Universidad del Rosario | Escuela de Ingeniería, Ciencia y Tecnología

Comprehensive Overview of Solar Energy Communities in Colombia

Submitted in fulfillment of the requirements for the degree of

Energy Systems Engineering

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ABSTRACT

This study focuses on the design, feasibility, and systemic behavior of solar energy communities in Colombia, using a system dynamics approach to explore the conditions under which these initiatives can thrive. Through the construction of causal loop diagrams and stock-and-flow models, the research identifies dominant feedback loops and systemic leverage points that influence the long-term sustainability of these communities. A web-based tool was developed to assess financial viability by calculating key indicators such as CAPEX, OPEX, ROI, payback period, and the levelized cost of electricity, under both private and public funding scenarios.

The findings reveal that while energy communities are viable in Colombia, their success is highly sensitive to external incentives and structural conditions. The study contributes to the existing literature by integrating dynamic systems modeling with economic evaluation, offering practical insights for Colombian policymakers, community leaders, and public institutions. It also provides a methodological foundation for future research focused on regulatory design, participatory planning, and long-term project resilience in the Colombian energy transition.

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INTRODUCTION

Historically, a small group of enterprises and government agencies have controlled the electricity sector [1]. However, the landscape of the power industry is rapidly evolving [2]. New actors—such as Energy Communities (*ECs*)—are becoming increasingly relevant, driven by the rise of Non-Conventional Sources of Renewable Energy (*NC-SREs*) [3]. These technologies have enabled more decentralized and environmentally conscious energy generation models, reshaping how energy is produced, distributed, and consumed [3]. In Colombia, the concept of ECs has gained increasing attention, especially in non-interconnected and rural zones. A national initiative led by the Ministry of Mines and Energy, in coordination with the Non-Conventional Energy and Efficient Energy Management Fund (FENOGE) and the Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones (IPSE), has promoted the creation and official registration of ECs across the country [4].

Although similar ideas arose in the 1970s with the Alternative Technology movement and the promotion of "*soft energy paths*" [3], interest in decentralized energy models has reemerged in recent years, particularly since the establishment of the Sustainable Development Goals (*SDGs*) in 2015 [5]. Still, there is no universally accepted definition of an Energy Community (*EC*). Most authors agree it refers to a geographically bound community [6] where members collectively manage and benefit from local energy initiatives, often through a shared economy [3].

Europe has led the way in implementing *ECs*, propelled by environmental priorities, high energy prices, and supportive policy frameworks. Countries like Germany and Spain have developed robust regulatory structures and incentive schemes to foster *ECs* [7]. In the Americas, the landscape varies: while parts of North America have a long tradition of community-managed energy systems [8], other regions—like Brazil—are experiencing a more recent emergence of impactful initiatives such as **REVOLUSOLAR**, which brings solar energy to marginalized neighborhoods in Rio de Janeiro [9].

In Colombia, the concept of *ECs* has gained increasing attention, especially in non-interconnected and rural zones. A national initiative led by the Ministry of Mines and Energy, in coordination with the Non-Conventional Energy and Efficient Energy Management Fund

(*FENOGE*) and the Institute for Planning and Promotion of Energy Solutions for Non-Interconnected Zones (*IPSE*), has promoted the creation and official registration of *ECs* across the country. In the first application phase, which closed in April 2024, over 18,000 communities registered, with a governmental goal of establishing at least 3,000 operational *ECs* by 2026 [4]. This document focuses specifically on solar energy-based *ECs* as most of these initiatives are expected to rely primarily on photovoltaic (*PV*) systems, currently the fastest-growing *NC-SREs* technology [11]. However, some may also incorporate other renewable energy alternatives, such as small hydropower plants, wind, biomass, or geothermal energy [12].

Despite this policy momentum, there is still a lack of accessible tools and methods for communities and decision-makers to evaluate the technical and economic feasibility of such initiatives [13]. Few studies in Latin America have incorporated a systemic perspective to analyze how social trust, adoption dynamics, and regulatory barriers influence the long-term success of *EC* [14].

