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Technical and Social Drivers of Renewable Energy Adoption: An Environmental Engineering Comparison of Andalusia (Spain) and Rize (Turkey)

KEYWORDS

renewable energy, hydropower, photovoltaics, regional energy systems, socio-cultural acceptance, energy potential analysis

ABSTRACT

This article presents a comparative assessment of renewable energy potential, actual utilization and socio-cultural adoption in two climatically and culturally contrasting regions: Andalusia (Spain) and Rize (Turkey). Andalusia is characterised by high solar irradiance and a diversified renewable portfolio dominated by solar photovoltaic (PV) and wind energy, whereas Rize relies almost exclusively on hydropower, which already covers approximately all regional electricity demand. Building on two detailed regional reports and additional institutional statistics, we quantify installed capacity, annual generation and technical potential for key technologies (solar PV, wind, hydropower and biomass), and analyse the "usage gap" between potential and realization. For Andalusia, solar and wind show high theoretical potential (30,000 MW and 15,000 MW respectively) but only partial utilisation (8,853 MW and 3,668 MW installed in 2024). In Rize, hydropower capacity of about 350 MW generates roughly 1.0–1.3 TWh per year, exceeding local demand, while solar, wind and biomass remain marginal. To bridge technical metrics with social and territorial conditions, we introduce a Socio-Cultural Renewable Adoption Index (SCRAI), composed of four dimensions: utilisation of technical potential, share of renewables in electricity demand, social & cultural acceptance, and practical compatibility (landscape, grid, environmental constraints). Each dimension is scored on a 0–10 scale for both regions, yielding a composite "integration score" and a two-number "Status/Future" profile. Results indicate that Rize represents a "saturated hydropower region" with a high current renewable share but limited room for further large-scale development, whereas Andalusia emerges as a "rising solar–wind region" with substantial remaining potential but infrastructural and regulatory challenges. The proposed framework supports multi-criteria regional energy planning by combining engineering indicators with socio-cultural factors in a transparent and transferable way.

Introduction

The rapid transformation of power systems across Europe and neighbouring regions is driven by decarbonisation targets, energy security concerns and the falling cost of renewable energy technologies [1]. Global assessments, such as the International Energy Agency's *World Energy Outlook*, highlight that record additions of renewable capacity have become the main driver of new power generation worldwide [2]. However, translating global trends into concrete regional strategies requires detailed understanding of local climatic [3], geographic [4], socio-cultural conditions [5], and system integration possibilities [6], [7].

Spain and Turkey illustrate two complementary pathways. Spain has become one of Europe's leaders in the deployment of wind and solar energy, and renewables already generate more than half of national electricity, with ambitious targets for 2030 [8]. In Spain, the autonomous community of Andalusia stands out due to its excellent solar resource, favourable wind conditions and large agricultural sector enabling biomass utilization. Recent regional statistics show that renewables account for over two-thirds of installed power capacity and annual generation in Andalusia, with solar PV as the dominant technology [9], [10].

Turkey, by contrast, is characterised by rapidly growing energy demand and a strong focus on hydropower, especially in the Eastern Black Sea region [11]. National studies emphasise the country's significant gross hydropower potential and the strategic importance of small hydropower plants in mountainous areas [12]. The province of Rize, located on the north-eastern Black Sea coast, is a typical high-rainfall, steep-terrain region, where hydropower provides almost all electricity supply, while solar, wind and biomass remain largely untapped [13].

The two regions therefore represent contrasting renewable energy development models:

- *Andalusia* – a diversified solar wind biomass system with high theoretical potential, facing mainly grid, land-use and permitting constraints.
- *Rize* – a hydropower-dominated system with high technical potential, but strong ecological sensitivity, complex topography and rising local opposition to new hydro projects.

Previous comparative studies often focus either on technical potentials or on socio-economic impacts [14]. Meanwhile, the literature on social acceptance of renewable energy demonstrates that public support, institutional trust and perceived fairness can decisively shape the success or failure of projects [15], [16]. Similar gaps between theoretical renewable energy potential and actual deployment have been reported in several regional and national studies, which point to the decisive role of non-technical barriers such as spatial constraints, regulatory frameworks and social acceptance in shaping real-world outcomes [17]. Integrating these strands at regional scale remains a methodological challenge.

The present paper responds to this gap with three objectives:

1. *Quantify* and compare renewable energy potential and actual utilisation in Andalusia and Rize, focusing on solar PV, wind, hydropower and biomass.
2. *Characterise* the "usage gap" between technical potential and current deployment, including technological dominance and diversification.
3. *Develop and apply* a simple Socio-Cultural Renewable Adoption Index (SCRAI) to capture social acceptance and territorial compatibility alongside technical metrics, and to position both regions in a common "Status vs. Future Feasibility" matrix.

