International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 12s,2025
https://theaspd.com/index.php

Methodology for assessing the feasibility of implementing energy communities through multi-dimensional territorial configurations

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***Abstract*–** *Energy communities constitute a promising mechanism for expediting an equitable, decarbonized energy transition. However, their deployment at a national scale is constrained by technological and environmental uncertainties, socio-economic asymmetries, and territorial heterogeneity, especially in off-grid or hard-to-reach regions where traditional planning instruments prove inadequate. This paper introduces an integrated five-stage methodology for systematically assessing at the national level the feasibility of energy community models, including collective distributed generation, microgrids, and shared self-consumption. Initially, a country-level conceptual framework elucidates definitions, nationwide success criteria, and spatial scope. Subsequently, variables identified at the national level across all pertinent dimensions are translated into indicators and metrics, and datasets, such as renewable resource maps, electricity-grid assets, demographic information, and regulatory records, are harmonized within a unified geographic information system. Thirdly, a multicriteria analysis employing Principal Component Analysis and hierarchical clustering delineates homogeneous territorial typologies and ranks implementation priorities. Fourthly, each zone undergoes a comprehensive technical, economic, social, and environmental assessment under alternative policy and incentive scenarios generated by a prospective modelling module. Finally, the methodology formulates governance guidelines, blended financing schemes, and phased implementation roadmaps that respect territorial diversity while ensuring scalability and community participation. The approach provides decision makers with a replicable toolbox for designing resilient, inclusive, and context-sensitive energy community programs at national and sub-national scales.*
***Keywords*–** *energy communities, feasibility assessment, geographic information systems, just energy transition, multivariable territorial analysis, national energy planning.*

INTRODUCTION

Energy transition and the decentralization of power systems represent global movements aimed at establishing sustainable, autonomous, and complementary energy frameworks. In this context, energy communities (EC) have emerged as a paradigm that fosters local renewable energy generation and optimizes consumption within a collective framework. An energy community is defined as a structured gathering of citizens, institutions, or local actors that collaborate in the production, management, and shared utilization of energy, typically derived from renewable sources, for social, environmental, and economic objectives. These communities implement strategies that aim to reduce dependence on fossil fuels, mitigate climate change, and improve resilience to energy crises. Furthermore, they advance technical solutions such as microgrids, shared self-consumption, and distributed storage, while advocating for the democratization of energy access through participatory governance frameworks and the equitable allocation of benefits.The rapid expansion of energy communities presents a complex challenge, impacting various aspects of the global energy sector. Despite their potential to revolutionize energy generation and consumption, a limited comprehension of their technological, social, environmental, economic, and regulatory impacts hinders the formulation of tools and strategies necessary for their adoption and integration into existing production and energy systems. A fundamental issue is the interconnection of energy communities with traditional electricity grids, which raises substantial concerns regarding transmission capacity and system stability. Ineffective energy management, low social acceptance, and uncoordinated governance schemes further constitute obstacles to their consolidation [1]. These challenges frequently originate from deficient planning, inadequate interconnection infrastructure, and the fragmented operation of energy systems that lack coordination mechanisms [2].

Moreover, the lack of systematic assessments regarding the technical feasibility of incorporating renewable technologies and energy-storage systems constrains the implementation of these solutions. The deficiency of dependable data on technological reliability escalates costs, exacerbates uncertainty, and erodes confidence in clean energy sources, thereby hindering their widespread adoption. Investments in non-conventional renewable energy sources (NCRES) encounter considerable challenges, including substantial initial costs, the underestimation of positive externalities, and the prevailing dominance of traditional technologies. Regulatory limitations and the challenges associated with obtaining reliable information also remain obstacles, exacerbated by a deficit of skilled human resources and an increased perception of risk associated with the adoption of novel technologies [3]. Addressing these challenges requires the implementation of enhanced educational and training programs, the provision of financial incentives, the development of streamlined and adaptive regulations, the improvement of information dissemination, and targeted assistance for small-scale investors. Additionally, social marketing strategies should be employed to generate interest in the deployment of NCRES. Currently, over 50% of the global population resides in urban areas, a proportion projected to increase to approximately 70% by the year 2050. This urban expansion presents significant challenges for metropolitan regions, particularly concerning housing, infrastructure, and sustainability. Approximately 1.1 billion individuals inhabit slums or similar conditions, and the United Nations forecasts indicate that this number may swell by an additional 2 billion within the next thirty years [4]. The absence of sustainable planning and development intensifies issues related to congestion, pollution, and the limited availability of public space. Consequently, this study seeks to evaluate the practicality of implementing energy communities that are predicated on multivariable territorial configurations. These configurations will incorporate technical, economic, sociocultural, environmental, and regulatory dimensions. The ultimate objective is to generate recommendations and action plans for the seamless integration of such communities into existing production and energy systems.

