Spatial Multicriteria Decision Aiding for Regional Energy Planning and Assessment. The Case Study of Gotland, Sweden

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Abstract. The transition to renewable energy requires regional planning approaches that integrate spatial, environmental, and social dimensions. This study develops a Multi-Criteria Spatial Decision-Support System (MC-SDSS) to support regional energy planning by combining geospatial data analysis, future scenario development, and multi-criteria evaluation techniques. The methodology is structured into four phases - contextual analysis, energy potential mapping and future scenarios, integrated evaluation and decision support, and implementation and monitoring. The approach is applied to Gotland, Sweden, a region with ambitious decarbonization goals and unique geographic characteristics. Renewable energy potential is assessed through thematic mapping using Geographic Information Systems (GIS) tools, focusing on wind, solar, and biomass resources. In the evaluation phase, a Spatial Multi-Criteria Analysis (SMCA) is conducted to assess and compare the scenarios. Five main criteria are identified Society and Culture, Technology and Infrastructure, Economy, Land-use, Environment each associated with specific measurable spatial indicators. Criteria weights are derived using the Simple Multi-Attribute Rating Technique Exploiting Ranks (SMARTER) method with the purpose of weighting the indicators maps and then aggregating them into suitability maps for Renewable Energy Sources (RES) power plants installation. By embedding the decision-support system within a spatial planning perspective, this study promotes a transparent, replicable, and stakeholder-sensitive approach to regional energy planning. The proposed framework supports the identification of hybrid scenarios and fosters alignment between energy objectives, territorial characteristics, and community needs—contributing to more resilient and place-based energy transitions.

Keywords: Spatial Multi-Criteria Analysis · Regional Energy Planning · Decision-Support System

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1 Introduction

Energy planning has become increasingly crucial across Europe, as the sector contributes about 73% of the EU's greenhouse gas emissions [1]. Achieving climate neutrality by 2050, as outlined in the European Green Deal and then the Climate Law [2, 3], requires energy policies across all governance levels, with regional planning playing a key role. Spatial planning links energy infrastructure to land use and environmental considerations, promoting holistic and sustainable approaches. However, integrating energy and spatial planning requires decision-support tools that can tackle multi-dimensional problems and conflicting objectives. The regional spatial planning level is suitable to reflect local consumption, environmental, and socio-economic conditions, requiring context-specific approaches [4]. Spatial Multi-Criteria Analysis (SMCA), combining GIS and multicriteria hierarchical approach, enables the assessment of renewable energy scenarios while managing land-use trade-offs.

This study proposes an integrated methodology to support the assessment and the localisation of Renewable Energy Sources (RES) to bridge the current gap of standardized methodologies in regional energy planning. The main research question explores how spatial and decision-making tools can aid regional integration of renewables. This can be unpackaged into three sub-questions, each one linked to definite phases of the proposed methodology (Fig. 1). In detail: (1) literature and case study review, (2) development of a framework combining SMCA, scenario building, and Geographic Information Systems (GIS) into a unique framework, and (3) application of the methodology to Gotland.

