- **International Agreements:** Chile's participation in international climate agreements such as the Paris Agreement and initiatives like the Global Offshore Wind Alliance (GOWA) reinforces its renewable energy commitments and opens opportunities for cooperation and funding [106, 92].

- **Promotion of Foreign Investment:** Through agencies like InvestChile, the government actively encourages foreign direct investment and maintains a track record of welcoming international businesses—favorable conditions for offshore wind projects[98, 13].

2. Economic

- **Growing Energy Demand:** Economic growth in Chile is driving rising electricity demand, highlighting the need for new generation capacity [39]. Offshore wind can play a significant role in meeting this demand, particularly for electrification and industrial uses.

- **Green Hydrogen Ambition:** Chile aims to become a global leader in green hydrogen production. Offshore wind's stable, clean power is essential for electrolysis, making it a potential catalyst for investment in this emerging market[38, 100] .

- **Cost Trends in Offshore Wind:** Globally, offshore wind's Levelized Cost of Energy (LCOE) has declined sharply, improving competitiveness. Although floating offshore wind (key for Chile's deep waters) remains costlier, similar cost reductions are expected [106].
- **Economic Impact and Job Creation:** Offshore wind offers substantial job creation opportunities in construction, operations, and maintenance, and can boost economic diversification [106].
- **Market Structure:** Chile's electricity market is generally competitive, and while long-term power purchase agreements (PPAs) are well established for onshore renewable projects through government auctions, such frameworks are still lacking for offshore wind. This absence creates financial uncertainty and risks for offshore wind developers [107].
- **Inflation and Supply Chain Risks:** Like Equinor's Empire Wind 2 project [97], which faced cost overruns and delays due to inflation and supply chain issues, Chilean offshore wind projects could also see increased costs and timeline risks from importing specialized components.

3. Social

- **Community Engagement and Social License:** Successful offshore wind development requires meaningful engagement with local communities—including fishing groups—to secure and maintain a social license to operate, particularly given past conflicts over industrial projects [108, 106].
- **Public Perception and Acceptance:** While there is general support for renewables, specific offshore wind projects may face opposition due to concerns about visual impacts, environmental effects, or disruptions to traditional activities. Transparent communication and benefit-sharing are critical [106].
- **Job Creation and Local Content:** Generating local employment and fostering domestic supply chains can create positive social outcomes and strengthen community support. Equitable distribution of benefits is essential [106].

- **Land Claims:** Chile's strong emphasis on ancestral land rights demands rigorous, inclusive consultation processes to avoid legal challenges or community resistance [93, 106].

4. Technological

- **Floating Offshore Wind Technology:** Due to Chile's deep coastal waters, floating offshore wind technology is vital for unlocking most of its potential. Although this technology is advancing rapidly, it remains less mature and more costly than fixed-bottom alternatives [7, 106].

- **Grid Modernization and Integration:** Large-scale offshore wind integration might require significant grid upgrades, expanded transmission infrastructure to maintain grid stability and reliability, specially for floating structures [12, 17] .

- **Data and Resource Assessment:** Advances in oceanographic and meteorological data collection, along with improved modeling, are essential for accurate resource assessments, site selection, and turbine optimization tailored to Chile's marine environment [7].

- **Supply Chain Development:** Building local manufacturing, assembly, and maintenance capabilities will require technology transfer, workforce training, and investment in specialized port infrastructure [7, 106].

5. Environmental

- **Rich Marine Biodiversity:** Chile's extensive coastline hosts diverse marine ecosystems, including whale migration routes and important fishing grounds. Offshore wind projects must minimize impacts on these sensitive areas in compliance with strict environmental regulations[109].

- **Environmental Impact Assessments (EIA):** Projects will face thorough EIAs evaluating effects on marine life, seabed habitats, and water quality—a process that can be lengthy, complex and there is room to improve in Chile [91, 106].

- **Climate Change Mitigation:** Offshore wind directly supports Chile's climate goals by replacing fossil fuel generation and reducing greenhouse gas emissions [106].
- **Coexistence with Other Marine Uses:** Offshore wind farms must coexist with fishing, shipping, aquaculture, and marine protected areas, requiring effective marine spatial planning to manage potential conflicts [7].
- **Climate Vulnerability:** Sea-level rise and extreme weather events such as storm surges (marejadas) may impact infrastructure resilience and increase insurance costs over the long term [7].

6. Legal

- **Emerging Offshore Wind Legislation:** Chile currently lacks a dedicated offshore wind permitting regime; existing maritime and environmental laws are fragmented and not tailored to offshore energy, creating legal uncertainty [7].
- **Environmental Legislation:** Offshore wind projects must comply with Chile's established environmental laws and the comprehensive Environmental Impact Assessment System (SEIA) [81].
- **Human Rights and International Obligations:** Projects must adhere to international frameworks such as ILO Convention 169, which requires free, prior, and informed consultation with communities potentially affected, especially in areas with ancestral or customary land claims [93].
- **Fisheries Law:** Existing fisheries regulations govern marine resource access and must be considered to avoid conflicts with the fishing sector [89].
- **Maritime Concessions:** Obtaining long-term maritime concessions for offshore energy use is a critical legal step, necessitating a clear and streamlined process [106].

4.5.2 SWOT

This section presents the SWOT analysis results to evaluate the internal and external factors impacting offshore wind development in Chile. By identifying the inherent strengths and weaknesses of the sector within the Chilean context, alongside the external opportunities it can leverage and the threats it must consider to mitigate afterwards.

Strengths

1. **Abundant and High-Quality Wind Resource:** Chile's extensive coastline, especially in the south, offers world-class offshore wind speeds and power density, ensuring strong and consistent energy output [7, 36].

2. **Huge Technical Potential:** Estimates suggest Chile could harness 957 GW of offshore wind potential, with 86% suitable for floating technology—far exceeding national electricity demand and positioning Chile as a future renewable energy leader [37].

3. **Strong Government Commitment:** Ambitious goals like 70% renewable energy by 2030 and carbon neutrality by 2050, along with a coal phase-out plan, provide a clear policy mandate supporting offshore wind [8].

4. **Strategic Position for Green Hydrogen:** Chile aims to be a global leader in green hydrogen, which requires stable, large-scale renewable power, and offshore wind offers a perfect complementary energy source [38, 8].

5. **Experience with Onshore Renewables:** Chile has successfully integrated onshore wind and solar, showing a favorable regulatory environment and institutional learning that can support offshore wind deployment [39].

6. **Suitability for Floating Wind Technology:** The country's narrow continental shelf and deep coastal waters make floating offshore wind essential, and Chile is well-positioned to lead in this emerging technology [7].

7. **Liberalized Electricity Market:** An open and competitive market facilitates the entry of independent power producers and the use of Power Purchase Agreements (PPAs) [107].

Weaknesses

1. **Lack of Dedicated Offshore Wind Regulation:** While general renewable energy laws exist, Chile still lacks a comprehensive legal framework tailored to offshore wind, creating uncertainty around permits, concessions, and grid connections [7].

2. **Immature Local Supply Chain and Infrastructure:** The country currently depends heavily on imports and foreign expertise due to limited specialized ports, manufacturing capacity, and workforce for offshore wind [7].

3. **High Capital Costs of Floating Technology:** Floating offshore wind remains expensive compared to fixed-bottom installations and other renewables, posing financial barriers [17].

4. **Grid Constraints:** Chile's long, narrow transmission system struggles to move large amounts of renewable energy from generation sites to demand centers; without upgrades, offshore wind may worsen congestion [96].

5. **Market Pricing and Revenue Stability Issues:** The marginal cost-based electricity market often leads to low prices during high renewable output periods, and the lack of long-term PPAs or stable revenue streams complicates project financing [107].

6. **Social Acceptance Challenges:** Potential resistance from coastal communities and local users, including fisheries, poses risks to gaining a social license to operate [95].

7. **Harsh Ocean Conditions:** Extreme waves and weather along parts of the coast increase engineering challenges, operational risks, and costs [7].

Opportunities

1. **Declining Costs Globally:** The cost of offshore wind, including floating platforms, is steadily falling, improving competitiveness [106].

2. **Rising Domestic Demand and Decarbonization:** Chile's growing economy and climate commitments drive demand for large-scale clean energy, opening a strong market for offshore wind [39].

3. **Green Hydrogen Export Potential:** Offshore wind can power electrolysis to produce green hydrogen for export, creating new revenue and industrial growth [100, 38].

4. **Technological Innovation:** Advances in floating platform design and installation will expand the economically viable offshore wind resource [17].

5. **Attracting International Investment and Partnerships:** Chile's relative political stability and resource potential make it attractive for foreign direct investment and technological collaboration [13, 98].

6. **Job Creation and Regional Development:** Offshore wind could generate thousands of jobs in manufacturing, construction, and operations, especially in coastal communities [106].

7. **Synergies with Maritime Industries:** Opportunities exist to collaborate with naval shipyards, port services, and aquaculture, leveraging existing expertise and infrastructure [106].

Threats

1. **Socio-Political Conflicts:** Ongoing tensions with community groups, especially in southern regions, risk project delays, increased costs, and reputational damage [80, 99].

2. **Environmental and Permitting Challenges:** Potential impacts on marine biodiversity and fisheries may lead to lengthy environmental assessments and legal disputes [7].

3. **Competition for Marine Space:** The Growing demand for ocean areas by fisheries, shipping, aquaculture, and tourism can create conflicts requiring careful marine spatial planning [7].

4. **Supply Chain Risks and Inflation:** Global material shortages, geopolitical tensions, and inflation threaten project costs and schedules [106].

5. **Regulatory Uncertainty:** Delays or sudden policy shifts in offshore wind regulations could discourage investors [98, 106].

6. **Financial Viability Concerns:** Without adequate incentives or stable revenue models, offshore wind may struggle to compete against cheaper onshore renewables in the short term [39, 107].

7. **Extreme Weather and Climate Risks:** Harsh sea conditions and climate change increase operational risks and insurance costs, particularly in southern areas [7].