The analysis is based on regional pre-studies, complemented by national and international statistics and selected peer-reviewed literature.

Study Areas and Data

Andalusia (Spain)

Andalusia is the southernmost autonomous community of Spain, with an area of 87,600 km^2 and a population of approximately 8.5 million. The region is characterised by Mediterranean and semi-arid climates with high annual solar irradiance, often between 1,800 and 2,000 kWh·m^{-2}· yr^{-1}, and favourable wind conditions, particularly in coastal provinces such as Cádiz. According to the latest regional energy statistics, Andalusia reached a total installed power capacity of 20,840 MW in 2024, of which 68.1% is from renewable sources. Annual renewable electricity generation was 20,756 GWh, again representing 68.1% of total regional generation. The technology mix is dominated by:

- Solar PV: Installed capacity 8,853 MW in 2024, following the addition of 2,253 MW in that year alone (40.1% growth compared to 2023).
- Wind energy: Installed capacity 3,636–3,668 MW, contributing roughly 22% of renewable generation.
- Hydropower: Approximately 639 MW of largely stable capacity, representing around 3% of renewable capacity.
- Biomass**:** Around 274 MW, mostly based on agricultural residues and forestry by-products.

The theoretical technical potential assessed in the Andalusia pre-study is approximately 30,000 MW for solar PV, 15,000 MW for wind and 4,500 MW for biomass, highlighting a substantial gap between potential and actual use, particularly for solar and wind. External studies confirm that Andalusia is among Spain's leading regions for renewable deployment and plays a key role in national energy security [18].

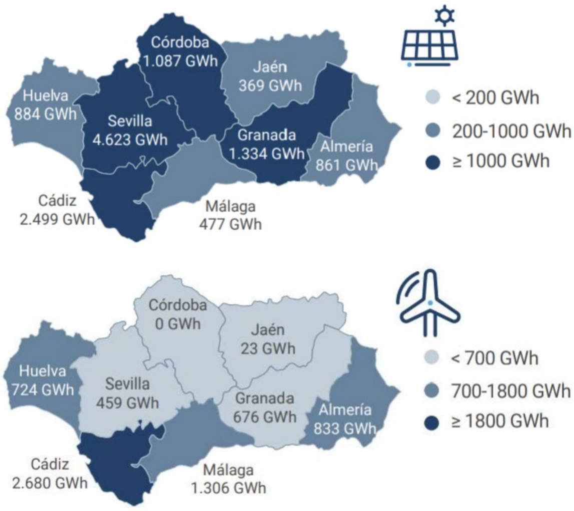

Fig. 1. Map of Andalusia with provincial boundaries and generation of renewable energy (solar & wind) for each province

Rize (Turkey)

Rize Province is located on the Black Sea coast of north-eastern Turkey and covers the area of 3,920 km^2. The terrain is strongly mountainous, rising quickly from the sea to the Kaçkar Mountains (>3,000 m). The region has a humid Black Sea climate, with annual precipitation of about 2,000–2,500 mm, among the highest in Turkey. This combination of steep gradients and high rainfall underpins substantial hydropower potential.

Rize's electricity system is almost entirely renewable and hydro-based. Recent data indicate:

- Total installed capacity ≈ 352–353 MW, almost all in 17–18 hydropower plants.
- Annual hydropower generation ≈ 1,034 GWh (some sources report ~1.30 TWh), corresponding to approximately 100–176% of local electricity demand, depending on the demand estimate used.
- Rize's annual electricity demand is in the range of 740–1,013 GWh, with more than half consumed by households.
- Only one small, unlicensed solar PV plant (0.75 MW rooftop-type) operates in the province; no wind power plants are installed.
- Biomass projects are at an early stage, exemplified by a planned 0.8 MW pyrolysis-biochar plant using tea waste, expected to produce roughly 6 GWh per year.

Hydropower potential assessments by the State Hydraulic Works (DSİ) and academic studies estimate the technical hydropower potential of the Rize basin at 1,200–1,230 MW and 2,000–4,600 $GWh \cdot yr^{-1}$. Given this spread, hydropower utilisation is reported explicitly as (i) capacity utilisation U^C ≈ 352/1231 ≈ 0.29 and (ii) energy utilisation U^E in the range (1.03-1.30 TWh)/(2.0-4.6 TWh) ≈ 0.22-0.65. This uncertainty is discussed in the Results & Discussion to avoid mixing capacity- and energy-based utilisation metrics.