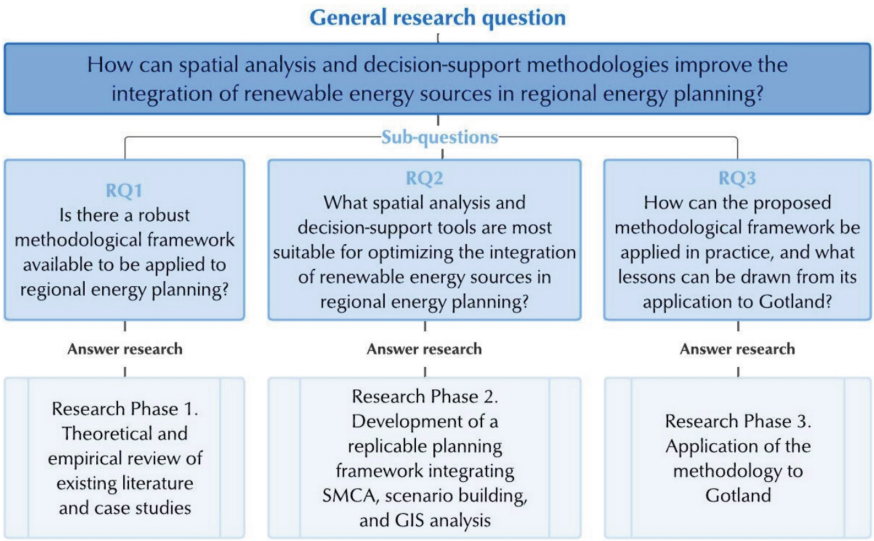

Fig. 1. Research questions and methodology.

The study is organized accordingly, concluding with a discussion on findings, replicability, and limitations. The Gotland case demonstrates the method's flexibility and stresses the relevance of data and stakeholder input.

2 Setting the Framework for Regional Energy Planning

The Brundtland Commission (1987) defined Sustainable Development (SD) as meeting present needs without compromising future generations [5]. This powerful concept continues to address global challenges today (e.g. climate change, resource depletion, or social justice). Over time, the concept has evolved from mere conservation efforts to include resilience—the ability of systems to adapt to disruptions [6, 7]. This vision shapes global agendas like the UN's Agenda 2030 and the Paris Agreement [8, 9], with the Sustainable Development Goals (SDGs) replacing the Millennium Development Goals in 2015. Yet, global crises such as COVID-19, conflicts, and climate emergencies continue to slow progress [10].

Renewable Energy Sources (RES)— i.e. wind, solar, bioenergy, hydropower, ocean, and geothermal—play a key role in sustainable development, offering an alternative to fossil fuels, which are the primary contributors to Greenhouse Gas (GHG) emissions and air pollution. As a matter of fact, the energy sector might be one of the engines for sustainability, but it accounts for approximately 73% of GHG emissions [11]. Despite their high potential, RES technologies can carry pressures on people's health and the Environment, but also noise pollution, visual disturbance, and land-use/land-cover issues [12]. For this reason, the 7th SDG, "Affordable and Clean Energy", highlights the sector's foundational role in achieving broader sustainability [13], since RES efficiency could be capable of cutting 94% of energy-related CO_2 emissions by 2050 [14].

For this reason, a multidisciplinary approach is essential to align energy development with long-term sustainability, especially as energy demand grows and fossil fuels decline [15, 16].

At the European level, policies such as the European Green Deal, Fit for 55 package, or the Energy Union Strategy aim to reach climate neutrality by 2050 or even the Renewable Energy Directive (RED), the Energy Efficiency Directive (EED), and the Energy Performance of Buildings Directive (EPBD) [17–19] guide EU countries members in adopting sustainable practices across sectors. Complementary instruments such as the Hydrogen Package and REPower EU aim to accelerate the deployment of clean energy technologies and reduce reliance on fossil fuel imports, by considering geopolitical disruptions [20, 21]. EU states have developed National Energy and Climate Plans (NECPs), to align with EU-wide targets (i.e. security, integration, efficiency, decarbonization, and innovation). For example, Sweden and Italy follow different energy scenarios—Sweden aims for 100% renewable electricity by 2040, whereas Italy includes a potential nuclear role [22, 23]. However, some knots must still be solved. If revised NECPs are expected to increase ambition, their success closely depends on more effective coordination, investment, and stakeholder engagement [24, 25]. In the Swedish government system, the Covenant of Mayors supports municipalities in adopting Sustainable Energy and Climate Action Plans (SECAPs), targeting emissions, climate resilience, and energy poverty [21, 26–28]. Yet regional authorities often lack resources or legal authority due

to centralized governance traditions, particularly in Eastern and Scandinavian countries [29]. Closing these gaps demands better policy alignment, inclusive governance, and capacity-building at the regional level [26, 30].