4.5.3 Stakeholder Mapping

This section presents the results of the stakeholder mapping exercise, identifying key actors relevant to the development of offshore wind energy in Chile. The primary aim was to identify and categorize stakeholders based on their potential influence over and interest in offshore wind projects across the coastline.

Identified Stakeholders

Based on the analysis, the following primary stakeholder groups were identified as having significant relevance to offshore wind development in Chile:

- **Government and Regulatory Bodies:** These institutions design and enforce the legal, regulatory, and technical frameworks for offshore wind development.

  - **Ministry of Energy:** Leads national energy planning and climate goals; has high influence in setting offshore wind targets and regulatory frameworks [79].

  - **Ministry of Environment:** Sets environmental policies, regulations, and standards for sustainable development, including offshore wind projects [82].

  - **Environmental Assessment Service (SEA):** Executes and manages the Environmental Impact Assessment (EIA) process, crucial for project approval and ensuring environmental safeguards [81].

  - **Subsecretary of Fisheries and Aquaculture (SUBPESCA):** Regulates marine resource use and assesses impacts on fisheries; moderate influence in marine spatial planning [89].

  - **Dirección General del Territorio Marítimo y de Marina Mercante (DIRECTEMAR):** Responsible for maritime safety and navigation; approves offshore area usage and ensures safety regulations are met [110].
  - **Ministry of National Assets:** Manages public marine and coastal assets; provides usage rights for offshore areas [83].
  - **Superintendence of the Environment (SMA):** Enforces compliance with environmental regulations; monitors project impacts during and after implementation [84].
  - **Coordinador Eléctrico Nacional (CEN):** National Electricity Coordinator. Plans and operates the national electricity transmission system, key for the grid operation integration of offshore wind [85].
  - **Regional Governments:** Participate in local planning, permit coordination, and community engagement; their support facilitates implementation [86].
  - **Ministry of Public Works (MOP):** Develops coastal and port infrastructure; enables logistical feasibility for construction and maintenance [87].
  - **Ministry of Finance:** Designs fiscal incentives, subsidies, and public investment schemes; influences project bankability [88].
  - **InvestChile:** Promotes foreign investment; instrumental in attracting international offshore wind developers [13].

- **Communities:** Include Chilean residents and groups whose territories or livelihoods may be directly affected by offshore wind infrastructure.
  - **Conflict Communities:** Concerned with land access, marine resource use, local job creation, and social-environmental impacts; high interest, varying levels of influence depending on legal and political engagement. The Southern Macrozone area represents a high influence and interest [93].
  - **General Public:** Mainly undifferentiated population not specifically represented by organized interest groups directly impacted by, or directly involved in, the project.

- **Industry and Private Sector:** Stakeholders directly investing in, operating, or affected by offshore wind development.
  - **Offshore wind developers:** Lead project design, financing, and operation; highest interest and operational influence.
  - **Fishing industry:** May face spatial conflicts with turbines; high influence, especially through organized associations in Chile.
  - **Shipping and port authorities:** Ensure maritime traffic safety and port logistics; moderate to high influence in site feasibility.
  - **Aquaculture industry:** Shares marine space with potential wind sites; moderate interest, can raise opposition or request compensation.
  - **Existing energy companies:** Potential competitors or collaborators; influence through infrastructure sharing or market positioning.
  - **Tourism sector:** Concerned about visual and environmental impact; low power, but may affect public acceptance in key areas.
- **Civil Society and NGOs:** Advocate for environmental protection, community rights, and sustainable development.
  - **Environmental NGOs:** Monitor biodiversity, marine ecosystems, and climate commitments; can shape public opinion and influence policy debates.
  - **Human rights organizations:** Defend community rights about land and sea access; moderate influence in permitting processes [93].
- **Academic and Research Institutions:** Generate data and knowledge on environmental, technical, and socio-economic aspects.
  - Conduct spatial analyses, feasibility studies, and environmental assessments; indirect but strategic influence through capacity-building and evidence-based planning.
- **International Organizations and Financial Institutions:** Provide funding, technical support, and guidance aligned with global climate goals.

– **Multilateral development banks:** Offer loans, grants, and technical cooperation; strong influence in project financing and social-environmental standards.

– **International renewable energy agencies:** Promote knowledge-sharing, policy alignment, and global best practices; could help or influence in strategic planning and benchmarking.

– **Climate finance and cooperation platforms:** Channel funding toward sustainable energy transitions; influence national policy alignment and project eligibility.

Stakeholder Categorization

To assess their potential influence and engagement, stakeholders were categorized using a Power-Interest Grid shown in Figure 4.22. This categorization highlights their capacity to affect or be affected by offshore wind projects.

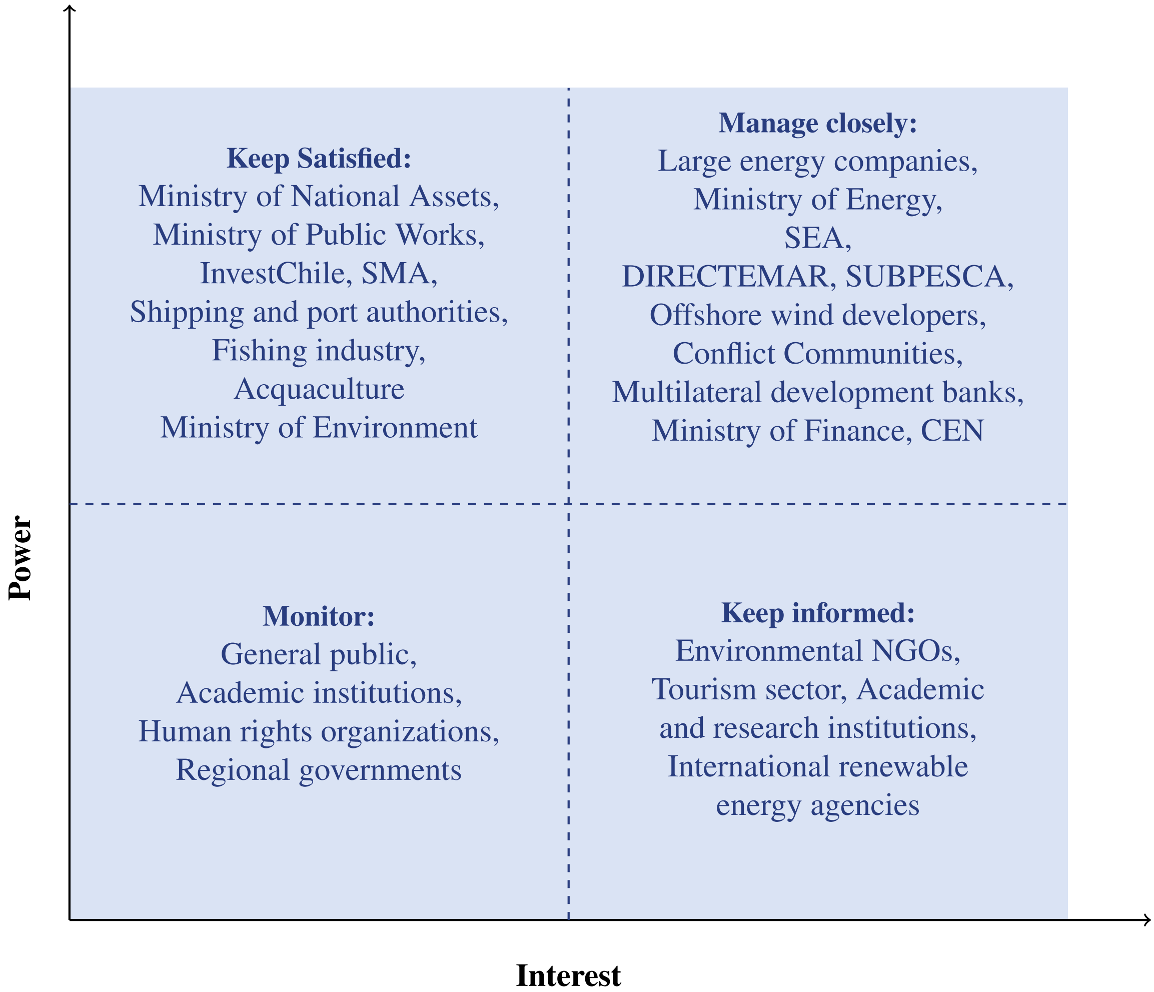

Figure 4.22: Stakeholder power-interest matrix.

4.5.4 Detailed Case Study: Southern Macrozone Conflict

The Southern Macrozone Conflict in Chile, referring to the ongoing socio-political and territorial disputes, significantly impacts the suitability of areas for both bottom-fixed and floating offshore wind structures. This conflict is characterized by historical grievances, land claims, and acts of violence (e.g., burning of machinery and trucks, resistance to development projects) [80] that introduce substantial risks and constraints, ultimately reducing the available suitable areas for wind farm development. This case study quantifies the spatial impact of this conflict on potential offshore wind development zones. Figures 4.23 and 4.24 alongside Tables 4.10 and 4.11, quantify these impacts, illustrating the tangible spatial implications of this complex social dynamic since this conflict introduces substantial constraints, reducing the available suitable areas for wind farm development.

Impact on Bottom-Fixed Offshore Wind Structures Figure 4.23 and Table 4.10 illustrate the spatial impact on areas suitable for bottom-fixed offshore wind structures.

The conflict affects a total suitable area of 1049.87 km^2 for bottom-fixed structures, which represents 7.41% of the overall suitable area identified in the study. The distribution of this impact varies across the analyzed zones:

- **Zone B** experiences the most significant reduction, with 607.47 km^2 which represents 12.86% of its suitable area for bottom-fixed structures being affected.
- **Zone A** shows a moderate impact, with 294.90 km^2 (6.25%) of its suitable area affected.
- **Zone B** is comparatively less impacted, with 147.50 km^2 (3.12%) of its suitable area for bottom-fixed structures falling within the conflict zone.

These figures indicate a clear spatial reduction in viable areas for bottom-fixed offshore wind due to the presence of the conflict.