RELATED WORKS

In recent years, the establishment of energy communities has evolved as a strategic approach for facilitating the transition toward more sustainable, decentralized, and participatory paradigms of energy generation and consumption. These communities, encompassing integrated community energy systems, collective distributed generation, energy hubs, microgrids, and analogous configurations, aspire to harness local renewable resources, augment energy efficiency, and promote citizen engagement in decision-making [5][6]. In pursuit of facilitating the implementation of energy communities across various territorial configurations, numerous studies have suggested methodologies that integrate technical, economic, social, and policy variables. For instance, Mutani et al. [7] formulated indicators and visualization tools to evaluate the technical and economic feasibility of establishing an energy community in Villar Pellice, Italy, by integrating elements such as self-consumption and self-sufficiency. Similarly, Belmar et al. [8] constructed models of diverse types of energy communities grounded in varying consumption profiles, available technological systems, and mechanisms for energy exchange (such as peer-to-peer trading or collective self-consumption). An essential component resides in the multivariable characterization and systematic arrangement of data through Geographic Information Systems (GIS), which consolidate layers of information concerning renewable energy potential, existing infrastructure, and sociodemographic indicators [9]. Concurrently, Colombo et al. [10] underscored the significance of considering not only the technical feasibility, but also urban limitations and the prospects presented by public facilities. This approach aims to promote the engagement of diverse stakeholders and enhance the optimization of local energy utilization. In the context of zone prioritization, academic literature highlights methodologies such as Cluster Analysis and Principal Component Analysis (PCA) as effective tools for the classification of regions with analogous characteristics, facilitating the identification of areas exhibiting the greatest potential or urgency [11][12]. The utilization of scenario simulation through modeling platforms, such as Calliope, is equally crucial for the quantitative assessment of profitability, emission reductions, and the level of social acceptance. Furthermore, it is instrumental in evaluating the impact of regulatory or incentive structure modifications on the viability of an energy community [13]. Caramizarun & Uihlein [14] offered a comprehensive examination of the social and energy innovations that form the basis of such projects, whereas Candelise & Ruggeri [15] conducted an analysis of the various institutional frameworks and examined the involvement of citizens within the Italian context. Caputo et al. [16] advanced urban-scale energy planning methodologies that underpin the structuring of energy-community proposals within densely populated contexts, wherein constraints of space and the heterogeneity of stakeholders are pivotal determinants. The existing body of literature emphasizes the critical role of governance alongside citizen engagement. Rescoop [17] has curated numerous examples and practical guides pertinent to the establishment of energy communities in Europe, underscoring the importance of participatory processes and the concept of social legitimacy. Similarly, Gui et al. [18] investigated the integration of community microgrids within the framework of new institutional economics, emphasizing the necessity for adaptable legal structures and strong organizational advancement to secure the sustainability of these initiatives. Conversely, the adoption of a multicriteria approach has become indispensable for addressing the complexities inherent in the implementation of energy communities. Andrews et al. [19] introduced a methodological framework for decision-making in rural contexts, encompassing the selection of technology, evaluation of environmental implications, and consideration of sustained economic viability. Investigations conducted by Zhou et al. [20] and Moroni et al. [21] further substantiated this concept by employing spatial decision-making tools and taxonomies to delineate the principal dimensions: technical, economic, social, and environmental, integral to the definition of community energy projects. From a perspective of systems integration and optimization, Zhang et al. [22] elucidated the advantages of peer-to-peer energy trading within microgrids, highlighting that the deployment of effective exchange mechanisms is contingent upon technological infrastructure, regulatory support, and the social acceptance of stakeholders. Moreover, IRENA [23] emphasized the necessity for implementing specific policies and incentives aimed at scaling and replicating these initiatives across various regions, thereby enhancing their contribution to the global energy transition. In this context, there is a consensus on the necessity for an all-encompassing approach to evaluate the viability of energy communities. Consequently, it is essential to develop a method for assessing the feasibility of implementing such communities based on multicriteria territorial configurations. This method should be capable of identifying priority areas, simulating adaptive scenarios, and proposing inclusive governance strategies. It must integrate technical, economic, environmental, and social analyses while deeply understanding the regulatory and cultural factors that influence citizen participation and the joint management of energy resources. \