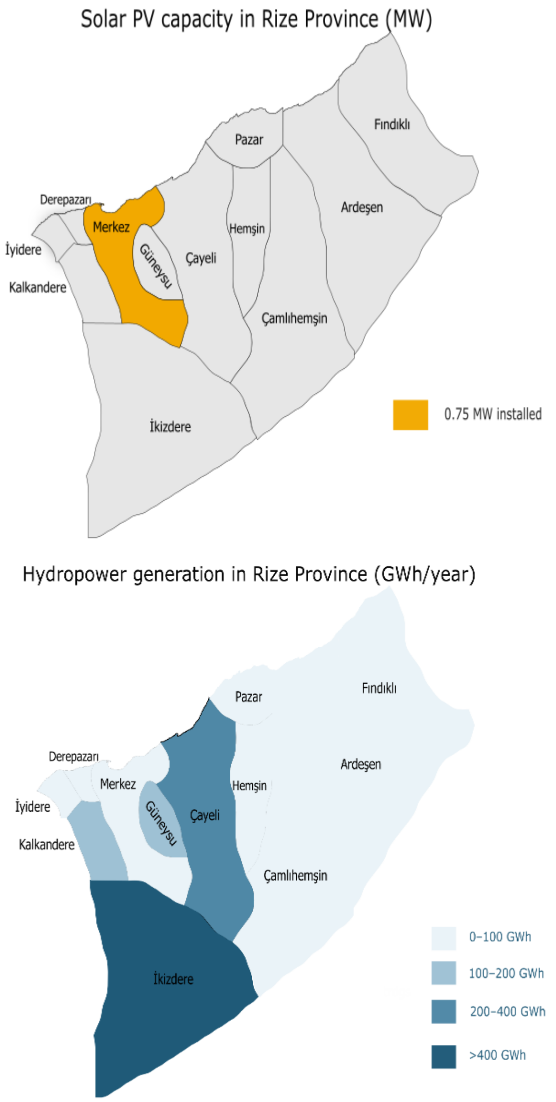

Fig. 2. Schematic map of Rize region based on administrative boundaries [19]

Data Sources

For Andalusia, the analysis draws on:

- Regional grid and generation statistics from Red Eléctrica de España (REE).
- Reports of the Agencia Andaluza de la Energía and the Spanish Ministry for Ecological Transition (MITECO).
- A detailed internal regional report on the renewable energy potential and utilisation in Andalusia covering the period 2015–2024.

For Rize, data sources include:

- TEİAŞ (Turkish Electricity Transmission Corporation) and EMRA (Energy Market Regulatory Authority) records on installed capacity and annual generation.
- DSİ hydrological data and hydropower potential estimates.

- TÜİK (Turkish Statistical Institute) and provincial reports on population and electricity demand.
- Project documents on biomass from tea waste and local wastewater treatment plants.

Global framing is informed by IEA and other international assessments of renewable energy and hydropower [20].

Methodology

Technical Potential Calculations

To ensure comparability, we adopt simple engineering formulations for estimating technical energy potential, where local studies provide compatible parameters.

For photovoltaic energy, yearly electricity production E_{PV} is approximated as (1):

$$E_{PV} = \eta\, A\, H \tag{1}$$

where:

- η – module and system efficiency,
- A – available area for PV deployment,
- H – annual global solar irradiance on the relevant surface (kWh·m^{-2}·yr^{-1}).

For hydropower, the instantaneous electrical power P is estimated by (2):

$$P = \eta\, \rho\, g\, Q\, H_w \tag{2}$$

where:

- η – overall turbine-generator efficiency,
- ρ – water density,
- g – gravitational acceleration,
- Q – volumetric flow rate,
- H_w – hydraulic head.

Annual energy output is then obtained by integrating P over time, accounting for flow variations. For the purposes of this study, we use published technical potential values from regional and national sources, rather than recalculating detailed hydrology, and we compare them with current installed capacities and generation.

Utilisation and Dominance Indicators

The degree of utilisation of technical potential for each technology i is approximated by two complementary ratios: capacity utilisation (3) and energy utilisation (4):

$$U_i = \frac{C_i}{C_{i,\mathrm{tech}}} \tag{3}$$

$$U_i = \frac{E_i}{E_{i,tech}} \tag{4}$$

where C_i is installed capacity and $C_{i,\mathrm{tech}}$ the estimated technical potential (both in MW), E_i is annual generation (GWh·yr^{-1}), and $E_{i,\mathrm{tech}}$ is technical potential (GWh·yr^{-1}). For solar and wind in Andalusia, this ratio can be evaluated directly from the prestudy-; for Rize, it is only meaningful for hydropower, given the limited or negligible technical potential for wind and the lack of consistent estimates for solar and biomass.