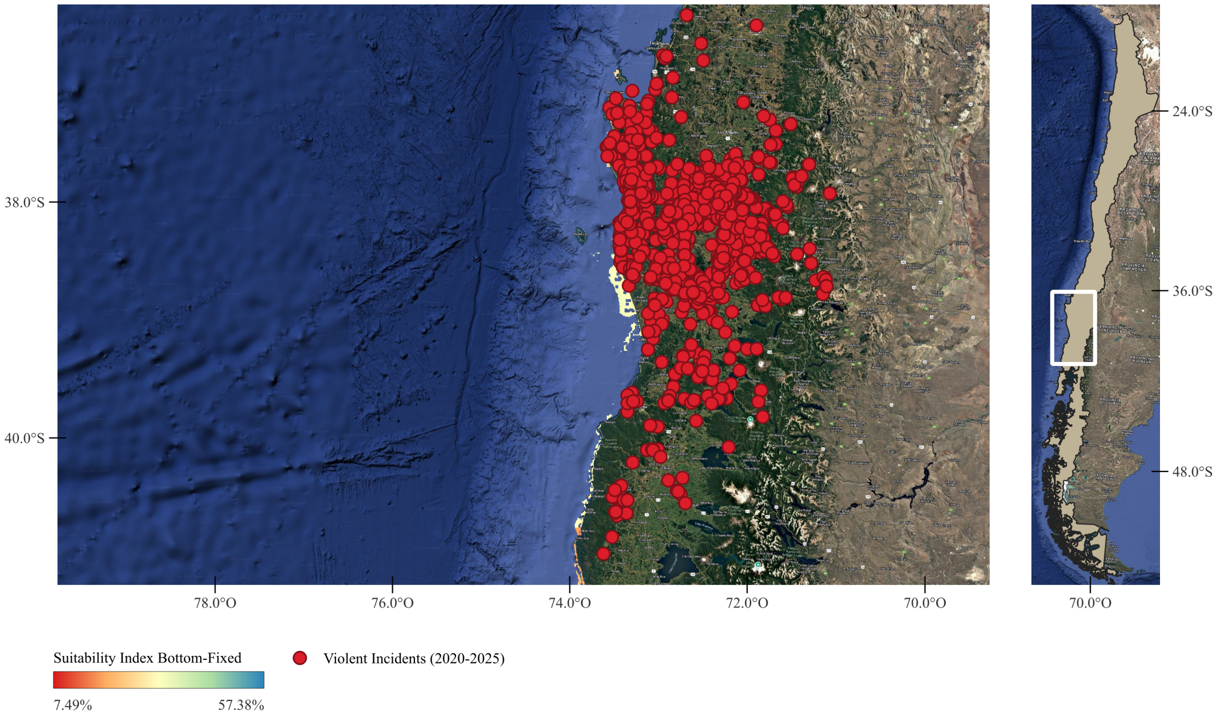

Figure 4.23: Impact of the Southern Macrozone Conflict on Bottom-Fixed Offshore Wind Structures Suitability

Table 4.10: Bottom-Fixed Structure Suitability Area Affected by the Southern Macrozone Conflict

Zone	Affected Area (km^2)	Percentage of Zone Affected (%)
Total Suitable Area Affected	1049.87	7.41%
Zone A	294.90	6.25%
Zone B	607.47	12.86%
Zone C	147.50	3.12%

Impact on Floating Offshore Wind Structures Figure 4.24 and Table 4.11 detail the spatial impact on areas suitable for floating offshore wind structures.

The conflict's effect on floating offshore wind structures is more pronounced than on bottom-fixed structures. A total of 5727.03 km^2 of suitable area is affected, accounting for a substantial 14.70% of the total suitable area for floating structures. The impact across zones shows similar patterns to bottom-fixed, but with larger magnitudes:

- **Zone B** is again the most severely impacted, with 4180.41 km^2 (32.19%) of its suitable area for floating structures being compromised.

- **Zone A** is affected by 900.11 km^2 (6.93%) of its suitable area.
- **Zone C** experiences the least impact, with 646.51 km^2(4.98%) of its suitable area affected.

These results highlight a significant reduction in suitable areas for floating offshore wind, particularly in Zone B.

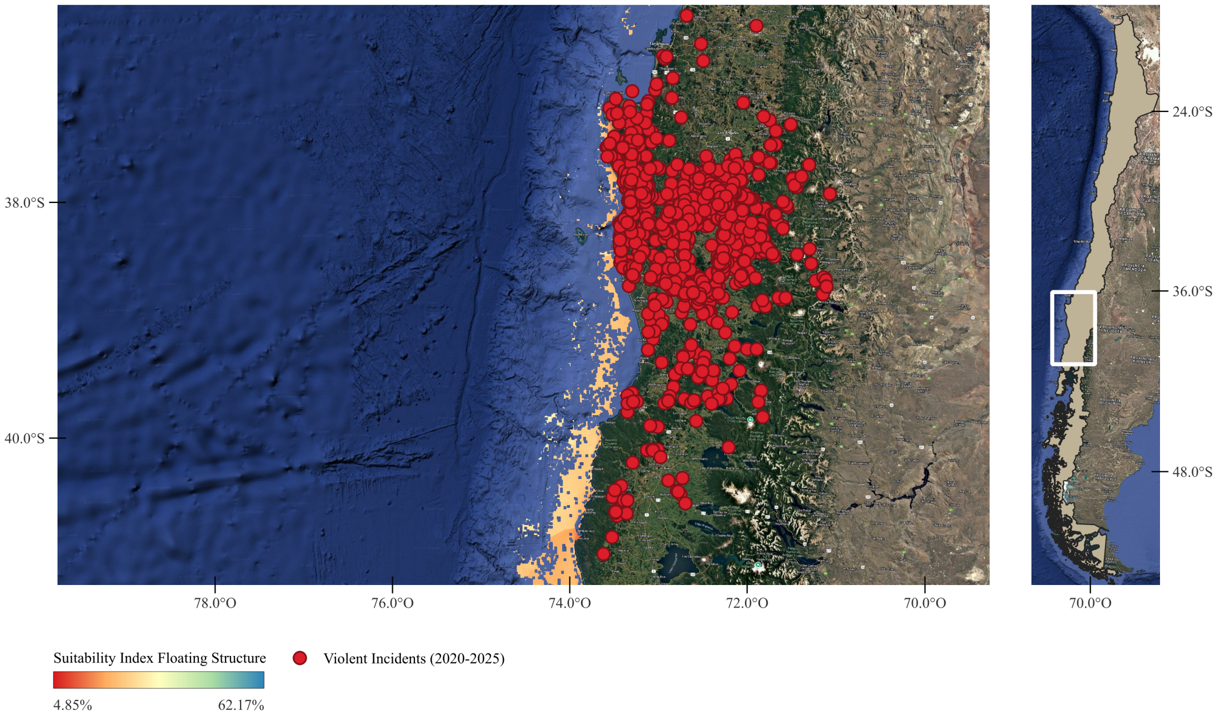

Figure 4.24: Impact of the Southern Macrozone Conflict on the Suitability of Floating Offshore Wind Structures

Table 4.11: Floating Structure Suitability Area Affected by the Southern Macrozone Conflict

Zone	**Affected Area (km^2)**	**Percentage of Zone Affected (%)**
Total Suitable Area Affected	5727.03	14.70%
Zone A	900.11	6.93%
Zone B	4180.41	32.19%
Zone C	646.51	4.98%

In conclusion, this case study presents a notable obstacle to offshore wind development, with a more severe impact on floating wind technologies compared to bottom-fixed ones. The disproportionate effect on Zone B for both types of structures highlights it as a critical area where conflict resolution or avoidance strategies will be paramount for maximizing offshore wind potential. Understanding these specific spatial limitations is crucial for informed decision-making in future offshore wind energy planning and policy within this macrozone.

4.6 Roadmap Development

The proposed strategic roadmap outlines a comprehensive timeline for the development of offshore wind energy in Chile from 2030 to 2055. It is divided into three overlapping phases reflecting the country's transition from early-stage to full commercial deployment and eventual regional leadership. The roadmap accounts for the unique challenges Chile faces as a late entrant compared to global leaders, including infrastructure development and market creation. Overlapping phases illustrate the dynamic and iterative nature of development, where foundational policy work continues alongside scaling and technological innovation. This phased approach is grounded in international best practices and tailored to Chile's socio-economic and environmental context.

Before 2030, and in order to prepare for the formal enabling phase, the period is then dedicated to critical early-stage activities. These encompass offshore wind resource mapping, initial feasibility and environmental studies, and foundational policy discussions that will build the essential knowledge base and framework required for successful launch, especially for a large-scale project such as this.

Phase 1 (2030–2038): Foundational Enablement Conditions & Early Projects

Goal: Establish enabling conditions and initiate the first commercial-scale projects.

Start condition: GIS-based Zone A areas identified with high suitability; institutional framework and stakeholder engagement initiated.

End condition: Foundational enabling conditions fully established, enabling smooth transition to commercial scaling.

Key Actions:

- **Policy & Regulatory:**
  - Enact comprehensive offshore wind regulations covering licensing, marine spatial

planning (MSP), environmental safeguards, and safety standards.

  - Implement a streamlined permitting process targeting approval times of less than 7 years post-site identification.
  - Officially designate marine spatial planning zones, prioritizing Zone A based on GIS suitability.
  - Integrate environmental and social impact assessment (EIA/SIA) requirements early in the permitting process.

- **Grid & Port Infrastructure:**
  - Conduct grid integration feasibility studies and develop a roadmap for approximately 500 MW offshore capacity by 2038, including necessary onshore transmission reinforcements.
  - Initiate preliminary upgrades on 1–2 strategic ports with proven logistics and industrial capacity to support pilot projects.
  - Carry out comprehensive EIA and SIA for Zone A sites, with robust stakeholder consultations.

- **Pilot & Pre-Commercial Projects:**
  - Facilitate 1–2 demonstration wind farms totaling 25 MW through public-private partnerships.
  - Establish project-specific environmental monitoring and mitigation programs.

- **Stakeholder Engagement & Environmental Protection:**
  - Establish continuous engagement platforms with coastal communities, artisanal fisheries, and local groups based on proximity analysis.
  - Develop and implement biodiversity mitigation and monitoring strategies near MPAs.
  - Promote transparency and local benefits-sharing mechanisms.