3 A Spatial Planning Approach to Regional Energy Planning

Spatial planning is crucial in managing human activities and mitigating their impact on ecosystems. Evolving from urban planning, it now integrates environmental, social, and economic factors across all governance levels: international, national, regional, and local. The European Spatial Development Perspective (ESPD), adopted in 1999, helped promote this approach, encouraging cross-border cooperation and subsidiarity [31].

The regional level emerges as a strategic scale for addressing cross-sectoral challenges such as energy, biodiversity, and infrastructure. Regions act as intermediaries, tailoring national strategies to local contexts and supporting participatory governance [32]. Sectoral planning, including energy, water and transport, benefits from integration into regional frameworks, improving policy coherence. For instance, coordinating regional energy infrastructure with land use supports sustainable renewable energy deployment [33, 34].

Energy planning itself has transitioned from a purely technical domain to a multifaceted discipline that integrates environmental and social objectives. Energy planning has shifted from a technical field to a multidimensional discipline that includes environmental and social goals. Regional energy planning can address local resource variations and encourage stakeholder involvement. Integrated Spatial and Energy Planning (ISEP) offers a holistic model linking land use with energy supply and demand [35]. As the energy transition advances, spatial planning helps manage decentralization, infrastructure upgrades, and public acceptance by aligning renewable energy development with ecological and cultural concerns [36, 37].

Community participation is vital for effective spatial and energy planning. It builds trust, improves acceptance, and ensures that local needs are reflected [38]. While resource and methodological challenges remain, participatory tools like workshops and digital platforms can help bridge technical planning with community priorities [39, 40].

In this context, participatory planning is essential for a fair and sustainable regional energy transition. Even if economic and/or social resources are not always available to open participation process to a wider pool of stakeholders and community (e.g. workshops, or digital platforms) these can make the difference in fostering sustainable inclusive development in REP scenarios [40].

4 Decision-Support Toolbox for Regional Energy Planning

Regional energy planning needs for addressing sustainability challenges by enabling strategies tailored to local environmental, socio-economic, and infrastructure conditions. Unlike top-down national policies, it offers a more detailed, place-based approach. REP can integrate a diverse set of decision-support tools, ranging from spatial analysis like GIS, strategic analysis tools as SWOT Analysis, scenario-building, or participatory analysis, and decision-aiding techniques like Multi-Criteria Decision Analysis (MCDA).

These aid Decision and Policy Makers in providing data-driven, inclusive, and spatially grounded planning for renewable energy deployment.

This paper lays the groundwork for developing a methodological framework capable of generating spatial energy scenarios aligned with regional needs and guiding decision-making processes.

4.1 Spatial and Strategic Analysis Tools

Geographic Information Systems (GIS) have evolved from logic mapping systems to sophisticated and interoperable platforms for aiding public bodies and urban planners freelancers, and other specialists to take decisions [41–43]. Despite their potential, GIS applications in energy planning remain limitedly widespread due to technical, financial, and institutional barriers [44]. Similarly, SWOT (Strengths, Weaknesses, Opportunities and Threats) Analysis—while often criticized for its subjectivity— remains the most common used method in strategic planning [45, 46] since its added value significantly increase when combined with other analysis and evaluation methods [47].

4.2 Decision-Making Tools

Given the multidimensional nature of energy planning, structured decision-aiding tools are essential. Drawing on foundations in operational research and decision theory [48–50] these tools support structured evaluations and take long-term decisions.

Multi-Criteria Decision Analysis (MCDA) is used to compare and prioritize alternatives based on multiple criteria, providing a robust framework for integrating environmental, technical, economic, and social factors into planning processes [51–53]. Within the MCDA family, several specific methods are particularly relevant in regional energy planning.

The Analytic Hierarchy Process (AHP) can assess the impact of renovation measures addressing consumer behavior in different scenarios or rather aiding the definition and implementation of policy decisions for energy saving in buildings [28]. Therefore, preferences elicited from stakeholder input are crucial. SMARTER [54, 55], on the other hand, has recently been considered more expedient than AHP for weights elicitation, since facilitate experts in the ranking of elements, often in contexts where time or data availability are limited [56]. SMCA extends the traditional MCDA approach by integrating spatial data and criteria within GIS environments, making it particularly valuable for territorial energy planning where location-based trade-offs are essential [57].