The share of renewables in total electricity demand is (5):

$$S_{\mathrm{RES}} = \frac{E_{\mathrm{RES}}}{E_{\mathrm{demand}}} \tag{5}$$

where E_{RES} denotes annual renewable electricity generation and E_{demand} total consumption in the region (GWh·yr^{-1}).

To assess technology dominance, we define a simple dominance index (6):

$$D = \frac{E_{\mathrm{max}}}{\sum_i E_i} \tag{6}$$

where E_{max} is the generation of the dominant renewable technology and $\sum_i E_i$ the sum of all renewable technologies. A value close to 1 indicates strong dominance by a single technology.

Socio-Cultural Renewable Adoption Index (SCRAI)

Technical indicators alone cannot fully explain the divergence between Andalusia and Rize. Therefore we propose a composite Socio-Cultural Renewable Adoption Index (SCRAI) that condenses four dimensions into a transparent scoring scheme.

Each dimension is scored on a 0–10 scale:

Utilisation of Technical Potential (U):
0 = negligible utilisation of available resources;
10 = technical potential largely exploited.

Share of Renewables in Total Demand (S):
0 = renewables cover 0% of demand;
10 = renewables cover ~100% or more of demand.
Social & Cultural **Acceptance** (A):
0 = strong opposition, frequent conflicts, low trust;
10 = broad public support, stable policy consensus [21].

Practical **Compatibility** (C):
0 = highly unfavourable terrain/land use, severe environmental conflicts, weak grid;
10 = favourable land availability, minimal conflicts, robust grid.

For each region, expert judgement based on the regional reports and secondary literature is used to assign scores (Section *SCRAI Scores for Andalusia and Rize*). From these, three indices are derived:

- Integration Score (I): a single "report-card" value (7):

$$I = \frac{U+S+A+C}{4} \tag{7}$$

- Status Score (X): captures current technical success (8):

$$X = \frac{U+S}{2} \tag{8}$$

- Future Feasibility Score (Y): captures socio-cultural and territorial conditions for future growth (9):

$$Y = \frac{A+C}{2} \tag{9}$$

The pair (X, Y) positions each region in a "Status vs. Feasibility" matrix, for example, differentiating "saturated" systems from "rising stars".