- **Economic and Financial Foundations:**

  - Launch initial incentive schemes to reduce investment risk.
  - Engage international financial institutions and development organizations to support early project development and capacity building.

Phase 2 (2035–2045): Commercial Scaling & Integration

Goal: Deploy multiple gigawatt-scale wind farms and develop a competitive domestic supply chain.

Start condition: Key enabling infrastructure and regulatory framework substantially established by 2035, enabling initial commercial scaling.

End condition: 3 GW operational or under construction; growing domestic manufacturing and service capabilities.

Key Actions:

- **Technological & Industrial Development:**
  - Establish incentives for local manufacturing of key components (towers, cables, foundations).
  - Develop vocational and technical training specialized in offshore wind construction, operation & , maintenance (O&M), and marine logistics.
  - Foster innovation partnerships with international technology leaders.
- **Project Development:**
  - Conduct competitive tenders for commercial leases in Zones A and B, prioritizing sites with near-port proximity.
  - Enforce grid connection agreements for final investment decisions (FID).
  - Streamline environmental permitting using adaptive management approaches learned from pilot projects.
- **Grid & Integration:**
  - Construct offshore substations and high-voltage direct current (HVDC) export lines as required.

  - Coordinate regionally to develop technical standards for floating wind technologies as a future pathway.

- **Financial & Economic Incentives:**
  - Issue green bonds and guarantee instruments to lower financing costs and attract institutional investors.
  - Implement feed-in tariffs or Contracts for Difference (CfD) schemes to stabilize revenues.

- **Enhanced Stakeholder & Environmental Management:**
  - Deepen community engagement and benefit-sharing to ensure social license to operate.
  - Monitor cumulative environmental impacts with multi-stakeholder oversight.

Phase 3 (2040–2055): Full Integration & Export Strategy

Goal: Position offshore wind as a cornerstone for Chile's decarbonization and a driver of export-oriented industrial growth.

Start condition: 3 GW capacity operational, established domestic supply chain, and mature policy framework.

End condition: 8 GW capacity, proven floating wind feasibility, and operational clean energy exports.

Key Actions:

- **Energy Mix & Decarbonization:**
  - Increase the offshore wind share in the national electricity generation.
  - Deploy hybrid renewable systems integrating offshore wind with green hydrogen or marine energy in co-located zones.

- **Floating Wind Technology:**
  - Launch 1–2 floating wind pilot farms in deep bathymetry zones.

– Leverage lessons from European pioneers to accelerate deployment.

- **Export Strategy and Regional Integration:**
  - Develop green hydrogen/ammonia production facilities linked to offshore wind at port-enabled sites.
  - Foster regional grid interconnections and green energy trade partnerships with Argentina, Brazil, and neighboring countries.
- **Policy, Institutional Maturity & Innovation:**
  - Establish a dedicated offshore wind agency responsible for regulation, R&D funding, and industry coordination.
  - Align marine spatial planning, biodiversity conservation, and industrial policies to ensure sustainable long-term growth.
  - Support continuous innovation in supply chain resilience, digitalization, and environmental monitoring.
- **Social License and Environmental Stewardship:**
  - Institutionalize community benefit mechanisms and ensure rights protection.
  - Implement advanced environmental monitoring using real-time data and adaptive management.

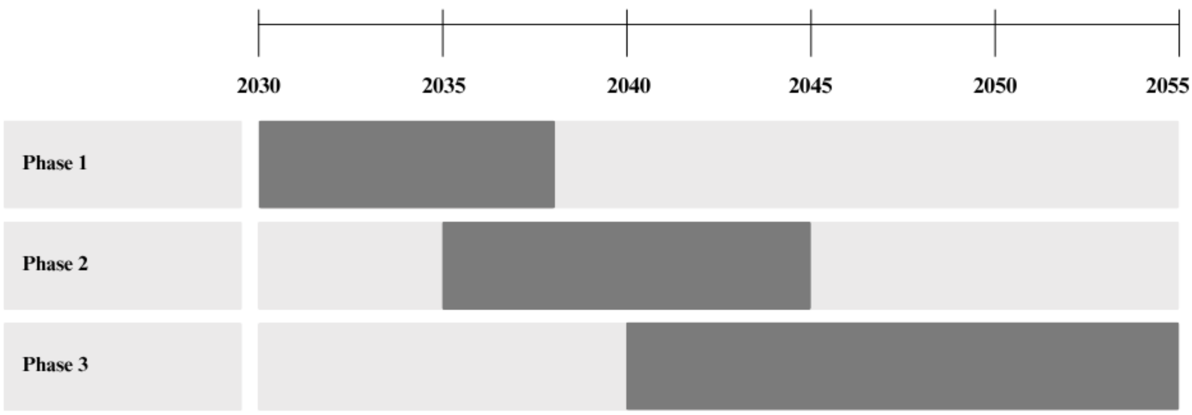

Figure 4.25: Offshore Wind Development Roadmap Gantt Chart

4.6.1 Alignment with International Best Practices

The roadmap aligns well with the strategies followed by countries that have successfully developed offshore wind industries, such as Denmark, the UK, and the Netherlands. Like in those cases, the roadmap for Chile proposes a gradual approach, which means starting with clear regulations and planning, then moving toward scaling up the market and strengthening infrastructure, and finally aiming for regional leadership. This step-by-step structure reflects how mature offshore wind countries created stable conditions that encouraged long-term investment and innovation. The use of tools like AHP, TOPSIS, and GIS also brings the analysis in line with international methodologies for site selection and planning. While the roadmap draws from global best practices, it also considers Chile's specific context, such as its geography, institutional capacity, and energy goals, making it both realistic and forward-looking.

Chapter 5

Discussion

5.1 Interpretation of Spatial Suitability Results

The spatial suitability analysis, conducted using a hybrid GIS and MCDM framework, reveals a heterogeneous distribution of offshore wind potential and suitable spots along the Chilean coastline. The highest suitability scores are concentrated primarily in the southern regions of Chile, notably off the coasts of the South and Far South zones. These areas are well known to exhibit favorable wind speeds and relatively proximity to port infrastructure, making them technically viable for near-term development. A detailed visualization of the different constraints and advantages is presented in Figures C.1 and C.2 in Appendix C.

Conversely, northern and central coastal zones show lower overall suitability despite the main ports being located in this area. This was primarily due to the lower quality of wind resources and high fishing activity as is shown on Figure C.2, which significantly reduced suitability in certain zones, emphasizing the importance of marine spatial planning in offshore wind site selection.

Also important to mention that spatial analyses indicate that the deep waters off Chile's coast are less suited for traditional bottom-fixed turbines compared to floating offshore wind technology. Floating wind farms provide flexibility to access resource-rich areas with challenging seabed conditions, thus expanding the geographic scope for development. In numbers, bottom-fixed structures represent a 26.67% of the total area of suitability, and floating structures a 73.33 %.

As shown on table 5.1, bottom-fixed structures account for an important suitability share on the Far South region, meanwhile floating structures show a strong dominance on the South region.

Table 5.1: Relative Share of Suitable Offshore Wind Areas by Region and Foundation Type

Region	Bottom-Fixed (%)	Floating (%)
Norte Grande (Far North)	0.03	0.42
Norte Chico (Near North)	0.41	4.43
Zona Centro (Central Chile)	0.73	4.44
Zona Sur (South)	7.45	45.73
Sur Austral (Far South)	18.04	18.31
Total	**26.67**	**73.33**

The results also highlight the role of enabling infrastructure. Areas close to major ports like Talcahuano or Punta Arenas scored higher due to port capacity and existing logistics. However, the limited grid infrastructure in some high-potential southern regions suggests that targeted investment would be necessary to unlock their full potential.

However, the southern region of Chile presents a promising opportunity for green hydrogen development. Although the area has a low population density, for which the energy generation could help, the high offshore wind suitability identified in this study suggests strong potential for large-scale renewable hydrogen production.

The classification of the suitability map into Zones A, B, and C further supports the strategic roadmap. Zone A areas are mainly characterized by high technical and logistical feasibility and could be prioritized for initial project development and pilot testing. Zone B areas may require infrastructure upgrades or regulatory clarifications, while Zone C should be approached with caution due to environmental or operational constraints.

As shown in Table 5.2, the most favorable areas for offshore wind development (Zone A) are highly concentrated in the Far South region (25.53%), indicating strong suitability based on combined technical, spatial, and environmental criteria. In contrast, the South region presents the largest shares for Zones B (23.08%) and C (27.78%), suggesting extensive areas with moderate to lower priority for immediate development, yet with long-term potential. Northern regions such as Far North and Near North show minimal contributions to Zone A and limited presence in other zones, indicating reduced priority in national deployment strategies. These results support a geographically phased approach to offshore wind development, with initial focus on Far South for high-priority projects, followed by strategic planning in the South region.

Table 5.2: Zoning Classification Share by Region Relative to Total Suitable Offshore Wind Area

Region	Zone A (%)	Zone B (%)	Zone C (%)
Norte Grande (Far North)	0.46	0.00	0.00
Norte Chico (Near North)	1.91	2.14	0.80
Zona Centro (Central Chile)	3.12	0.85	1.20
Zona Sur (South)	2.32	23.08	27.78
Sur Austral (Far South)	25.53	7.27	3.56

Overall, the spatial analysis underscores the potential for offshore wind development in Chile, while also identifying key spatial and infrastructural challenges that must be addressed. These findings provide a geographically grounded basis for phased deployment and regional planning strategies.

5.2 Implications of Managerial Analysis for Policy and Planning

The qualitative insights gleaned from the managerial analysis offer critical implications for the policy and planning frameworks necessary to foster offshore wind in Chile. These analyses transcend the purely technical suitability, revealing the strategic, operational, and social enablers and inhibitors that must be addressed.

1. Prioritization of Enabling Conditions The results from AHP and TOPSIS revealed that Chile lags in key enabling factors such as grid infrastructure, industrial capacity, and the regulatory environment. These dimensions emerged as critical differentiators between Chile and high-performing countries. Policymakers should prioritize:

- Fast-tracking regulatory clarity, including permitting and environmental assessment procedures.
- Investing in grid modernization and defining grid integration protocols.
- Developing incentive structures to attract private sector investment.
- Integrate offshore wind's future capacity into national transmission expansion plans, identifying necessary upgrades and new infrastructure.