PROPOSED APPROACH

The proposal is structured as a five-phase methodological cycle: *Initial Diagnosis*, *Multidimensional Territorial Characterization, Territorial Prioritization and Delimitation, Integrated Evaluation and Scenario Design, and Roadmap with Adaptive Governance*, as it is represented in Fig 1. Upon completion, the outputs are reintegrated into the subsequent iteration. This approach recognizes that the formation of energy communities (ECs) transforms the foundational technical dimension (solar, wind, hydro, geothermal potential, storage options), economic dimension (CAPEX/OPEX, levelized cost of energy, tariffs), social dimension (population density, local governance, public acceptance, presence of armed groups), environmental dimension (carbon footprint, land use, protected areas), and regulatory dimension (licensing requirements, fiscal incentives). Consequently, each deployment alters the conditions that will sustain the following cycle of analysis and planning.

A. Initial Diagnosis

The initial phase involves a comprehensive examination of the prevailing regulatory framework and institutional arrangements within the study area. This examination encompasses sectoral legislation, regulatory mandates, tariff directives, and incentive schemes. The outcomes of this review are encapsulated in a Regulatory Maturity Index (*RMI*), which is constructed from four components:

- Clarity of norms *(C)*
- Temporal stability *(E)*
- Citizen participation mechanisms *(P)*
- Level of enforcement *(L)*

Each constituent is assigned a weighting factor W_i, derived through a multicriteria decision-making approach endorsed by regional stakeholders. Subsequently, the comprehensive *RMI* is computed as the weighted summation of these four constituents:

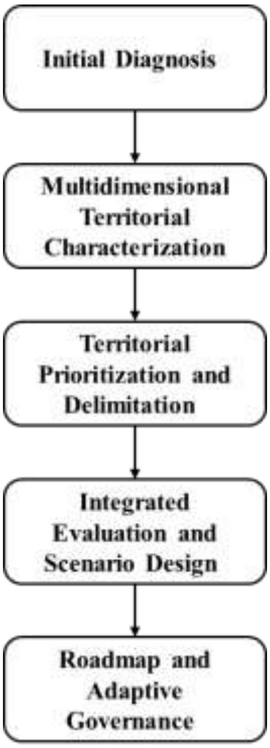

Fig 1. Method for Evaluation of Energy Communities.

$$RMI = W_1C + W_2E + W_3P + W_4L$$

The literature indicates that *RMI* values exceeding 0.7, as attained in various EU jurisdictions pursuant to Directive 2019/944 [24], are associated with markedly higher success rates in the establishment of energy communities [25]. In conjunction with this legal evaluation, quantitative goals are established, such as the proportion of local demand to be satisfied or the reductions in tCO_2, while principal stakeholders are identified according to their degrees of interest and influence. These three components, the regulatory framework, targets, and actors, collectively constitute the “context draft,” which finalizes the Initial Diagnosis phase.

B. Multidimensional Territorial Characterization

The subsequent phase involves the formulation of a geospatial atlas that amalgamates the five identified dimensions within a Geographic Information System (GIS), encompassing technical, economic, environmental, social, and regulatory data. Pertaining to renewable resources, encompassing global horizontal irradiance, reanalyzed anemometric data, and specific flow rates, satellite-derived time series are transformed into spatial percentiles with a granularity of between one and five kilometers. The representation of electrical infrastructure is characterized by the projected carrying capacity of the network, defined as the permissible power margin that does not infringe upon thermal or stability thresholds, as well as the calculated proximity to extant substations, which are georeferenced utilizing network operators' cartographic resources. The socioeconomic component comprises population density, mean income, and an *Energy Poverty Index* derived in accordance with the methodology delineated by Halkos & Aslanidis [26]. In contrast, environmental variables encompass the carbon footprint of the foundational matrix and the nearness to regions that are either protected or exhibit high levels of biodiversity [23]. Finally, licensing requirements, power limits for self-generation and the existence of tax incentives are coded.Key territorial data prove essential irrespective of scale or context. In Latin America, for instance, the distribution and location of Indigenous populations or, in certain areas, armed factions significantly impact governance, security, and social integration. In the Amazonian and Andean regions, high concentrations of Indigenous communities necessitate free, prior, and informed consultation protocols in addition to culturally respectful criteria. In rural areas or border zones historically plagued by violence, an analysis of security risks is imperative, and mitigation strategies must be developed. Integrating renewable-potential maps with demographic and conflict-risk data results in a more comprehensive territorial assessment, facilitating the formulation of technology solutions, financial models, participatory methods, and governance structures that are aligned with each locality's specific circumstances.