This research seeks to address these gaps by exploring the case of solar electric-powered *ECs* in Colombia through two main research objectives. Research Objective 1: Apply a system dynamics methodology to better understand the long-term behavior of *ECs*.

- Task 1. The first step involves the development of a causal loop diagram to conceptualize the key relationships, feedback mechanisms, and behavioral patterns governing the implementation of *ECs*. This qualitative structure identifies the systemic leverage points, which represent variables or connections where strategic interventions could have the greatest impact on the system's evolution and stability.
- Task 2. Building on the causal structure, a stock-and-flow model was developed to enable the quantitative simulation of *EC* dynamics over time. Three prospective scenarios were designed to evaluate the impacts of different intervention strategies under varying conditions. These simulations aim to support informed decision-making in complex environments and to identify the structural and dynamic variables that most influence the long-term endurance of *ECs* at the local scale.

Research Objective 2: Develop a web-based tool to estimate key technical and financial indicators (*CAPEX*, *OPEX*, energy generation, and *ROI*).

By completing these research objectives, this study aims to contribute both as a practical instrument for project design and as a resource for understanding how *ECs* can reshape Colombia's electricity landscape in the coming years.

OBJECTIVES

1.1 General Objective

Develop an analytical and practical framework for the comprehensive assessment of energy communities in Colombia, using system dynamics, scenario simulation, and techno-financial tools, to identify critical conditions for their viability and guide their implementation in real-world contexts.

1.2 Specific Objectives

I. Conduct a systemic analysis of energy communities by identifying feedback loops, dominant structures, and leverage points, using the system dynamics methodology.

II. Design and simulate a System Dynamics model that represents the behavior of energy communities under various implementation scenarios, to identify trend patterns and success conditions.

III. Develop a techno-financial evaluation application to estimate the feasibility of implementing specific energy communities, considering the particularities of the Colombian context.

PROBLEM AND JUSTIFICATION

Despite global efforts toward achieving the *SDGs*, progress remains insufficient [15]. Goal Seven—Affordable and Clean Energy—is far from being met [15]. Therefore, international cooperation is increasing to address the projected 660 million people who will still lack electricity access by 2030, according to the 2023 Sustainable Development Goals Report [15].

As greater access and reduced carbon emissions become the main drivers of current energy demands, a new concept has emerged: the energy transition [16]. This transition is largely driven by the adoption of *NC-SREs* and the implementation of energy efficiency measures. It represents not only a technological shift but also a structural transformation aimed at decarbonizing the economy while ensuring fair access to clean energy [16].

Within this context, *ECs* help address these challenges. First, they primarily rely on *NC-SREs* to generate electricity [5]. Additionally, because they operate at the local community level, the generation point is geographically close to the consumption point. There is theoretically no need for high-voltage transmission systems or extensive complementary infrastructure, which significantly increases grid efficiency and reduces energy losses [16].

Because of the clear benefits associated with these initiatives, *ECs* are expanding globally, with varying levels of development depending on the country. Germany and Denmark stand out as pioneers, with well-established models and strong citizen participation, particularly in wind energy [16]. In countries like the United Kingdom and Spain, the focus is on energy efficiency and the promotion of *PV* projects [15]. France has only recently adopted these models, while the United States is experiencing rapid growth in community solar initiatives [16]. This diversity of approaches highlights how *ECs* are becoming a key tool in the transition toward more decentralized, sustainable, and participatory energy systems.

Colombia has progressively incorporated *ECs* into its just energy transition policy, recognizing them as legitimate actors in the provision of public services, especially in the generation, commercialization, and efficient use of energy from *NC-SREs* [17].

Since Law 1715 of 2014, Colombia has progressively developed a legal and regulatory framework to support community participation in the energy sector. This effort was strengthened by Law 2099 of 2021 and Law 2294 of 2023, which formally recognizes *ECs* and makes them eligible for public funding and technical help. Decree 2236 of 2023 and Resolution 40509 of 2024, specify the *EC* institutional structure and the creation of the Single Registry of Energy Communities (*RCE*) to give priority to aid for vulnerable populations. Most recently, Resolution 101 072 of 2025 established the regulatory framework for integrating *ECs* into Colombia's National Energy System.