2. Informed Spatial Planning The GIS-based site suitability analysis offers actionable intelligence for marine spatial planning. Planners can use the resulting maps to:

- Identify high-potential areas for early-stage project development.
- Avoid zones with high environmental sensitivity or socio-political conflict.
- Integrate offshore wind in highly suitable areas into existing maritime uses through multi-use zoning frameworks.

3. Local Content and Supply Chain Development During this study it was identified a limited local supply chain and specialized infrastructure were identified as a significant weakness. Policy and planning should aim to:

- Develop industrial policies that promote local manufacturing, assembly, and maintenance capabilities, leveraging existing industries where possible.
- Implement targeted education and training programs to build a skilled local workforce capable of supporting all phases of offshore wind projects, from construction to operation and maintenance.
- Strategically plan and invest in the necessary port upgrades to handle the large components and specialized vessels required for offshore wind.

4. Risk-Informed Investment Decisions By combining spatial suitability with socio-political risk indicators such as conflict areas, this framework supports more resilient investment strategies. Development in moderate-risk areas can be enabled through:

- Early stakeholder engagement.
- Conflict-sensitive design and adaptive project management.
- Policy support mechanisms such as risk guarantees or blended finance instruments.

5. Strategic Roadmapping and Phasing The roadmap developed in this thesis, based on site classification and scenario analysis, provides a practical guide for the phased rollout of offshore wind projects. Policymakers can align infrastructure investments, workforce development, and port upgrades with the identified Zones A, B, and C, ensuring a coordinated and scalable transition.

6. Benchmarking and Performance Monitoring The TOPSIS-based international comparison offers a tool for continuous performance monitoring. Chilean authorities can use this to:

- Set policy benchmarks based on international best practices.
- Track progress in critical dimensions such as policy maturity, social license, and technological readiness.
- Adapt policies dynamically in response to evolving market and geopolitical conditions.

5.3 Analysis of Southern Macrozone Conflict and Broader Social Challenges

The results presented in Chapter 4 demonstrate that the Southern Macrozone Conflict in Chile poses a substantial constraint on offshore wind development. This ongoing socio-political conflict—rooted in historical land disputes and characterized by episodes of resistance and violence, has a direct and measurable impact on the availability of suitable areas for both bottom-fixed and floating offshore wind installations. This section explores the broader implications of these findings for Chile's energy transition.

The reduction in technically viable areas is only one dimension of the risks associated with the conflict. The inherent instability of the zone introduces significant non-technical risks that cannot be easily mitigated through conventional project planning methods.

- **Increased Costs and Delays:** Incidents such as arson attacks and supply chain disruptions translate into higher capital and operational expenditures. Additional costs stem from enhanced security measures, insurance premiums, and the need for more robust infrastructure. Project timelines may also be extended due to protests, blockades, or broader logistical challenges.

- **Reputational and ESG Risks:** With growing emphasis on ESG standards, projects located in conflict zones face heightened scrutiny. A lack of meaningful engagement with local communities can lead to reputational damage, investor withdrawal, and difficulties in obtaining financing.

- **Legal and Political Uncertainty:** The ongoing constitutional process and debates around land disputes in this zone and rights legislation contribute to an unpredictable legal and regulatory landscape. This uncertainty complicates long-term investment decisions in this matter.

The findings underscore the need for a more nuanced and flexible approach to spatial planning for offshore wind development in Chile. For site selection a place where to develop offshore wind, it is necessary to do a conflict-sensitive analysis that clearly identifies zones of varying conflict intensity, offering a critical input for risk-aware decision-making. While certain high-conflict areas may need to be excluded, others could still be viable with the implementation of robust community engagement strategies.

The challenges observed in Chile's Southern Macrozone are emblematic of a broader global trend: the growing interdependence between technical feasibility, social license to operate, and land disputes. As such, Chile's experience offers important lessons for other countries navigating similar socio-environmental complexities in the context of energy transition planning.

5.4 Challenges and Opportunities Identified

The comprehensive analysis conducted through this study, encompassing spatial suitability, international benchmarking, and managerial frameworks, reveals a dual landscape of significant challenges and compelling opportunities for offshore wind development in Chile. Understanding this dynamic interplay is crucial for strategic planning and successful deployment.

The spatial and MCDM analysis conducted in this study reveals a complex landscape of both constraints and enablers for offshore wind development in Chile. Several key challenges persist across the territory, yet they are accompanied by significant strategic opportunities, particularly in the far south, where offshore wind potential aligns with national ambitions for green hydrogen production.

One of the most pressing challenges identified is the limited grid infrastructure along large stretches of Chile's coastline, especially in remote regions where the wind resource is strongest. This gap poses a technical and financial hurdle for integrating the technology into the national electricity system. In parallel, environmental and social constraints, such as the presence of high fishing activity, impose spatial limitations on development, especially in central and northern zones.

Moreover, the lack of specialized port infrastructure and local industry capabilities may delay deployment and increase dependence on foreign expertise and equipment. These factors underscore the need for long-term capacity building, regulatory adaptation, and targeted investment to unlock Chile's offshore wind potential.

However, the analysis also highlights critical opportunities, with the Magallanes region in the far south standing out as a strategic zone. Despite its remoteness and limited grid connectivity, this area exhibits exceptionally high wind speeds, suitable bathymetric conditions, and relatively low spatial conflicts. These characteristics make it an ideal candidate, most notably the production of green hydrogen for both domestic use and international export.

Chile's national hydrogen strategy already identifies Magallanes as a priority region for large-scale hydrogen projects, and the suitability results in this thesis provide strong spatial validation for that focus. The potential of offshore wind farms located near port infrastructure, such as Punta Arenas, represents a transformative opportunity to bypass traditional grid limitations and catalyze a new export-driven energy sector.

Furthermore, this hydrogen-oriented development model may help de-risk offshore wind investments by creating dedicated off-takers and enabling economies of scale. It also opens the door to synergies with existing maritime infrastructure and the potential repurposing of fossil fuel logistics chains for clean energy export.

In conclusion, while infrastructure and regulatory challenges must be addressed across the country, the far south of Chile offers a unique first-mover opportunity. By strategically integrating offshore wind development with green hydrogen production, Chile can not only diversify its energy matrix but also establish itself as a global leader in the emerging clean hydrogen economy.

5.5 Limitations of the Study and Methodology Considerations

A key limitation of the methodology employed in this research is the availability and quality of spatial data, particularly for marine-specific layers such as updated fishing grounds. While global datasets provide a useful starting point, they often lack the resolution and recency needed for detailed marine spatial planning. This limitation affects the precision of the GIS-based suitability analysis and requires cautious interpretation, especially when informing critical policy or investment decisions.

Another important challenge lies in the assumptions and subjectivity inherent in the MCDM methods applied (AHP and TOPSIS). First, AHP relies on expert judgment for pairwise comparisons, which, despite its structured nature, can introduce bias or inconsistency. TOPSIS, on the other hand, assumes linear trade-offs and normalization of criteria, potentially oversimplifying the complex interactions present in offshore wind systems. Furthermore, the process of assigning weights to evaluation criteria would benefit from broader stakeholder involvement to better capture local priorities and sensitivities.

Uncertainties related to technological development and evolving regulatory frameworks also influence the robustness of the analysis. For example, new emerging floating offshore wind technologies could enable the use of areas currently deemed unsuitable due to water depth, while future policy reforms may reshape spatial priorities and permitting requirements.

From a practical perspective, regulatory complexity is a significant barrier. Overlapping jurisdictions and unclear permitting processes can delay project implementation. Environmental considerations, such as marine protected areas and biodiversity corridors, impose constraints that are difficult to fully quantify in spatial models. Additionally, stakeholder conflicts, including opposition from different communities or port operators, may arise despite favorable technical conditions.

These limitations underscore the importance of viewing the results as a strategic decision-support tool rather than a deterministic solution. They highlight the need for adaptive, inclusive, and continuously updated planning processes.

Despite these challenges, the framework developed in this study remains a valuable and flexible tool to support offshore wind development in Chile. Its design is also applicable to other emerging economies facing similar barriers in their transition toward renewable energy.

Chapter 6

Conclusion

6.1 Summary

This thesis has developed a comprehensive and hybrid framework for offshore wind energy development in Chile by integrating Geographic Information Systems (GIS) with Multi-Criteria Decision-Making (MCDM) methods. The goal was to support strategic site selection and long-term development planning, responding to both national and global imperatives for a sustainable energy transition. Chile, with its abundant wind resources and deep coastal waters, holds substantial untapped potential for offshore wind, especially in the context of its growing green hydrogen ambitions.

Through the integration of AHP-TOPSIS methodology and GIS-based spatial analysis, the study successfully identified and characterized areas with the highest offshore wind suitability. Wind power density and wind speed emerged as the most influential criteria in determining site viability. Spatially, the results pointed to the South and Far South zones, particularly the Magallanes region, as the most promising areas. These regions combine strong wind resources, relatively favorable bathymetric conditions, and proximity to emerging port infrastructure, making them especially suitable for offshore wind projects. Their potential is further amplified by their alignment with Chile's green hydrogen strategy. While the northern and central coastal areas presented lower suitability due to weaker wind regimes and overlapping maritime uses such as fishing, the study also emphasized Chile's future potential in floating offshore wind, given its extensive deep waters in the South region. Conversely, bottom-fixed structures are highly recommended in the Far South region due to favorable shallow water conditions.. This could significantly broaden the technical and economic feasibility of offshore wind across the national coastline.

The suitability map was classified into percentile Zones A, B, and C, with Zone A representing the areas with the highest development potential, providing a clear prioritization for future projects. Among them, the Magallanes region consistently emerged as a top-ranked zone, reinforcing its strategic value for early deployment.