Therefore, MCDA can support in structuring fostering transparency, especially when combined with participatory inputs and spatial analysis.

4.3 Stakeholder and Participation Tools

Stakeholder analysis ensures that diverse interests are acknowledged and balanced using tools such as social network analysis or power-interest grids [58, 59].

Participation methods are analyzed through democratic, social learning, and policy-driven lenses. Arnstein's ladder illustrates power dynamics in participation, while authors

like Rowe and Frewer [60] and Palm & Thoresson [61] highlight practical shortcomings. Participatory tools such as ESTEEM, MCDA, and participatory GIS enhance inclusiveness, yet challenges such as cost, time, and unequal power relations often limit their effectiveness [38, 40].

4.4 Scenario Building

Scenario building, whether qualitative or quantitative, helps explore plausible energy futures, often including baseline, trend, and policy-driven trajectories [61–63]. When integrated with GIS and MCDA, scenario methods become powerful tools for testing the implications of planning decisions under uncertainty.

4.5 Insights from Regional Energy Plans and Research Case Studies

The literature review on regional energy planning included both real-world planning documents and academic case studies, each offering different contributions to the development of the proposed framework. This review focused on frameworks from the Central-Western Europe government systems such as the *Schéma Régional Climat Air Energie* (SRCAE) *de la Corse* (France) and the *Integriertes Energie und Klimaschutzkonzept* (IEKK) of Baden-Württemberg (Germany).

The review of actual plans focused on understanding the practical structure, content, and outputs of existing strategies—generally aligned with national and EU directives, but often lacking in the use of MCDA techniques, with limited GIS application and varying levels of community participation.

By contrast, academic case studies reflected evolving research trends, highlighting integrated methods (e.g., MCDA with GIS), participatory approaches, and scenario modeling. The findings can bridge the gap between practical issues (e.g. how to engage stakeholders more effectively) and methodological innovation in regulatory frameworks.

5 A Decision-Support Framework for Regional Energy Planning

A flexible four-phase framework for regional energy planning is proposed (Fig. 2), integrating spatial analysis, decision-support tools, and participatory processes to create tailored, evidence-based strategies. Each phase targets specific components of the energy planning process, from baseline assessments to strategic recommendations and performance tracking.

The first phase, Contextual analysis, assesses geographic, climatic, socio-economic, and energy system features. GIS is employed to analyze topography, climate, land use, and demographic patterns, whereas a spatial SWOT analysis summarizes strengths, weaknesses, opportunities, and threats. An organigraph is suggested to map governance structures, clarifying institutional roles and responsibilities. This phase identifies initial renewable energy opportunities [64].

In the second phase, Energy potential mapping and future scenarios, RES are evaluated through GIS and scientific datasets. Areas with development constraints are spatially excluded to produce maximized energy scenarios. These conceptual maps serve