ECs are thus emerging as key platforms for democratizing energy, decentralizing its management, promoting territorial autonomy, and contributing to the social, economic, and environmental development of the country—especially in rural, ethnic, and post-conflict areas [18]. However, despite their numerous benefits, these initiatives can also fail easily if not carefully designed and supported [12]. Weak institutional capacity, lack of community engagement, poor technical planning, and insufficient long-term financing can lead to project abandonment [13].

THEORETICAL FRAMEWORK AND STATE-OF-THE-ART

1. Energy Communities

ECs respond to the current needs of decentralizing the electricity grid and reducing greenhouse gas emissions while simultaneously promoting social well-being among their members [5].

In Colombia, the National Development Plan 2022–2026 establishes that the *ECs* model will be formally defined and regulated to enable both natural and legal persons to participate in the electricity value chain. This participation will be facilitated by *NC-SREs*, renewable fuels, and distributed energy resources. Additionally, public funding will be available to support *ECs*, under the guidelines issued by the Ministry of Mines and Energy regarding the allocation, distribution, and targeting of these resources [16].

1.2 Types of Energy Communities

Traditionally, an *EC* is organized by following a bottom-up approach, where members of a place who perceive themselves as a community—a neighborhood or a building—have a latent interest in generating and managing their electricity supply [8]. Residents started this movement and primarily financed it, mainly in Australia, the United States, and Europe. Key motivations for this approach include:

- **Economic Motivations:** Lower electricity costs, increased efficiency, and income generation
- **Environmental Motivations:** Climate change mitigation and eco-friendly living
- **Political Motivations:** Energy independence
- **Social Motivations:** Community cohesion and local development

There can also be a top-down approach, in which the community members do not develop interest on their own. An external actor such as a development bank, a government, or a private entity instead leads the project [8]. Key motivations for this approach include:

- **Quality of Life Motivations:** Expanding energy access and reducing energy poverty
- **Socio-Economic Motivations:** Promoting education and job creation in vulnerable areas
- **Safety Motivations:** Preventing illegal connections and fostering safer neighborhoods.
- **Social Justice Motivations:** Supporting energy decarbonization and energy justice.

Besides the distinction mentioned above, *ECs* may also distribute energy differently. For example, only some community members can generate electricity and produce a surplus (i.e., their generation exceeds consumption). These members can sell the excess energy at a lower price than the traditional market or share it with another property within the community, a model known as a mixed *EC* [17].

An *EC* may also aggregate all members' total demand and consumption, resulting in a jointly positive or negative energy balance. Here, during periods of high generation, they can sell the surplus energy to the grid, and during times of scarcity, they can purchase additional energy. This model requires connecting the *EC* to the local grid and is known as a homogeneous *EC* [19].

Finally, an *EC* can also be self-sufficient, meaning its collective generation consistently exceeds the demand of its members, eliminating the need for external energy sources or connections to the grid.

1.3 Benefits Associated with Energy Communities

There are various reasons *ECs* are gaining significant interest worldwide; however, much of this rapid development is because of their numerous benefits.

ECs provide significant social, economic, and environmental benefits. For instance, projects based on *NC-SREs* generate local employment, offering direct economic value to the community. At the local level, improved electrical infrastructure enhances system resilience by reducing dependence on external providers and minimizing service disruptions [19]. Benefits also extend to technological and regulatory innovation.

It is also important to note that these advantages come with certain needs. For example, the deployment of smart electricity meters is essential to enable accurate measurement of the energy generated (and sold) or purchased from the grid. Additionally, tools that foster citizen participation are needed.