The thesis contributes several strategic insights for Chilean policymakers and industry actors. First, it offers a data-driven roadmap covering the 2030–2055 period, outlining a phased approach to offshore wind deployment that is aligned with international best practices. This roadmap emphasizes a transition from pilot projects to full-scale integration, with a strong focus on synergies with green hydrogen. Second, the research highlights the importance of addressing critical enabling conditions, and in particular, the need for improved grid infrastructure, specialized industrial capacity, and a regulatory framework tailored to offshore wind technology. These areas are essential for unlocking Chile's offshore potential and attracting long-term investment. Third, the spatial analysis provides actionable intelligence for marine planning, identifying zones that optimize energy output while minimizing conflicts with environmental and economic marine uses. These zones can serve as anchor points for future green hydrogen production hubs, ensuring alignment between energy generation and downstream hydrogen applications.

Despite the promising outlook, several challenges remain. The lack of transmission infrastructure in southern Chile, the absence of specialized port and logistics capacity, and the limited local supply chain present major technical and logistical barriers. Additionally, the Southern Macrozone Conflict introduces a layer of socio-political complexity that could delay or hinder development. These non-technical risks underscore the need for inclusive, conflict-sensitive planning processes and proactive stakeholder engagement.

Nonetheless, Chile holds unique advantages. Its vast and deep maritime areas are ideally suited for floating offshore wind technologies. The convergence between wind resources, hydrogen strategies, and emerging global demand offers a compelling case for integrated renewable energy development. By building on this alignment, Chile can not only meet its domestic energy goals but also become a key player in the global clean energy market.

6.2 Future directions

While this study offers a strong spatial and managerial framework for offshore wind planning in Chile, several research gaps remain. First, economic feasibility at the site level was not addressed. Future studies should assess the Levelized Cost of Energy (LCOE), investment needs, and returns for each zone, especially in remote areas like the Far South region, where wind potential is high but grid access and population density are limited.

Second, the study assumed static conditions, without considering climate variability or extreme weather risks. Incorporating dynamic climate models, estimations, and risk assessments could improve long-term site resilience.

Third, local social impacts were only partially addressed. Future work should include community engagement, participatory mapping, or social impact assessments to gain a better understanding of coastal stakeholders' views and enhance social acceptance.

Finally, future research should explore synergies between offshore wind and green hydrogen. Zones with high wind potential and weak grid infrastructure, like the Far South area, could benefit from co-located hydrogen production. Detailed techno-economic studies are needed to assess these hybrid opportunities and support Chile's positioning in the global green hydrogen market.

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APPENDICES

A MCDM Tables

Table A.1: Pairwise Comparison Matrix for AHP GIS Criteria Weighting

	CR 1	CR 2	CR 3	CR 4	CR 5	CR 6	CR 7	CR 8
CR 1	1	1	3	5	3	2	3	5
CR 2	1	1	3	5	3	2	3	6
CR 3	1/3	1/3	1	2	1/2	1/2	1/2	2
CR 4	1/5	1/5	1/2	1	1/2	1/3	1/2	1/3
CR 5	1/3	1/3	2	2	1	1/2	2	2
CR 6	1/2	1/2	2	3	2	1	2	3
CR 7	1/3	1/3	2	2	1/2	1/2	1	5
CR 8	1/5	1/6	1/2	3	1/2	1/3	1/5	1

Table A.2: Pairwise Comparison Matrix for AHP Ports

	CR 1	CR 2	CR 3	CR 4	CR 5
CR 1	1	3	4	5	6
CR 2	1/3	1	2	3	4
CR 3	1/4	1/2	1	2	3
CR 4	1/5	1/3	1/2	1	2
CR 5	1/6	1/4	1/3	1/2	1

Table A.3: Pairwise Comparison Matrix for AHP Strategic Criteria Weighting

	CR 1.1	CR 1.2	CR 1.3	CR 1.4	CR 2.1	CR 2.2	CR 2.3	CR 3.1	CR 3.2	CR 3.3	CR 4.1	CR 4.2	CR 5.1	CR 6.1	CR 6.2
CR 1.1	1	5	1	5	5	5	3	1/3	1/3	1/3	9	9	1	5	5
CR 1.2	1/5	1	1/5	1	1/3	1/3	1	1/5	1/7	1/7	3	3	1/3	1	1
CR 1.3	1	5	1	5	5	5	3	1/3	1/3	1/3	9	9	1	5	5
CR 1.4	1/5	1	1/5	1	1/3	1/3	1	1/5	1/7	1/7	3	3	1/3	1	1
CR 2.1	1/5	3	1/5	3	1	1	1/3	1/5	1/3	1/3	5	5	1/3	1/3	1/3
CR 2.2	1/5	3	1/5	3	1	1	1/3	1/5	1/3	1/3	5	5	1/3	1/3	1/3
CR 2.3	1/3	1	1/3	1	3	3	1	1/3	1/3	1/3	7	7	1/3	1/3	1/3
CR 3.1	3	5	3	5	5	5	3	1	1/3	1/3	7	7	1	1	1
CR 3.2	3	7	3	7	3	3	3	3	1	3	9	9	3	3	3
CR 3.3	3	7	3	7	3	3	3	3	1/3	1	9	9	3	3	3
CR 4.1	1/9	1/3	1/9	1/3	1/5	1/5	1/7	1/7	1/9	1/9	1	1	1/5	1/5	1/5
CR 4.2	1/9	1/3	1/9	1/3	1/5	1/5	1/7	1/7	1/9	1/9	1	1	1/5	1/5	1/5
CR 5.1	1	3	1	3	3	3	3	1	1/3	1/3	5	5	1	1	1
CR 6.1	1/5	1	1/5	1	3	3	3	1	1/3	1/3	5	5	1	1	1
CR 6.2	1/5	1	1/5	1	3	3	3	1	1/3	1/3	5	5	1	1	1

B MATLAB Codes

Listing B.1: Scored Proximity to Marine Protected Areas

```
% Load MPA Raster
[inputRaster, R] = readgeoraster('MPA_Binary.tif');

% Calculate Pixel Size in km, assuming square pixels:
pixelSize_m = R.CellExtentInWorldX;  % in meters
pixelSize_km = pixelSize_m / 1000;

% Compute Euclidean Distance (in pixels), then convert to km
distance_pixels = bwdist(binaryMPA == 1);  % Distance to nearest MPA
    pixel
distance_km = distance_pixels * pixelSize_km;

% Initialize Suitability Score Raster
score = nan(size(distance_km));

% Apply Suitability Scoring Based on Distance (in km)
score(binaryMPA == 1) = 0.0;  % Inside MPA
score(binaryMPA == 0 & distance_km > 0 & distance_km <= 0.5) = 0.1;
score(distance_km > 0.5 & distance_km <= 1.5) = 0.2;
score(distance_km > 1.5 & distance_km <= 5) = 0.4;
score(distance_km > 5 & distance_km <= 10) = 0.7;
score(distance_km > 10) = 1.0;

% Export Scored Raster - EPSG:32718
geotiffwrite('MPA␣Proximity.tif', ...
    single(score), R, 'CoordRefSysCode', 32718);
```

Listing B.2: Clean Port Data

```
% Clean the dataset to select the important variables
```

```
filename = 'ports_chile.csv';
opts = detectImportOptions(filename);
data = readtable(filename, opts);

% List of relevant columns
relevantVars = {
    'portName', 'regionName', 'countryName', ...
    'latitude', 'longitude', ...
    'harborSize', 'harborType', ...
    'chDepth', 'anDepth', 'cpDepth', 'otDepth', 'lngTerminalDepth', ...
    'maxVesselLength', 'maxVesselBeam', 'maxVesselDraft', ...
    'offMaxVesselLength', 'offMaxVesselBeam', 'offMaxVesselDraft', ...
    'shelter', 'erTide', 'erSwell', 'erIce', 'erOther', 'overheadLimits',
        ...
    'crFixed', 'crMobile', 'crFloating', 'cranesContainer', ...
    'loRoro', 'loSolidBulk', 'loContainer', 'loBreakBulk', 'loOilTerm', '
       loDangCargo', 'loLiquidBulk', ...
    'suProvisions', 'suWater', 'suFuel', 'suDiesel', 'suDeck', 'suEngine'
       , ...
    'repairCode', 'drydock', ...
    'cmTelephone', 'cmRadio', 'cmRail', 'cmAir', ...
    'portSecurity', 'searchAndRescue', 'vts', 'tss'};

% Keep relevant variables
existingVars = ismember(relevantVars, data.Properties.VariableNames);
cleanVars = relevantVars(existingVars);
cleanedData = data(:, cleanVars);

% Save cleaned dataset
writetable(cleanedData, 'cleaned_ports_chile.csv');
```