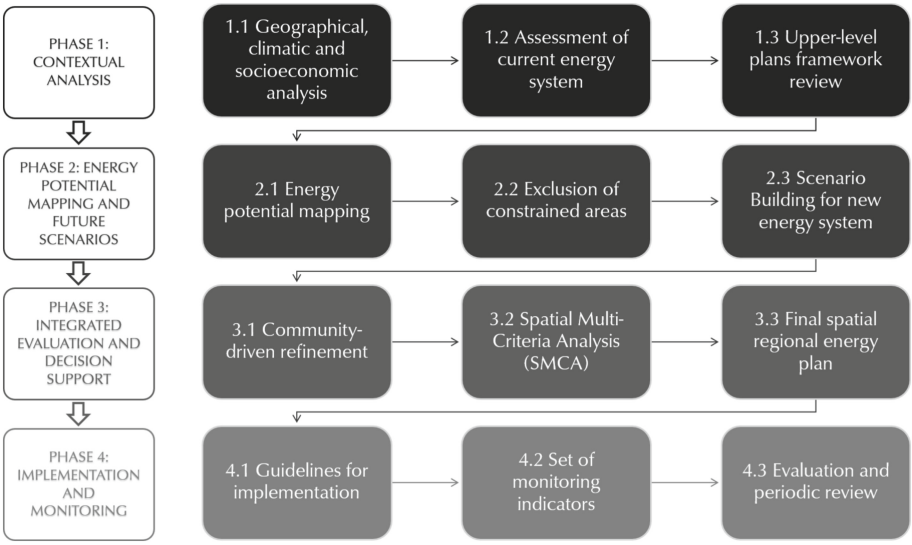

Fig. 2. Methodological workflow

as discussion tools to gather stakeholders and community feedback. This process favors negotiation between technical assessments and local perceptions, involving a diverse range of stakeholders—such as regional and municipal authorities, energy providers, environmental organizations, local businesses, and citizen associations—each bringing specific knowledge, interests, and priorities. Negotiation gaps can be mitigated through transparent communication, early involvement, and simple elicitation techniques such as surveys or facilitated workshops. In this phase, scenario building is supported by storytelling techniques, which help communicate alternative development paths during the ongoing evaluation phase.

The third phase, Integrated evaluation and decision support, applies SMCA with weighted criteria via the SMARTER method [54, 55], incorporating community input to generate suitability maps and prioritize interventions. A sensitivity analysis tests the robustness of the outcomes by adjusting criterion weights, while comparative surface analysis supports the identification of priority intervention zones and informs policy directions.

In the fourth phase, Implementation and monitoring, guidelines are defined for action prioritization, financial planning, and institutional responsibilities. A set of quali-quantitative indicators monitor and review performance and adaptability to new data, technologies, and policy shifts.

To ensure an active participation, it is important to involve a diverse range of stakeholders—including regional and municipal authorities, energy providers, environmental organizations, local businesses, and citizen associations—each bringing specific knowledge, interests, and expectations. Differences in influence and technical understanding may lead to negotiation gaps, which can be mitigated through transparent communication, early involvement, and simple elicitation techniques such as surveys or facilitated

workshops. In this phase, scenario building through storytelling can help actors in better communicating alternative development paths during the ongoing evaluation process.

6 Application to the Case Study of Gotland

6.1 Introduction and Contextual Analysis

Gotland, Sweden's largest island, is both a municipality and a region, making it a unique setting for testing regional energy planning. Its governance reflects the Scandinavian model of local autonomy and state coordination. Gotland's energy ambitions, as a pioneer in renewables, are guided by national and regional strategies aimed at sustainability and decarbonization. The contextual analysis shows strong potential for wind, solar, and biomass energy on the island, while other RES are constrained by natural limitations. The island's context—defined by dispersed rural settlements, an aging population, and an economy rooted in tourism and clean energy—highlights both the challenges and opportunities of sustainable development in insular regions.

6.2 Energy Potential Mapping and Scenario Building

The second phase mapped energy potential using spatial data from authoritative sources: Global Wind Atlas, Global Solar Atlas, and Swedish Forest Agency. The final energy potential maps, rasterized into five levels of potential, are shown in Fig. 3. Exclusion layers—military zones, protected areas, and 1 km building buffers—were overlaid to create optimized development scenarios for each energy source (Fig. 4). The intention was to use the outcomes of this hypothetical consultation as one of the criteria in the subsequent phase, serving as a spatial indicator for the socio-cultural criterion. However, due to time and resource limitations, this was not possible, and alternative approximations were considered for this evaluation.