1.4 Challenges Associated with Energy Communities

In the initial stages, *ECs* often face a lack of technical expertise and organizational capacity, relying heavily on volunteers and lacking access to professional support [20]. This situation is worsened by the absence of legal recognition in national legislation, which limits their ability to formalize operations and secure institutional support. Additionally, many new initiatives operate in isolation, without links to intermediary organizations or translocal networks that could provide essential knowledge, strategic guidance, and governance models.

Over time, *ECs* encounter structural and systemic barriers, particularly due to the dominance of incumbent actors in the energy sector [20]. Despite their growth, these communities are still not widely perceived as professional or trustworthy by governments, grid operators, and industry players. Many rely on policy incentives that, when withdrawn or replaced by market mechanisms, undermine the financial viability of their projects. Finally, some critics argue that *ECs* have been co-opted as policy tools, used to generate local support for large-scale renewable projects without addressing deeper issues of equity and participation.

2. Regulation

2.1 In Colombia

The success of the *ECs* depends on several technical and economic factors. Still, it also depends on the regulations of the territory where the project is located. In Colombia, because of the high interest generated by this type of initiative, the government of Gustavo Petro has accelerated legislation on the subject, which appears to be entirely in line with its government plan for a "just energy transition" [16].

ECs are defined under Colombian regulation as organized communities established through agreements between natural and/or legal persons—whether public or private entities—that cooperate through contracts or associative arrangements to engage in activities such as energy generation, commercialization, and efficient energy use [21]. These activities must be based on *NCRES*, renewable fuels, and distributed energy resources, in accordance with Article 2.2.9.1.2 of Decree No. 2236 of 2023. This decree also introduces the key concepts and new legal structures that enable the creation of multiple *ECs* across the national territory. In this document, the following are established:

- Collective Self-Generation (by its initials in Spanish: *AGRC*): An activity in which energy production is intended, in principle, for its consumption. However, if surpluses are generated, they can be sold to the electricity grid on the terms provided by the Energy and Gas Regulatory Commission (*CREG*) for this purpose [21].
- Collective self-generator (by its initials in Spanish: *CA*): Potential or current users who are constituted as an *EC* and wish to develop the activity of *AGRC*.
- Collective Distributed Generation (by its initials in Spanish: *GDC*): An activity that enables the production of electricity by the *EC* in locations close to consumption centers, allowing the community to sell its generated power to the local distribution network, as outlined in the technical concepts established by Decree 2236.

In addition, specific key terms were established, such as Vulnerability Conditions, Subsistence Consumption, Energy Demand of the Members of the Energy Community, Exported Energy, Surplus, Maximum Power Limit (5 MW in urban and rural areas for the AGRC and GDC according to UPME resolution 000501 of 2024 [21]), Microgrid, and Local Distribution System.

It is also worth mentioning that Article 2.2.9.2.1 specifies that *ECs* may receive public resources through the targeting criteria established by the Ministry of Mines and Energy. It is also key that the infrastructure financed with public money may be ceded or transferred to the communities.

Following the publication of this decree, the *CREG* drafted Resolution No. 701 051 of 2024, which outlines the technical criteria to be considered when establishing *ECs* in Colombia. All natural and legal persons who are part of an *EC* will be subject to the rights and obligations established in *CREG* Resolution 108 of 1997, as well as all applicable legislation related to user protection. Additionally, a special legal status may apply when an *EC* is formed through the self-governing structures of Indigenous peoples or communities, including peasant, Black, Afro-Colombian, Raizal (Afro-Caribbean), and Palenquero (descendants of African slaves) populations. In such cases, the *EC* is recognized as a *CEEP* and is granted additional benefits [23].

It is worth mentioning that everything established by Draft Resolution 701 051 of 2024 and (technical conditions and economic remuneration) will not be dealt with in this document, since it is an administrative act that is not yet firm and is open to changes and comments. Therefore, the final version may differ from the now-known document.

It is also important to mention the *CREG* Resolution 101 072 of 2025, which establishes the regulatory framework for *ECs* in Colombia, promoting collective self-generation and enabling their integration into the national power grid. It defines key concepts such as collective self-generators and energy agreements among community members. The resolution also states that any surplus energy delivered to the grid will be compensated based on agreements between *ECs* and the service provider, fostering flexibility and the development of distributed generation models [24].