Listing B.3: Ports Scored Layer

```
% -------- Port Suitability Ranking using AHP --------
% Load Cleaned Port Data
```

```
filename = 'cleaned_ports_chile.csv';
opts = detectImportOptions(filename);
data = readtable(filename, opts);

% Define Variables by AHP Criteria
depthVars = {'cpDepth', 'lngTerminalDepth'}; % CR1
infraVars = {'crFixed', 'crMobile', 'crFloating', 'cranesContainer', ...
            'loContainer', 'loBreakBulk', 'loOilTerm', 'loLiquidBulk'};
               % CR2
shelterVars = {'shelter', 'erTide', 'erSwell', 'erIce'}; % CR3
logisticsVars = {'suFuel', 'suDiesel', 'suWater', 'suProvisions', ...
                'repairCode', 'drydock'}; % CR4
safetyVars = {'portSecurity', 'searchAndRescue', 'vts', 'tss'}; % CR5


% --- Combine all relevant variables ---
allVars = [depthVars, infraVars, shelterVars, logisticsVars, safetyVars
   ];


% Some data considered string, Nan, binary

for i = 1:length(allVars)
   var = allVars{i};
   if iscell(data.(var))
       % Replace 'Y'/'N' with 1/0, 'U'/'UNK'/'' with NaN
       data.(var)(strcmpi(data.(var), 'Y')) = {'1'};
       data.(var)(strcmpi(data.(var), 'N')) = {'0'};
       data.(var)(strcmpi(data.(var), 'U') | strcmpi(data.(var), 'UNK')
          | strcmpi(data.(var), '')) = {NaN};
       data.(var) = str2double(data.(var));
   elseif iscategorical(data.(var))
       data.(var) = double(data.(var) == 'Y');
   end
End
```

```matlab
% Normalization Function
normalize = @(x) (x - nanmin(x)) ./ (nanmax(x) - nanmin(x) + eps);

% Calculate Criterion Scores
depthScore     = normalize(nanmean(data{:, depthVars}, 2));
infraScore     = normalize(nanmean(data{:, infraVars}, 2));
shelterScore   = normalize(nanmean(data{:, shelterVars}, 2));
logisticsScore = normalize(nanmean(data{:, logisticsVars}, 2));
safetyScore    = normalize(nanmean(data{:, safetyVars}, 2));

% Replace NaNs with 0
depthScore(isnan(depthScore))         = 0;
infraScore(isnan(infraScore))         = 0;
shelterScore(isnan(shelterScore))     = 0;
logisticsScore(isnan(logisticsScore)) = 0;
safetyScore(isnan(safetyScore))       = 0;

% AHP Weights
weights = [0.4847, 0.2268, 0.1431, 0.0888, 0.0566];

% Final Suitability Score
finalScore = weights(1)*depthScore + ...
             weights(2)*infraScore + ...
             weights(3)*shelterScore + ...
             weights(4)*logisticsScore + ...
             weights(5)*safetyScore;

% Compile Results
outTable = table;
outTable.portName         = data.portName;
outTable.regionName       = data.regionName;
outTable.latitude         = data.latitude;
outTable.longitude        = data.longitude;
outTable.SuitabilityScore = finalScore;
```

```
% Sort and Export
outTable = sortrows(outTable, 'SuitabilityScore', 'descend');
writetable(outTable, 'Port␣Capacity.csv');
```

Listing B.4: Site Selection with AHP and TOPSIS

```
%----Site Selection Offshore Wind Farms with AHP and TOPSIS----%
close all; clearvars; clc;
% Reference raster and criteria layers
[wind_speed, R] = readgeoraster('Wind_Speed.tif');
wind_power = readgeoraster('Wind_Power_Density.tif');
bathymetry = readgeoraster('Bathymetry.tif');
distance_port = readgeoraster('Distance_to_Port.tif');
marine_proximity = readgeoraster('MPA_Proximity.tif');
grid = readgeoraster('Grid_Proximity.tif');
ports = readgeoraster('Port_Capacity.tif');
fishing = readgeoraster('Fishing_Grounds.tif');
land = readgeoraster('Land_Mask.tif');
% Apply restrictions
% Bathymetry for floating:
%bathymetry_mask = bathymetry < -1000 | bathymetry >= -50;
% If Bottom-Fixed, use:
bathymetry_mask = bathymetry < -50 | bathymetry >= 0;
wind_speed_mask = wind_speed < 7;
distance_portmask = distance_port >= 150000 | distance_port < 0;
grid_mask = grid >= 150000 | grid  <= 0 ;
port_mask = ports <= 0;
fishing_mask = fishing <= 500;
land_mask = land == 1;
%Apply restrictions
bathymetry(bathymetry_mask) = NaN;
wind_speed(wind_speed_mask) = NaN;
distance_port(distance_portmask) = NaN;
grid(grid_mask) = NaN;
```

```
ports(port_mask) = NaN;
fishing(fishing_mask) = NaN;
%Land restriction
wind_speed(land_mask) = NaN;
wind_power(land_mask) = NaN;
bathymetry(land_mask) = NaN;
distance_port(land_mask) = NaN;
marine_proximity(land_mask) = NaN;
grid(land_mask) = NaN;
ports(land_mask) = NaN;
fishing(land_mask) = NaN;
% Normalize each criterion (0-1) - all transformed so higher is better
wind_speed_n    = normalize_percentile(wind_speed, 1, 99);
wind_power_n    = normalize_percentile(wind_power, 1, 99);
distance_port_n  = 1 - normalize_percentile(distance_port , 1, 99);  %
    Lower better => invert
bathymetry_n    = 1 - normalize_percentile(bathymetry, 1, 99);         %
    Lower better => invert
marine_n        = normalize_percentile(marine_proximity, 1, 99);
grid_n = 1 - normalize_percentile(grid, 1, 99);                        %
    Lower better => invert
ports_n = normalize_percentile(ports, 1, 99);
fishing_n = normalize_percentile(fishing, 1, 99);
% Stack normalized criteria layers (rows x cols x criteria)
criteria_layers = cat(3, wind_speed_n, wind_power_n, bathymetry_n,
    marine_n, ...
                         distance_port_n, ports_n, grid_n, fishing_n);
% AHP weights vector (sum should be 1)
weights = [0.2437, 0.2489, 0.0711, 0.0411, 0.1010, 0.1424, 0.1005,
    0.0513];
% Call TOPSIS function
best_spot = topsis(criteria_layers, weights);
% Export TOPSIS closeness coefficient map as GeoTIFF
outputFilename = 'suitability.tif';
geotiffwrite(outputFilename, single(best_spot.CC_map), R, '
```

```
    CoordRefSysCode', 32718);


% --------- Supporting functions ---------
function x_norm = normalize_percentile(x, pmin, pmax)
    % Normalize between percentiles pmin and pmax to range [0,1]
    x_no_nan = x(~isnan(x));
    low = prctile(x_no_nan, pmin);
    high = prctile(x_no_nan, pmax);
    x_clipped = min(max(x, low), high);
    x_norm = (x_clipped - low) / (high - low);
    x_norm(isnan(x)) = NaN;
end
function best_spot = topsis(criteria_layers, weights)
    % TOPSIS
    [rows, cols, n] = size(criteria_layers);
    data = reshape(criteria_layers, [], n);
    valid_idx = all(~isnan(data), 2);
    data_valid = data(valid_idx, :);
    % Normalize by vector norm for each criterion
    norm_data = zeros(size(data_valid));
    for i = 1:n
        norm_data(:, i) = data_valid(:, i) / norm(data_valid(:, i));
    end
    % Weighted normalized decision matrix
    weighted_data = norm_data .* weights;
    % Ideal and negative ideal solutions
    ideal_solution = max(weighted_data, [], 1);
    negative_ideal = min(weighted_data, [], 1);
    % Distances to ideal and negative ideal
    dist_to_ideal = sqrt(sum((weighted_data - ideal_solution).^2, 2));
    dist_to_negative = sqrt(sum((weighted_data - negative_ideal).^2, 2));
    % Closeness coefficient (CC)
    CC = dist_to_negative ./ (dist_to_ideal + dist_to_negative);
    % Build full CC map with NaNs
```

```
    CC_map = nan(rows*cols, 1);
    CC_map(valid_idx) = CC;
    CC_map = reshape(CC_map, rows, cols);
    % Find best location
    [max_CC, lin_idx] = max(CC);
    [valid_rows, valid_cols] = ind2sub([rows, cols], find(valid_idx));
    best_row = valid_rows(lin_idx);
    best_col = valid_cols(lin_idx);
    best_spot.row = best_row;
    best_spot.col = best_col;
    best_spot.CC_value = max_CC;
    best_spot.CC_map = CC_map;
end
```

Listing B.5: Zoning by Percentiles

```
% Zoning  Map into 3 Zones
close all; clearvars; clc;
% Load the closeness coefficient map and its spatial reference
[CC_map, R] = readgeoraster('suitability.tif');
% Flatten and remove NaNs
cc_flat = CC_map(:);
cc_valid = cc_flat(~isnan(cc_flat));
% Compute 33rd and 66th percentiles
p = prctile(cc_valid, [33.33 66.67]);
% Create zoning map
zoning_map = NaN(size(CC_map));
zoning_map(CC_map <= p(1)) = 3;                          % Zone C - Low
    Suitability
zoning_map(CC_map > p(1) & CC_map <= p(2)) = 2;          % Zone B -
    Moderate
zoning_map(CC_map > p(2)) = 1;                           % Zone A - High
    Suitability
% Export as GeoTIFF
outputFilename = 'zoning.tif';
```

```
geotiffwrite(outputFilename, uint8(zoning_map), R, 'CoordRefSysCode',
   32718);
```

Listing B.6: Suitability Areas

```
%Calculate suitability areas
[suitability_map, R] = readgeoraster("suitability.tif");
% Only pixels where suitability > 0
valid_mask = suitability_map > 0;
% Count valid pixels
num_valid_pixels = sum(valid_mask(:));
% Area per pixel (in km2)
pixel_area_km2 = abs(R.CellExtentInWorldX) * abs(R.CellExtentInWorldY) /
    1e6;
% Total area in km2
total_area_km2 = num_valid_pixels * pixel_area_km2;
%First total area in the map
disp(['Total suitable area: ', num2str(total_area_km2), ' km2']);
%Then we calculate for each zone
% Get pixel coordinates in map units (EPSG:32718)
[cols, rows] = meshgrid(1:R.RasterSize(2), 1:R.RasterSize(1));
[x_coords, y_coords] = pix2map(R, rows, cols);
% Define zone bounding boxes in EPSG:32718
zones = struct();
zones(1).name = 'Norte Grande';
zones(1).xmin = -100935.038; zones(1).xmax = 1107000.966;
zones(1).ymin = 7350000.325; zones(1).ymax = 8100000.675;
zones(2).name = 'Norte Chico';
zones(2).xmin = -200000.040; zones(2).xmax = 1009000.968;
zones(2).ymin = 6600000.008; zones(2).ymax = 7350000.000;
zones(3).name = 'Zona Centro';
zones(3).xmin = -210000.072; zones(3).xmax = 1000000.000;
zones(3).ymin = 5850000.000; zones(3).ymax = 6600000.000;
zones(4).name = 'Zona Sur';
zones(4).xmin = -309000.072; zones(4).xmax = 900000.000;
```

```
zones(4).ymin = 5100000.000; zones(4).ymax = 5850000.000;
zones(5).name = 'Sur Austral';
zones(5).xmin = -900935.072; zones(5).xmax = 1200000.000;
zones(5).ymin = 3800000.000; zones(5).ymax = 5100000.000;
zones(6).name = 'Macrozona sur';
zones(6).xmin = 100044.241; zones(6).xmax = 980000.181;
zones(6).ymin = 5430184.391; zones(6).ymax = 5963636.609;
for i = 1:numel(zones)
   zone = zones(i);

   % Create mask inside zone
   in_zone = x_coords >= zone.xmin & x_coords <= zone.xmax & ...
             y_coords >= zone.ymin & y_coords <= zone.ymax;

   % Extract suitability values inside zone
   suitability_zone = suitability_map(in_zone);
   valid_mask = suitability_zone > 0;
   num_valid_pixels = sum(valid_mask(:));
   pixel_area_km2 = abs(R.CellExtentInWorldX) * abs(R.CellExtentInWorldY
      ) / 1e6;
   total_area_km2 = num_valid_pixels * pixel_area_km2;

   fprintf('Zone: %s\n', zone.name);
   fprintf(' Suitable pixels: %d\n', num_valid_pixels);
   fprintf(' Suitable area: %.2f km^2\n\n', total_area_km2);
end
```