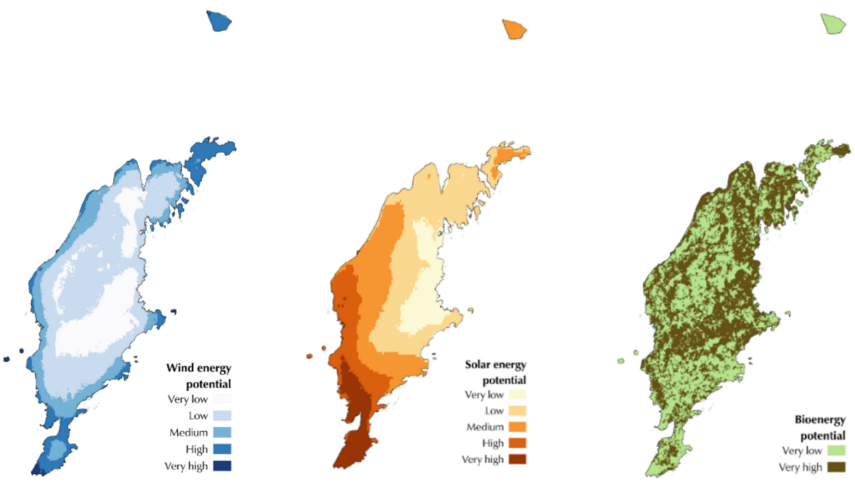

Fig. 3. Energy potential maps: wind (left), solar (middle), biomass (right)

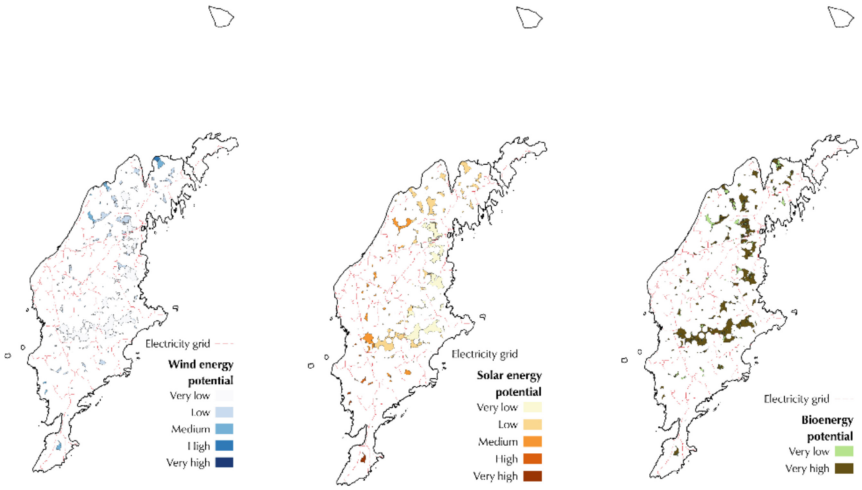

Fig. 4. Maximized development scenarios for wind (left), solar (middle), bioenergy (right)

6.3 Integrated Evaluation and Spatial Decision Support

The third phase implemented a SMCA to integrate qualitative and quantitative factors using the SMARTER method, including technical-infrastructural, environmental, economic, social-cultural, and land-use conflict dimensions, each further broken down into measurable sub-criteria (Fig. 5).

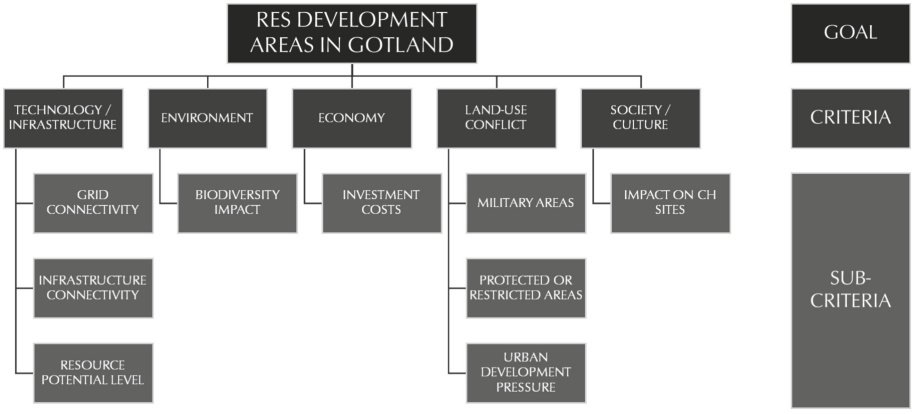

Fig. 5. Decision tree

These sub-criteria were translated into spatial indicators, represented as score maps, each displaying performance values from 1 to 5 across the regional territory from the perspective of that specific sub-criterion. Figure 6 provides examples of these maps, where darker shades consistently indicate higher scores, representing areas most suitable for RES development according to that criterion.