2.1 In Europe

The European continent is a pioneer in implementing and managing *ECs*. Therefore, exploring the common regulatory framework for Europe and the different national implementation by countries is essential.

With the 2015 launch of the Energy Union Package (*EUP*), the *ECs* acquired continent-wide momentum. This document emphasizes the importance of incorporating innovative options into the electricity generation matrix through a "*smart energy system*" that empowers consumers [7]. Subsequently, in 2019, the second version of the *EUP* was introduced, this time called the Clean Energy for All Europeans Package, more commonly known as the Clean Energy Package (*CEP*) [7].

Seven documents published by the *CEP* introduce new players, activities, rights, and obligations to the electricity generation sector, such as citizen energy communities (*CECs*), renewable energy communities (*RECs*), active consumers (*ACs*), jointly acting renewable self-consumers (*JARSCs*), and renewable self-consumers (*RECs*). Of particular interest is the fact that, in the *CEP, ECs* do not have to generate energy through *NC-SREs* and can use fossil fuels to meet their electricity needs.

Although the same legislative bases were established throughout Europe in some countries, such as Ireland, Spain, and Germany*, ECs* were effective. In contrast, it did not work out in other places, such as Poland, Bulgaria, and Latvia [7].

Germany

ECs have thrived in Germany largely due to strong civic engagement, supportive legal frameworks, and a long-standing culture of cooperative organization. These initiatives often emerge as citizen-led responses to dissatisfaction with traditional energy providers, as illustrated by the iconic case of Schönau, where residents took control of the electricity grid after the Chernobyl disaster [13]. The cooperative model—valued for its transparency and equitable governance—has enabled communities to organize around renewable energy production and, increasingly, local grid ownership. Urban *ECs,* despite facing higher regulatory and financial barriers, have adapted by positioning themselves as knowledge hubs and intermediaries among stakeholders [13]. Moreover, the growing public commitment to climate goals has created fertile ground for innovations like thermal *ECs* and shared electricity storage systems, reinforcing the collective momentum behind Germany's decentralized energy transition.

Bulgaria

ECs initiatives in Bulgaria have not gained significant traction due to a combination of legal, institutional, and structural barriers. Although the country has strong renewable energy potential and growing public interest in environmental issues, there is currently no formal legal definition of *ECs*, which creates uncertainty for collective action [25]. Existing references to *ECs* in national policy documents remain largely conceptual and lack implementation mechanisms. Additionally, economic incentives have diminished—notably, the feed-in tariff scheme that once stimulated solar investment became ineffective after 2012, offering little motivation for new projects. Most renewable energy efforts remain privately driven, rather than community based. Further compounding the issue is the lack of technical expertise and professional motivation, with a shortage of skilled engineers and limited knowledge among architects and technicians.

3. System Dynamics

Initially developed by Jay W. Forrester at the Massachusetts Institute of Technology (*MIT*), System Dynamics (*SD*) is founded on the premise that complex problems cannot be fully understood through isolated events or superficial statistical correlations [26]. Instead, this method offers a structural and dynamic perspective to uncover the underlying causal relationships that generate behavioral patterns.

Building a Causal Loop Diagram (*CLD*) is the initial step in *SD* model development; this involves stocks (levels), flows (rates), auxiliary variables, influence connectors, and feedback loops [27]. Stocks represent accumulations, such as population, capital, resources, pollution, or knowledge, and constitute the system's memory as they retain the effects of past decisions. Flows regulate the rate at which stocks increase or decrease. Auxiliary variables help break down complex relationships into intermediate components, facilitating representation and analysis. Influence connectors indicate functional relationships between variables and support the tracing of causal structures.

Within this structural framework, feedback loops constitute the minimal unit capable of generating system behavior. A feedback loop arises when a sequence of causal relationships forms a closed circuit [28]. Two fundamental types of loops exist: reinforcing loops (positive) and balancing loops (negative). Reinforcing loops amplify changes in the direction they occur, producing exponential, accumulative, or collapse dynamics. Balancing loops stabilize the system by guiding it toward a goal or desired state.