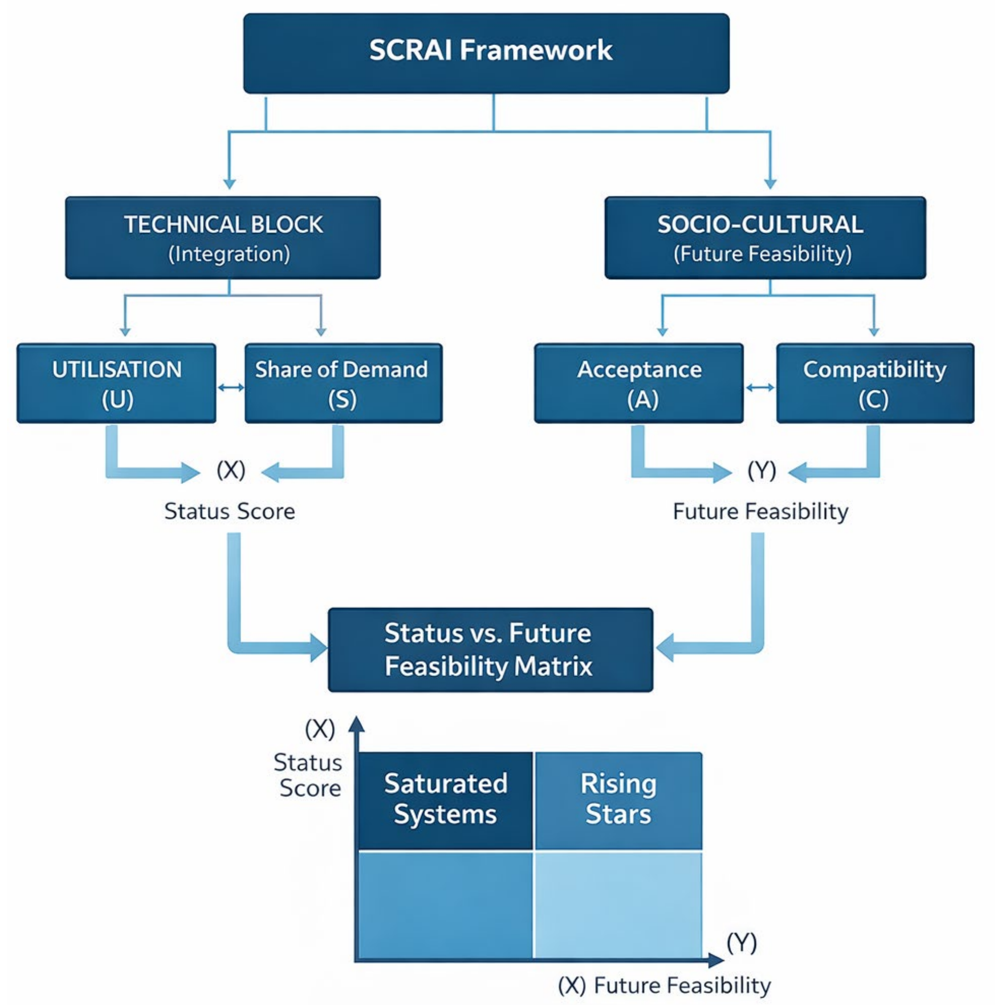

Fig. 3. Conceptual structure of the SCRAI framework, showing the four components (U, S, A, C) and their aggregation into Integration, Status and Future Feasibility scores

SCRAI scores were assigned with complementary expertise in renewable energy engineering, regional energy systems and socio-environmental assessment. Each expert scored the four dimensions independently using the rubric in Table 1a. Final scores were obtained by arithmetic averaging; when any dimension differed by more than 2 points across reviewers, the underlying evidence in the regional reports and cited literature was re-checked and a consensus score was agreed.

To reduce subjectivity, the two quantitative dimensions (U and S) are mapped to explicit percentage thresholds, while the qualitative dimensions (A and C) are anchored to documented indicators such as the presence of protected areas, frequency of local conflicts, land-use constraints and grid bottlenecks (Table 1).

Table 1. SCRAI scoring

Dimension	0	2	4	6	8	10
U – Utilisation of technical potential	U_i <5% (or negligible use)	5–15%	15–30%	30–50%	50–80%	>80% (near-saturation)
S – Share of RES in total demand	<10%	10–30%	30–50%	50–70%	70–100%	>100% (net exporter)
A – Social & cultural acceptance	Systematic opposition; repeated project cancellations	Frequent protests/ legal disputes	Mixed attitudes; recurrent local conflicts	Generally accepted with some localised conflicts	Broad support; few conflicts	Strong support; stable policy consensus
C – Practical compatibility	Severe terrain/grid constraints; high environmental conflicts	Major constraints; many protected areas/weak grid	Multiple constraints; limited siting options	Moderate constraints; feasible siting with mitigation	Favourable conditions; minor constraints	Very favourable conditions; robust grid and land availability

Results & Discussion

Andalusia: Potential, Utilisation and Gaps

Table 2 summarises the main indicators for Andalusia in 2024, based on the regional report.

Table 2. Renewable energy indicators for Andalusia (2024).

Technology	**Installed capacity (MW)**	**Theoretical potential (MW)**	**Utilisation of potential U_i (%)**	**Role in renewable mix**
Solar PV	8,853	30,000	≈ 29.5	Dominant technology
Wind	3,668	15,000	≈ 24.5	Second largest
Biomass	274	4,500	≈ 6.1	Niche but strategic
Hydropower	639.4	(limited expansion)	≈ stable	Balancing & storage

Total installed capacity: 20,840 MW (68.1% renewable). Renewable generation: 20,756 GWh (68.1% of total generation).

Solar PV has experienced particularly rapid growth, with 2,253 MW added in 2024 alone (+40.1% year-on-year), consolidating Andalusia's position as Spain's leading PV region. Wind capacity growth has been more moderate, though coastal areas still offer untapped potential [22]. Biomass and hydropower remain relatively small contributors in terms of capacity, but they are important for flexibility and rural development.

The utilisation ratios in Table 1 illustrate a significant usage gap, especially for solar and wind: less than one-third of the estimated solar potential and roughly a quarter of wind potential are currently exploited. Biomass remains far below its estimated potential of 4,500 MW. The main constraints identified in the regional report and supporting literature are:

- Grid congestion and the need for substantial transmission and distribution upgrades;
- Land-use conflicts and environmental restrictions on large PV farms and onshore wind parks;
- Lengthy permitting procedures and regulatory uncertainty for new projects;
- Limited deployment of large-scale storage and demand-side flexibility [23].