C. Territorial Prioritization and Delimitation

The identification of viable zones for energy communities is initiated through the Analytic Hierarchy Process (AHP), which allocates relative weights to technical, economic, environmental, and social criteria. A panel comprising experts from institutional, academic, and community sectors constructs a pairwise comparison matrix, subsequently validating a consistency ratio below 0.1. This ensures coherent judgments and results in a priority vector being employed in all ensuing stages.

Example criteria include:

- **Technical feasibility:** average irradiance above 4.5 kWh/m^2/day or wind speed over 5 m/s [27].
- **Energy poverty index:** areas where more than 30 % of households have limited or insecure access.
- **Proximity to electricity infrastructure:** within 2 km of a substation [27].
- **Low environmental pressure:** outside protected areas and on slopes under 15° [27].

Upon determination of the AHP weights, the spatial evaluation proceeds through five stages as adapted from Bernal-del Rio et al. [27]:

1. **Criteria tree construction.** Assembly of an exhaustive inventory of variables, categorized into technical, economic, environmental, and social dimensions. These variables are to be organized hierarchically into three levels: objectives, global criteria, and specific variables. Experts are responsible for completing the Analytic Hierarchy Process (AHP) matrix, ensuring that any variable possessing a final weight below 5% is excluded. The resulting weights from this process are then forwarded to the GIS processing phase.
2. **Data layering.** Transform each selected variable into a raster or vector layer within a GIS, utilizing authoritative sources such as the IGAC, USGS, Global Solar Atlas, etc. Reformat and standardize all inputs to ensure spatial consistency.
3. **Spatial processing.** For criteria dependent on location, it is essential to compute the Euclidean distances to benchmark features such as rivers, roads, transmission lines, and forests. Subsequently, each layer should be reclassified according to a difficulty scale ranging from 1 to 3, ensuring their alignment to a uniform resolution.
4. **Weighted Overlay scenarios.** Integrate the reclassified layers by employing the AHP-derived weights through the application of the GIS Weighted Overlay tool. Produce an array of suitability grids, including those with social prioritization, economic prioritization, as well as balanced scenarios, while ensuring that the aggregate of the weights collectively equals 100%.
5. **Candidate zone identification.** Aggregate cells designated as "highly suitable" into prospective polygons. Subsequently, intersect these polygons with supplementary social indicators (energy poverty index, population density, local governance) to ensure their concordance with just-transition objectives.

Most quantitative and qualitative data is derived from authoritative government studies, household energy consumption surveys, socioeconomic censuses, and perception matrices, which are supplemented by georeferenced GIS layers that include renewable resources, electrical network infrastructure, land-use classifications, and documentation of armed or criminal group activity. The integration of these high-resolution datasets guarantees that the prioritization phase is grounded in reliable evidence and offers the analytical depth required for effective, context-sensitive community energy planning.

D. Integrated Evaluation and Scenario Design

For the prioritized territories, a comprehensive evaluation is undertaken, integrating techno-economic modeling, social valuation, and environmental analysis, all within the parameters of the existing regulatory framework.The optimal sizing of generation storage systems is determined using multiperiod solvers such as *HOMER Pro* or *Calliope*, aiming to minimize the Levelized Cost of Energy (*LCOE*) while maximizing resilience, understood as the system's recovery time after major failures. The LCOE is calculated as the ratio of the total life cycle cost (*TLCC*) times the capital recovery factor (*CRF*) to the total energy produced over the system's lifetime [27]:

$$LCOE = \frac{TLCC \times CRF}{E_{ca}}$$

where *TLCC* is the total life cycle cost (in USD), *CRF* is the capital recovery factor, and E_{ca} is the total energy delivered over the system's lifetime [28].

In parallel, the Net Present Value (*NPV*) is computed using a social discount rate aligned with World Bank guidelines:

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t}$$

where CF_t is the cash flow in year t, and r is the social discount rate [29].

In conjunction with technical and financial modeling, a social assessment is performed utilizing surveys and focus groups to evaluate two principal indicators:

- An Index of Social Participation, predicated upon the frequency of workshop attendance and engagement in decision-making processes.
- A Technology Acceptance Scale, demonstrating Cronbach's alpha reliability coefficient of 0.87 [24].