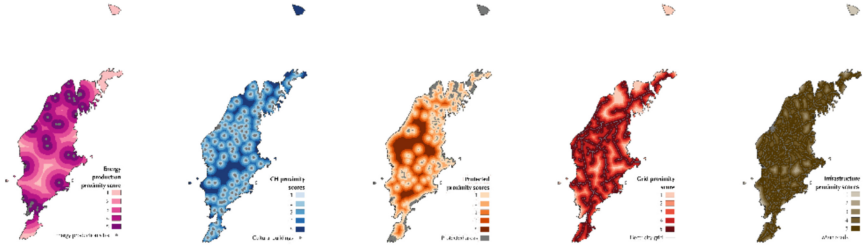

Fig. 6. Score map examples

Next, a qualitative ranking of the five main criteria was established in consultation with local university experts (see Table 1). A similar ranking process was applied at the sub-criteria level when a criterion included multiple sub-criteria. A linear weighted sum was then used to aggregate the scores into calibrated suitability maps, providing overall suitability values from 1 to 5. These values accounted for all criteria, each weighted according to the ranking-based weights derived from the SMARTER method.

The weights, which range from 0 and 1 and sum to 1 by convention, can be calculated using the following formula:

$$w_k = \left(\frac{1}{K}\right)\sum_{i=k}^{K}\left(\frac{1}{i}\right) \tag{1}$$

where K represents the total number of attributes, and w_k is the weight assigned to the k th attribute.

These weights were then used in the final aggregated utility calculation, following the additive model proposed by Barron and Barrett [50]:

$$U_h = \sum_{k=1}^{K} w_k u_h(x_{hk}) \tag{2}$$

where U_h is the total utility score for each evaluation unit h (in this case, a 50 × 50 m pixel of the regional territory). The term $u_h(X_{hk})$ represents the single-dimensional utility scores for each criterion, while w_k denotes the weights assigned to each criterion or value dimension.

Table 1. Criteria ranking using the Rank Order Centroids by SMARTER.

Rank	Criterion	ROC weight
1	Economy	0,4567
2	Land-use	0,2567
3	Environment	0,1567
4	Society and culture	0,0900
5	Technology and infrastructure	0,0400
	Total	1,0000

Despite limited stakeholder involvement, expert input from Campus Gotland guided the weighting process. The analysis produced four suitability maps—general and source-specific—identifying optimal areas for RES development (Fig. 7). Results indicated that central Gotland is the most suitable area for renewable energy development, while coastal and protected zones were deprioritized due to land-use and regulatory constraints. The contrast between energy potential maps and overall suitability maps underscores how contextual factors like infrastructure and land-use outweigh raw resource availability, validating the robustness of the adopted criteria hierarchy.