Moreover, the behavior of a system emerges not merely from the presence of multiple feedback loops, but from the shifting dominance that each loop exerts under different structural or parametric conditions [29]. Loop dominance determines which feedback structure governs the system's behavior at a given moment, allowing for dynamic transitions over time. For instance, a reinforcing loop may initially drive exponential growth, but its influence can be moderated as a balancing loop becomes dominant in later stages. As Richardson states, “what matters dynamically is not the mere existence of a feedback loop but whether it is dominant—whether it is exerting a significant influence on behavior at a particular time” [29].

In smaller or simpler models, loop dominance can often be assessed intuitively through trial-and-error simulation—turning individual loops or links on and off. However, in larger or nonlinear systems, this approach becomes increasingly difficult and less reliable, necessitating the use of more rigorous analytical tools [30]. Richardson (1986) proposed a structure contribution approach, which focuses on evaluating how specific structural elements—such as a feedback loop—contribute to system behavior. If modifying or removing a loop causes a significant change in the system’s dynamics, that loop is considered dominant [30].

Within *SD*, leverage points are strategic elements where a small intervention can significantly change system behavior. According to Meadows [31], a leverage point is "a place within a complex system where a small shift in one thing can produce big changes in everything". Identifying them requires a deep understanding of systemic logic. Once located, leverage points enable the design of systemic intervention strategies.

Following *CLD* creation, a System Dynamics model (stock and flow diagram) is built; this diagram translates causal and accumulative system elements into simulation-ready visuals [27]. In these diagrams, stocks are represented as rectangles, flows as thick arrows with valves, auxiliaries as labeled circles or intermediate functions, and influences as unidirectional lines. This method allows the exploration of alternative scenarios resulting from applying different intervention strategies at the identified leverage points [26]. Simulation shows how system behavior varies under initial conditions, decision policies, or structural changes.

4. Economic Indicators

Implementing a thorough economic analysis is essential for assessing the financial viability, long-term profitability, and operational sustainability of *PV* energy projects used to power *ECs*. For instance, this process involves estimating Capital Expenditure (*CAPEX*), Operational Expenditure (*OPEX*), or projecting energy generation based on local solar resources, etc. To achieve the objectives of this study, a range of different economic indicators were used; each of them is explained below.

4.1 Capital Expenditure

CAPEX covers all initial costs for a PV project's operation. These include costs related to physical hardware (such as *PV* modules and inverters), the balance of the system (e.g., site preparation, installation, electrical infrastructure), and financial elements (including development costs and interest during construction) [32].

4.2 Operational Expenditure

OPEX refers to the annual costs associated with the operation and maintenance (*O&M*) of a *PV* plant throughout its lifespan. These expenditures cover both preventive and corrective maintenance activities, including cleaning, repairs, equipment replacement, system monitoring, insurance, and labor [33]. *OPEX* plays a crucial role in determining the economic and energy performance of a *PV* plant, affecting both its Levelized Cost of Electricity (*LCOE)* and Return on Investment (*ROI*).

Despite its growing importance, there is still a lack of standardization and technical consensus regarding what tasks should be included in an *O&M* protocol and how *OPEX* should be calculated [33]. Some sources estimate it as a percentage of the system's initial cost (ranging from 0.8% to 5% annually), while others express it in terms of $/kWp or as a percentage of the plant's energy production [33].

4.3 Return on Investment

ROI is a financial indicator that measures the profitability of an investment. In *PV* projects, *ROI* represents the ratio between the economic benefits obtained (such as electricity savings or revenues from energy sales) and the initial *CAPEX* investment in the system. The *ROI* of a *PV* project is influenced by various factors, including system type (distributed or utility-scale), geographic location, *O&M* quality, and the local regulatory framework. Since economic conditions vary across regions, *ROI* evaluation requires a multi-dimensional approach [34].