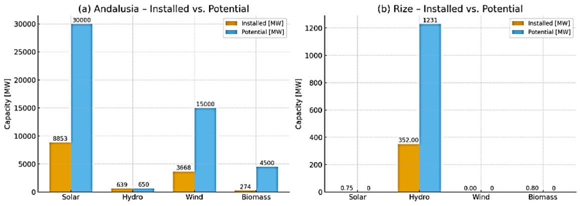

Fig. 4. Installed capacity versus theoretical potential for four renewable energy technologies (solar, hydropower, wind, and biomass) in (a) Andalusia and (b) Rize

The figure illustrates the magnitude of the usage gap for each technology. Andalusia shows a diversified renewable energy portfolio with large untapped solar, wind, and biomass potential, whereas Rize exhibits a hydro-dominated system with limited or negligible potential for other RES technologies. The comparison highlights the contrasting structural constraints and development pathways of both regions.

Rize: Hydropower Dominance and Untapped Resources

Table 3 presents key indicators for Rize's electricity system, based on provincial data and hydropower studies.

Table 3. Renewable energy indicators for Rize Province (latest available year, 2023/2024)

Technology/item	Value	Notes
Total demand	≈ 740–1,013 $GWh{\cdot}yr^{-1}$	Different data sources (distribution company vs. academic study)
Hydropower installed capacity	≈ 352 MW (17–18 plants)	Nearly all regional capacity
Hydropower generation	≈ 1,034–1,300 $GWh{\cdot}yr^{-1}$	Covers 102–176% of local demand
Technical hydropower potential	≈ 1,200–1,230 MW; 2,000–4,600 $GWh{\cdot}yr^{-1}$	Depending on methodology
Solar PV capacity	0.75 MW (unlicensed rooftop)	Negligible generation (~1 GWh)
Wind capacity	0 MW	Technical potential effectively zero in provincial maps
Biomass capacity	0 MW installed; planned 0.8 MW	Pilot pyrolysis plant (~6 $GWh{\cdot}yr^{-1}$ projected)

From these figures, the following observations emerge:

- Share of renewables in demand: Hydropower alone already exceeds local consumption (S_RES ≈ 1.0–1.76), making Rize a net exporter of renewable electricity within the Turkish grid.
- Hydropower utilisation: Depending on the reference technical potential (2,023 or 4,644 $GWh{\cdot}yr^{-1}$), the utilisation of hydropower potential ranges from about 28% (capacity-based) to about 64% (energy-based), indicating significant remaining potential, but also substantial environmental and social constraints.
- Other renewables: Solar PV has limited resource quality (≈1,100–1,400 $kWh{\cdot}m^{-2}{\cdot}yr^{-1}$), and land constraints make large-scale plants unattractive. Wind potential is assessed as negligible in provincial wind maps. Biomass offers niche opportunities through tea waste, forest residues and wastewater, but projects are in pilot phases.

The dominance index for Rize is extremely high: hydropower accounts for approximately 99.5–99.9% of renewable generation, leading to $D \approx 1.0$. In other words, Rize is effectively a single-technology renewable system.

Environmental and socio-cultural factors further constrain future hydropower expansion. Several studies report local opposition to new projects in the Eastern Black Sea region, due to impacts on river ecosystems, landscapes and traditional livelihoods [24].

Comparative Technical Assessment

Table 4 compares core technical indicators for Andalusia and Rize.

Table 4. Comparative technical indicators for Andalusia and Rize.

Indicator	Andalusia	Rize
Total installed capacity (MW)	20,840	≈ 352
Renewable share of capacity (%)	68.1	≈ 100
Renewable generation share in demand S_RES	68.1%	≈ 100–176%
Dominant technology	Solar PV	Hydropower
Dominance index D	≈ 0.5–0.6 (solar share in RES)	≈ 0.99 (hydro share in RES)
Diversity of mix	High (solar, wind, biomass, hydro)	Very low (hydro only)
Key usage gaps	Solar, wind, biomass	Nonhydro renewables; remaining hydro potential under environmental constraints

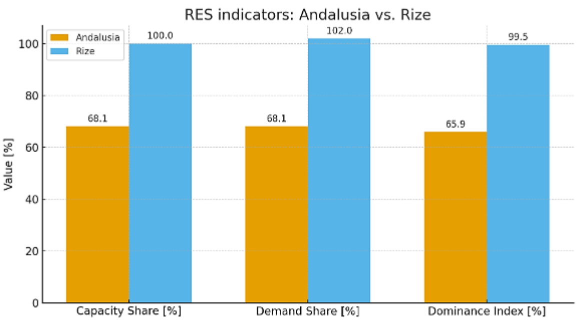

Fig. 5. Combined bar chart for Andalusia and Rize comparing (a) renewable share of capacity; (b) renewable share of demand; (c) dominance index, to visualise the contrast between a diversified and a hydro-dominated system

In summary:

- Andalusia is a diversified, high-potential but not fully utilised system: renewables cover about two-thirds of demand, and large unused technical potential exists, especially for solar and wind.
- Rize is a hydro-dominated, near-self-sufficient system: renewables (almost entirely hydro) already cover or exceed local demand, but options for further expansion are limited by geography, environmental protection and social acceptance.