Listing B.7: Suitability Areas by Percentile Zoning

```
[suitability_map, R] = readgeoraster("suitability.tif");
% Get pixel coordinates
[cols, rows] = meshgrid(1:R.RasterSize(2), 1:R.RasterSize(1));
[x_coords, y_coords] = pix2map(R, rows, cols);
% Pixel area in km2
pixel_area_km2 = abs(R.CellExtentInWorldX) * abs(R.CellExtentInWorldY) /
```

```
   1e6;
% Define zone bounding boxes in EPSG:32718
zones = struct();
zones(1).name = 'Norte␣Grande';
zones(1).xmin = -100935.038; zones(1).xmax = 1107000.966;
zones(1).ymin = 7350000.325; zones(1).ymax = 8100000.675;
zones(2).name = 'Norte␣Chico';
zones(2).xmin = -200000.040; zones(2).xmax = 1009000.968;
zones(2).ymin = 6600000.008; zones(2).ymax = 7350000.000;
zones(3).name = 'Zona␣Centro';
zones(3).xmin = -210000.072; zones(3).xmax = 1000000.000;
zones(3).ymin = 5850000.000; zones(3).ymax = 6600000.000;
zones(4).name = 'Zona␣Sur';
zones(4).xmin = -309000.072; zones(4).xmax = 900000.000;
zones(4).ymin = 5100000.000; zones(4).ymax = 5850000.000;
zones(5).name = 'Sur␣Austral';
zones(5).xmin = -900935.072; zones(5).xmax = 1200000.000;
zones(5).ymin = 3800000.000; zones(5).ymax = 5100000.000;
zones(6).name = 'Macrozona␣sur';
zones(6).xmin = 100044.241; zones(6).xmax = 980000.181;
zones(6).ymin = 5430184.391; zones(6).ymax = 5963636.609;
% Define your suitability classes
suitability_classes = [1, 2, 3];
for i = 1:numel(zones)
   zone = zones(i);

   % Mask for pixels inside current zone
   in_zone = x_coords >= zone.xmin & x_coords <= zone.xmax & ...
             y_coords >= zone.ymin & y_coords <= zone.ymax;

   % Extract suitability values inside zone
   suitability_zone = suitability_map(in_zone);

   fprintf('Zone:␣%s\n', zone.name);
```

```
    % Loop over each suitability class
    for c = suitability_classes
        % Count pixels equal to class c
        class_mask = suitability_zone == c;
        num_pixels = sum(class_mask);

        % Calculate area
        area_km2 = num_pixels * pixel_area_km2;

        fprintf('␣␣Suitability␣class␣%d:␣Pixels␣=␣%d,␣Area␣=␣%.2f␣km^2\n'
            , c, num_pixels, area_km2);
    end
    fprintf('\n');
end
```

Listing B.8: Best Spot

```
% Best spot
% Read the raster and spatial reference
[suitabilityMap, R] = readgeoraster('suitability.tif');
% Find the maximum value and its index
[maxValue, linearIdx] = max(suitabilityMap(:));
% Convert linear index to row and column
[row, col] = ind2sub(size(suitabilityMap), linearIdx);
% Convert row/col to spatial coordinates using the reference object R
[x, y] = pix2map(R, row, col);
% Display result
fprintf('Best␣suitability␣value:␣%.4f\n', maxValue);
fprintf('Coordinates␣(UTM␣Zone␣18S):␣X␣=␣%.2f,␣Y␣=␣%.2f\n', x, y);
```

C GIS Layers

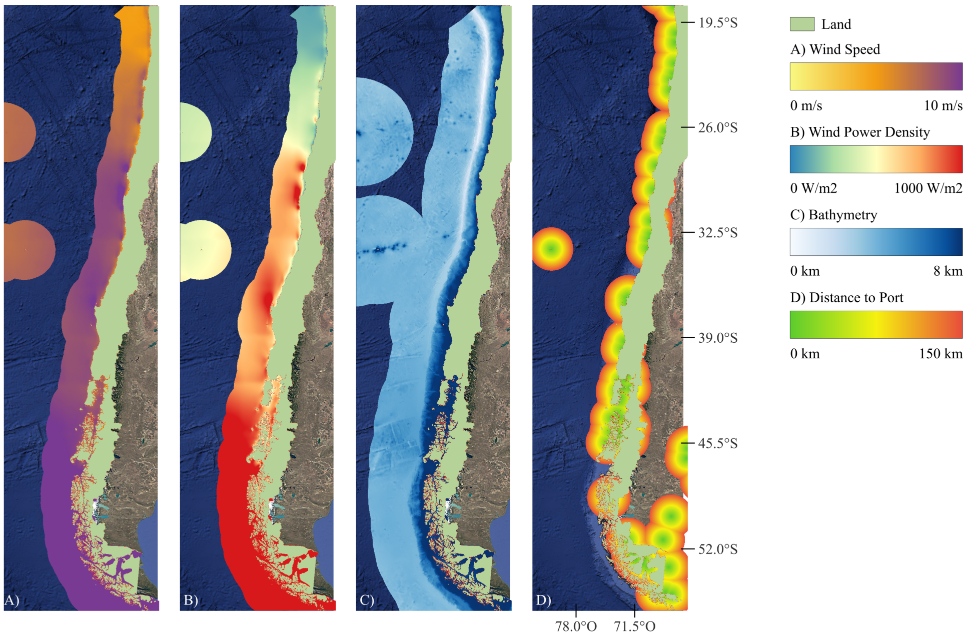

Figure C.1: GIS Layers: Wind Speed, Wind Mean Power, Bathymetry and Distance to Port

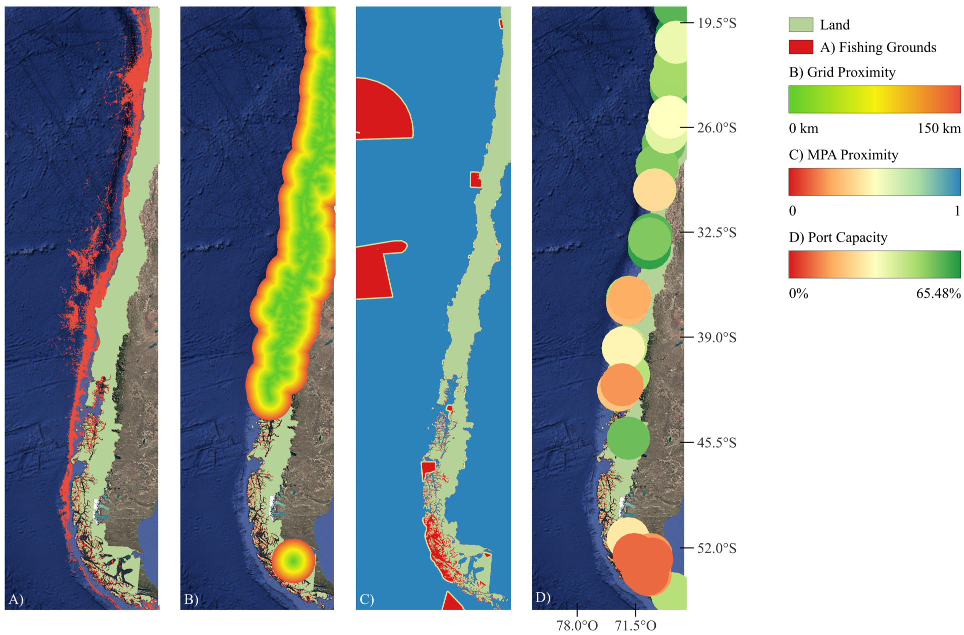

Figure C.2: GIS Layers: Fishing Grounds, Grid Proximity, MPA Proximity and Port Capacity

D GIS Data and Layers

The GIS layers used for site selection and analysis, and the results of this thesis, are available online at the following repository:

Access GIS Data and Results

`https://drive.google.com/drive/folders/1uhlVZ8KPjyzF5iVcJMdk9IPPziTUyzbf`

Table D.1: List of GIS data layers available in the online repository.

Layer Name	Description	Format
Wind_Speed	Raster data of wind speed measurements	GeoTIFF
Wind_Power_Density	Raster data representing mean power density of wind	GeoTIFF
Bathymetry	Depth measurements of marine areas	GeoTIFF
MPA_Proximity	Boundaries of marine protected zones and proximity scores	GeoTIFF
Distance_to_Port	Raster representing proximity to ports	GeoTIFF
Port_Capacity	Raster of location and capacity attributes of ports scored	GeoTIFF
Grid_Proximity	Proximity of grid infrastructure	GeoTIFF
Fishing_Grounds	Raster of areas with fishing activity based on AIS data	GeoTIFF
Land_Mask	Raster of the continental shelf of the country	GeoTIFF
Suitability_Floating	Suitability results for floating structures	GeoTIFF
Suitability_BF	Suitability results for bottom-fixed structures	GeoTIFF
Zoning_Floating	Zoning results for floating structures	GeoTIFF
Zoning_BF	Zoning results for bottom-fixed structures	GeoTIFF
Violence_Incidents	Violence incidents registrated between 2020 - 2025	KML