4.4 Pay-Back Period

The payback period is a frequently employed metric in investment project assessment. It measures the time required for an investment to recover its initial cost from the net cash inflows it generates. In simple terms, it answers the question: *"How long will it take for this project to pay for itself?"* [35].

4.5 The Levelized Cost of Electricity

The *LCOE* is a financial metric used to estimate the average cost of producing one kilowatt-hour (kWh) of electricity over the entire operational lifetime of an energy system. It is calculated using discounted cash flow methods, considering all capital (*CAPEX*), operational (*OPEX*), maintenance, and financing costs, as well as system performance and lifespan [36].

4.6 Social Return on Investment (SROI)

SROI is a methodological framework for measuring and communicating the social, environmental, and economic value created by a project, policy, intervention, or organization. Unlike traditional financial metrics such as *ROI*—which focus solely on monetary returns—*SROI* incorporates broader social impacts, aiming to quantify and monetize outcomes that typically fall outside conventional financial accounting [37].

METHODOLOGY

Causal Loop Diagram Construction

The first step in the methodological design comprised the development of a *CLD* to qualitatively explore the dynamic interactions governing the formation, operation, and long-term viability of *ECs*. This diagram was developed through an extensive review of relevant literature and expert consultations.

The causal structure captures key feedback mechanisms that explain how *ECs* based on *PV* systems evolve in response to technological, economic, institutional, and social factors. Variables were carefully selected to reflect operational, financial, and behavioral components. Arrows indicate the direction of causality, and polarity signs (+/-) represent the nature of the relationships (reinforcing or balancing).

Five core feedback loops were identified and labeled:

- **R1: Decentralized Generation Incentive Loop** — a reinforcing loop showing how decentralized *PV* generation reduces operational costs, creates the possibility of selling surplus energy into the grid, and enhances financial maintenance.
- **R2: Efficiency and Energy Sovereignty Loop** — a reinforcing loop where increased energy efficiency reduces transmission losses, further motivating the adoption of local energy models.
- **R3: Community Empowerment Loop** — a reinforcing loop highlighting how autonomy in managing *PV* infrastructure encourages community permanence and broader replication.
- **B1: Dependence Reduction Loop** — a balancing loop that describes how the emergence of *ECs* decreases dependency on the national grid.
- **B2: Procedural Complexity Loop** — a balancing loop capturing how regulatory and administrative burdens can delay or limit community adoption, despite growing interest.

This diagram served as the foundation for the subsequent development of stock-and-flow models, and the identification of leverage points and dominance.

Stock-and-Flow Model Construction and Simulation

Building upon the *CLD*, a stock-and-flow model was developed to transition from qualitative understanding to quantitative simulation. This model captures the structural complexity and feedback dynamics of ECs, enabling the exploration of system behavior over time under different policies and operational scenarios.

This model uses 49 endogenous variables, 3 state variables (stocks), and multiple auxiliary and constant parameters (See Annex 1 for the model's structure). Among them, 23 variables were designated as control levers to perform sensitivity analyses and scenario testing. These levers were selected based on their strategic role in influencing system feedback, such as financial stability, adoption dynamics, efficiency gains, and institutional interactions.

Key Model Components and Logic

- Stocks:

  - Energy communities: based on the net balance between community creation and community losses.
  - Interest in new energy communities: accumulates over time depending on perceived benefits and social feedback.
  - Revenue from surplus energy sale: accumulations based on the rate of energy injection into the grid and market price.
- Nonlinear Relationships and Saturation:

The model integrates sigmoidal (logistic) and saturation functions to represent decreasing returns and behavioral thresholds. For example:

  - Operational cost savings apply a saturation function to reflect decreasing marginal efficiency gains.
  - Dependence on the National Interconnected System (*SIN*) and financial stability of decentralized producers are modeled using logistic functions, capturing tipping point behaviors in response to economic incentives.
- Control Variables

The model includes sliders for 23 parameters, allowing experimental manipulation of factors, such as:

  - Electricity price, degree of saturation, training and technological adoption percentage, and effectiveness of policy incentives.
  - Sensitivities that influence cost savings and *SIN* dependency.
  - Rates of community creation/losses, surplus energy injection, and interest generation.
- Parameterization and Initial Conditions
  - Pre-planned initial values and parameter ranges enabled the simulation of various scenarios. For example, the initial number of *ECs* was set at 50, with a policy target of 500 by 2026.