These differences motivate the introduction of a joint socio-cultural index to understand where each region stands not only technically, but also in terms of readiness for further renewable deployment.

SCRAI Scores for Andalusia and Rize

Using the four dimensions defined in Section 3.3 and the information from the regional reports, we assign scores to Andalusia and Rize (Table 5).

Table 5. SCRAI component scores and derived indices for Andalusia and Rize (0–10 scale)

Component	Andalusia (ES)	Rationale (ES)	Rize (TR)	Rationale (TR)
U – Utilisation of technical potential	3.0	Solar, wind and biomass far below potential (≈25–30% for solar/wind, ≈6% for biomass)	3.0	Large hydropower potential still untapped; nonhydro renewables marginal
S – Share of RES in total demand	6.8	Renewables supply ≈68% of electricity demand	10.0	Hydropower already covers ≥100% of demand, region is net exporter
A – Social & cultural acceptance	8.0	High public support for renewables; largely positive perception of solar and wind, with localised conflicts only	4.0	Mixed attitudes; hydropower historically accepted, but growing opposition due to ecological impacts
C – Practical compatibility	7.0	Good land availability for solar/wind; some grid and landuse constraints	4.0	Steep terrain, flood risk, high biodiversity and protected areas; grid and access limitations

From these component scores we compute:

- Integration Score **I**
  - Andalusia: $I = (3.0 + 6.8 + 8.0 + 7.0)/4 = 6.20$
  - Rize: $I = (3.0 + 10.0 + 4.0 + 4.0)/4 = 5.25$
- Status Score **X**
  - Andalusia: $X = (3.0 + 6.8)/2 = 4.9$
  - Rize: $X = (3.0 + 10.0)/2 = 6.5$
- Future Feasibility Score **Y**
  - Andalusia: $Y = (8.0 + 7.0)/2 = 7.5$
  - Rize: $Y = (4.0 + 4.0)/2 = 4.0$

These results imply:

- Rize (6.5/4.0) **–** strong current technical status due to high hydropower share, but limited feasibility for further expansion because of environmental constraints, contested hydropower projects and lack of alternative resources. Rize can be characterised as a "saturated hydro region".
- Andalusia (4.9/7.5) – moderate current status, as renewables do not yet fully cover demand, but very favourable conditions for future expansion of solar and wind, supported by policies and social acceptance. Andalusia can be seen as a "rising solar wind region".

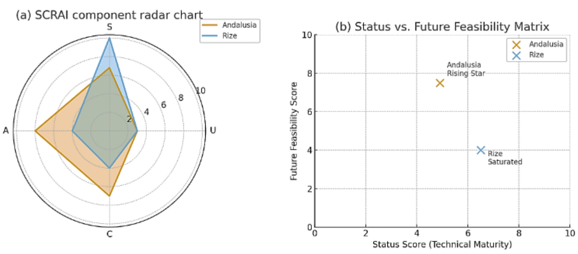

Fig. 6. (a) Radar chart of the four SCRAI components (U, S, A, C) for Andalusia and Rize; (b) "Status vs. Future Feasibility" matrix plotting Andalusia and Rize in X–Y space, visually distinguishing the saturated and rising-star profiles

Technical Pathways under Different Resource Endowments

The comparison between Andalusia and Rize demonstrates how regional resource endowments strongly influence renewable energy pathways. Andalusia's high solar irradiance and favourable wind corridors naturally support large-scale PV and wind deployment, while biomass and hydropower play balancing and niche roles. Rize's mountainous terrain, abundant precipitation and narrow valleys, by contrast, are optimally suited to hydropower, but unsuitable for extensive wind or ground-mounted solar fields.

Yet resource endowment alone does not explain the full picture. Andalusia's substantial unused solar and wind potential is constrained by grid bottlenecks, land-use conflicts and regulatory processes. Rize's hydropower potential faces a different set of constraints: ecological sensitivity, flood risks and the spatial concentration of projects in environmentally fragile valleys.

SocioCultural Acceptance and Territorial Compatibility

The SCRAI framework unpacks these differences in a structured way. The social acceptance literature emphasises that renewable energy projects are embedded in multi-level contexts, involving socio-political, community and market acceptance. European case studies show that local acceptance improves when communities perceive tangible benefits, fair procedures and consistency with local identity [25].