The environmental dimension encompasses the evaluation of greenhouse gas (GHG) emission reductions by utilizing national emission factors, accompanied by the assessment of land utilization per unit of energy produced. These data inputs facilitate the development of three distinct scenarios:

1. Baseline – assumes market prices without incentives.
2. Regulatory Incentives – includes premium tariffs for surplus injection and tax exemptions.
3. Soft Credit – assumes capital costs are financed at a preferential 3% annual interest rate, with a five-year grace period.

The results are evaluated through the application of multidimensional radar charts and cost-benefit matrices quantified in **USD per incremental IPS point**. This methodological approach facilitates the identification of configurations that provide concurrent enhancements across economic, social, and environmental dimensions.

E. Roadmap and Adaptive Governance

The concluding phase of the initiative articulates the outcomes into a structured action plan. In the immediate short-term, spanning the initial two years, pilot projects are to be executed, secondary regulations refined, and public awareness campaigns initiated to facilitate the consolidation of social acceptance. In the medium-term timeframe, extending from two to five years, the objective is to scale efficacious solutions through the establishment of a national technical–financial assistance platform that interlinks public institutions, development banks, and community organizations. Ultimately, in a timeframe extending beyond five years, the objective is to incorporate ECs into the national goals for decarbonization and universal energy access. This integration is to be underpinned by a stable regulatory framework that encompasses metrics that ensure equity and transparency. Responsibilities are codified within an Actor–Function Matrix, wherein the governmental bodies, private sector entities, community groups, and academic institutions assume commitments to regulation, financing, operation, and training functions, respectively. The monitoring process is predicated upon four principal indicators: the number of operational communities, the total installed megawatts, the diminution in energy poverty as quantified by a reference index, and the progression of the Social Participation Index (SPI). Annually, data collection prompts an update to the geospatial atlas, thereby initiating a new methodological cycle and corresponding revisions to the Regulatory Maturity Index (RMI) and quantitative objectives.

CONCLUSIONS

The article introduces an iterative and multidimensional methodological framework purposed to systematically evaluate, prioritize, and advance community energy (CE) initiatives in a manner that is adapted to territorial contexts. The five-phase cycle, comprising initial diagnosis, geospatial characterization, hierarchical delimitation and prioritization, integrated evaluation with scenarios, and roadmap with adaptive governance, illustrates that the success of CE projects relies not solely on physical and technical characteristics but also on regulatory maturity, social acceptance, and institutional resilience.The findings substantiate, firstly, that the development of a Regulatory Maturity Index (RMI) serves as a synthetic and comparative metric that facilitates the anticipation of the viability of community initiatives: regions with RMI scores ≥ 0.7 demonstrate a higher propensity for project implementation, whereas lower scores expose legal or participatory constraints that necessitate resolution prior to scaling interventions. Secondly, the integration of AHP and GIS workflows, as adapted from Bernal-del Río et al. [27], is demonstrated to be efficacious in the translation of expert evaluations into reproducible suitability maps. The inclusion of vital socio-political variables, such as the existence of Indigenous communities or the risks associated with armed conflict, expands the conventional notion of renewable resource suitability toward a just transition perspective. The techno-economic analysis, augmented by social and environmental metrics, indicates that the implementation of regulatory incentives and accessible credit lines has the potential to decrease the Levelized Cost of Energy (LCOE) by as much as 18% and to reduce the payback period to less than eight years, while concurrently enhancing the Social Participation Index. Nonetheless, the simulations caution financial enhancements may become ineffectual in regions lacking robust democratic governance structures. Consequently, institutional training and support strategies are considered equally vital as technical optimization. The structured roadmap delineates the way annual iterations via updates to the geospatial atlas and RMI facilitate the swift incorporation of acquired insights, adaptation to regulatory modifications, and alignment with national decarbonization objectives. This iterative feedback mechanism transforms the framework into a dynamic instrument, capable of perpetuating an ongoing process of enhancement and expansion of CE initiatives. The study identifies several limitations, particularly the reliance on high-resolution data and GIS expertise, which may not be readily available in smaller municipalities. It suggests that future research should investigate methodologies for expeditious participatory assessment as well as the implementation of downscaling techniques applicable to open data. Furthermore, the current model exhibits limited integration of gender equity metrics and local employment impacts, indicating a significant avenue for future advancements.

ACKNOWLEDGEMENT

This research has been developed in the framework of the project “Energy Community Configuration in the Colombian Territory Considering Technological, Environmental, Social, Legal, and Economic Aspects,” code 1231-12310062023 (short title: “Integrated Energy Communities”), supported by Universidad EAFIT.

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