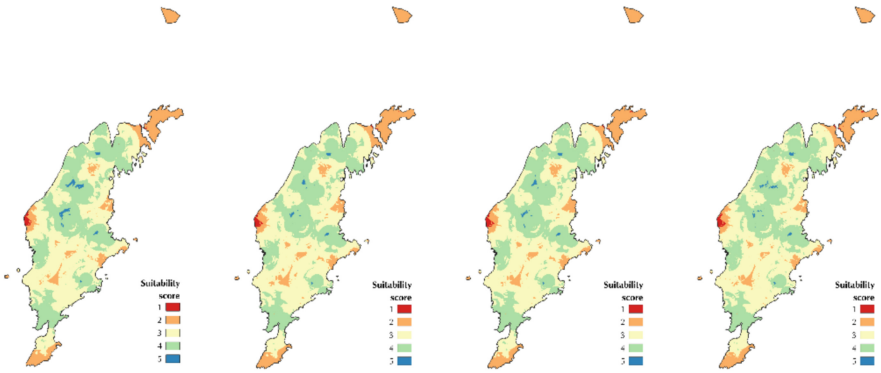

Fig. 7. Suitability maps

6.4 Sensitivity Analysis and Final Reflections

The final phase tested the model's resilience through sensitivity analysis, revealing how prioritizing individual criteria—such as technical and infrastructural factors—expanded high-suitability zones, particularly for wind energy. However, this often came at the expense of environmental and land-use considerations, reinforcing the need for a balanced, multi-criteria approach. While infrastructure and resource availability shape feasibility, long-term planning must also account for biodiversity, cultural heritage, and social acceptance. The study concludes that Gotland's conditions support diversified renewable energy development, and the methodology is broadly replicable, with adjustments for governance, geography, and data availability.

7 Discussion of Results

The proposed methodological framework for regional energy planning demonstrates the capacity to combine and integrate spatial analysis, scenario building, and participatory processes into a structured, adaptable planning method aligned with national and EU sustainability goals.

Applied to Gotland, the framework successfully identified renewable energy potentials, mapped spatial constraints, and generated plausible future development scenarios.

As previously presented, the final suitability maps revealed that central areas of the island are the most promising zones for renewable energy deployment. Conversely, coastal and environmentally protected areas, although rich in physical energy potential, were deprioritized due to regulatory or land-use constraints.

The comparison between source-specific and aggregated suitability maps showed that, in this case, the low weight assigned to the technological and infrastructural criterion—including source-specific energy potential—resulted in minimal differences among the RES options, with development priorities shaped primarily by socio-environmental constraints. However, in other regional contexts, differing priorities or needs may elevate the influence of specific criteria, making one energy source consistently more favorable than others. These specific spatial findings confirm that the methodology is capable of translating complex trade-offs into clear, actionable outputs—an essential condition for effective planning.

The study confirms the framework's replicability, with adjustments for regional governance, data access, and technical capacity. Gotland's streamlined governance and strong renewable resources eased implementation, but challenges such as data requirements and stakeholder engagement remain. Overall, the framework's strength lies in generating context-sensitive strategies through spatial data, local insights, and a transparent, replicable workflow using GIS and SMCA.

8 Conclusions and Future Perspectives

This study proposed a robust and flexible methodological framework for regional energy planning that integrates GIS, scenario modeling, multi-criteria assessment, and participatory tools. Developed to address fragmented governance and implementation gaps, the framework aligns with EU and national sustainability goals and is adaptable to various territorial contexts.

The application to the case study of Gotland demonstrated its effectiveness in identifying renewable energy potential, managing spatial constraints, and structuring development scenarios. While the island's simplicity and resource availability aided implementation, limitations in data resolution and stakeholder engagement pointed to areas for refinement. The results help answer the core research question on how spatial and decision-support tools can strengthen regional planning, along with sub-questions on tool selection, coherence, and applicability.

To support broader adoption, the framework could be embedded within the Strategic Environmental Assessment (SEA) process, as required by Directive 2001/42/EC. The procedural compatibility between SEA and the framework—across phases such as scoping, environmental reporting, and stakeholder consultation—offers opportunities to strengthen the spatial and participatory dimensions of energy planning. A comparison with both the Italian *Valutazione Strategica Ambientale e Territoriale* (VALSAT) and the Regional Energy Plan of Emilia-Romagna confirms the frameworks feasibility for institutional integration. However, effective implementation will require improved data infrastructures, technical training, and long-term political commitment.

Looking forward, further research should focus on enhancing participatory components, increasing the resolution and reliability of spatial data, and applying the framework

in more complex regional contexts. Integrating emerging technologies—such as artificial intelligence and dynamic geospatial platforms—may further increase planning responsiveness and support evidence-based decision-making. As energy transition accelerates, structured yet adaptable tools such as the one developed in this study will be crucial to support inclusive, data-informed, and spatially grounded regional energy strategies.

Disclosure of Interests. The authors declare they have no competing interests.

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