In this light, Andalusia's high score for social acceptance (A = 8.0) and practical compatibility (C = 7.0) reflect:

- a generally positive public discourse around renewables, embedded in national and EU decarbonisation strategies;
- visible economic benefits (jobs, investment) from solar and wind projects;
- a landscape where large-scale projects can often be sited away from densely populated areas, albeit with localised conflicts.

Rize, conversely, shows lower acceptance (A = 4.0) and compatibility (C = 4.0), despite hydropower being historically central to regional development. Ethnographic and political ecology studies in the Eastern Black Sea region document conflicts over river regulation, concerns about landslides and floods, and perceptions of unequal distribution of benefits. In a narrow and ecologically rich landscape, the cumulative impact of multiple hydropower plants amplifies local opposition, even when national energy policy strongly promotes hydropower.

Policy Implications

The combined technical and socio-cultural assessment suggests differentiated policy priorities:

- For Andalusia:
  - Further exploit solar and wind potential by accelerating grid reinforcement and smart-grid deployment;

  - Streamline permitting procedures while maintaining environmental safeguards;
  - Promote storage (pumped hydro, batteries) and demand-side management to enhance system flexibility;
  - Use participatory planning to address local land-use conflicts and protect high-value ecosystems.
- For Rize:
  - Prioritise modernisation and efficiency improvements in existing hydropower plants, rather than extensive greenfield development;
  - Expand small-scale, low-impact options such as micro-hydro, rooftop PV and biomass from tea waste;
  - Strengthen environmental assessment and public participation processes to address conflicts;
  - Explore regional energy storage and grid solutions that enable better integration of flexible demand and local renewables.

The SCRAI's Status vs. Future Feasibility matrix provides a useful visual tool for policymakers: regions in the "high-status/low-future" quadrant (like Rize) require strategies for diversification and conflict mitigation, while those in the "medium-status/high-future" quadrant (like Andalusia) need to prioritise infrastructure and policy frameworks that unlock remaining potential [26].

Methodological Limitations and Transferability

The proposed SCRAI has several limitations:

- Component scores rely on expert judgement based on available reports and literature, rather than systematic surveys;
- The four dimensions are given equal weight, which may not reflect all stakeholders' priorities;
- Technical potential estimates, especially for Rize's hydropower, vary across sources, introducing uncertainty into utilisation metrics.

Nonetheless, the framework is intentionally simple and transparent. It can be replicated for other regions using publicly available data and qualitative assessments, and refined by incorporating survey-based measures of acceptance, more detailed GIS analyses of land-use constraints and additional indicators (e.g. institutional capacity, investment climate).

Conclusions

This paper has provided a comparative assessment of renewable energy potential, utilisation and socio-cultural adoption in Andalusia (Spain) and Rize (Turkey), combining detailed regional data with a novel Socio-Cultural Renewable Adoption Index (SCRAI).

The main conclusions are:

1. Contrasting resource driven pathways:
   * Andalusia is a solar wind region with high theoretical potential and a diversified renewable mix, yet with a substantial usage gap for solar, wind and biomass.
   * Rize is a hydropower region where renewables already cover or exceed local electricity demand, but where further large scale development faces strong environmental and social constraints.
2. Different dominance and diversification profiles:
   * In Andalusia, solar PV is dominant but embedded in a diversified system; the dominance index is moderate (~0.5–0.6).
   * In Rize, hydropower is overwhelmingly dominant ($D \approx 0.99$), making the system vulnerable to hydrological and socio-political risks.
3. Socio-cultural and territorial conditions matter:
   * The SCRAI reveals that Andalusia combines medium current status with high future feasibility (4.9/7.5), a "rising solar–wind region".
   * Rize combines high status with low future feasibility (6.5/4.0), a "saturated hydro region" requiring diversification and conflict mitigation.
4. Policy priorities differ accordingly:
   * Andalusia should focus on grid modernisation, storage deployment, and regulatory reforms to accelerate solar and wind development while managing land use conflicts.
   * Rize should prioritise optimisation of existing hydropower, promotion of small scale and low impact technologies, and strengthening of environmental and participatory governance.
5. Methodological contribution:

* The SCRAI offers a simple yet insightful tool to integrate technical and socio-cultural dimensions in regional energy planning and can be adapted to other regions with minimal data requirements.
* Future work should: (i) extend the analysis to more regions, covering a broader spectrum of resource types and socio-political settings; (ii) validate and refine SCRAI component scores through stakeholder surveys; and (iii) link SCRAI outcomes with quantitative energy system modelling and GIS-based spatial planning.

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