- Simulation Setup
    - The simulation spans a period of 100 years (from year 0 to year 100), with a 0,0625-time step.
    - The model was implemented in Vensim using the Runge-Kutta 4 Auto integration technique.
- Validation Techniques
    - To validate the model and the underlying assumptions, several methods were applied following the recommendations of Barlas [37]. First, an empirical test was conducted with the guidance of a group of subject-matter experts, through which both the parameter values and the structure of the feedback loops were validated. Next, a dimensional consistency test was conducted directly within the Vensim environment to ensure that all equations-maintained coherence in their physical units. Finally, an extreme conditions test was performed to explore the model's behavior under boundary scenarios, thus helping to identify structural limitations and assess the model's robustness.

Purpose and Use

This model enables the assessment of:

- The long-term viability of *ECs* under different policy settings.
- The effectiveness of incentives and their influence on reinforcing and balancing loops.
- The identification of leverage points through sensitivity testing.

This modeling phase laid the groundwork for scenario development and policy experimentation.

Building a Web-Based Tool to Assess the Economic Feasibility of Solar Energy Communities

Besides the *SD* analysis, a web-based application was developed to support the validation of the economic feasibility of solar *ECs* in Colombia. Users such as policy makers or engaged citizens can estimate solar panel needs, *CAPEX*, *OPEX*, and financial indicators (cash flow, payback, *ROI*) using this tool (See Annex 2 for details).

The backend was developed in Python, where custom functions were implemented to calculate solar generation potential, cost structures, and economic projections over a 25-year period. To ensure realistic simulations, solar radiation data from NASA's database was integrated, allowing the tool to adapt estimations based on geographic location.

The front end was built using JavaScript, Leaflet.js, and Chart.js, offering a dynamic and user-friendly interface. Users can select locations on an interactive map, input household numbers and panel types, and immediately visualize outputs, such as required panel area, optimal tilt angle, and expected generation. The interface is enhanced with interactive charts and tailored design components using Bootstrap.

All components were organized following a modular file structure with dedicated folders for static assets, HTML templates, and Python scripts, ensuring maintainability and scalability for future improvements.

SYSTEMIC UNDERSTANDING OF SOLAR ENERGY COMMUNITIES

The constructed *CLD* is shown in Figure 1 (the detailed bibliography supporting the construction of each feedback loop is provided in Annex 1). The aim is to illustrate the community's ongoing interaction with various stakeholders and the influence of territorial regulations and context. This diagram serves not only as a visual synthesis of the system's structure but also as a platform for understanding the reinforcing and balancing feedback that governs the trajectory of *ECs*. The figure highlights how internal community dynamics—such as technological autonomy, operational cost reductions, and collective learning—interact with external pressures, including regulatory complexity and grid dependency. Including both reinforcing (R1, R2, R3) and balancing (B1, B2) loops reflect the coexistence of growth drivers and systemic constraints. These feedback structures form the analytical basis for identifying leverage points, assessing potential trade-offs, and exploring long-term stability.

Given the model's structure—multiple loops dedicated to a single topic—a detailed description of each loop is required.

R1: Surplus Sales and Financial Stability of Decentralized Generation

As decentralized solar energy generation increases, some of the produced electricity exceeds local consumption and is injected into the power grid (only if the community is connected). This surplus energy can be sold, generating additional income for *ECs*. These earnings improve the financial stability of decentralized systems, allowing operators to cover *O&M* costs. As financial security strengthens, confidence in decentralized energy models grows, encouraging more individuals and organizations to adopt them.

This loop focuses on the role of surplus energy sales in making decentralized solar generation more economically viable. These revenues maintain and stabilize existing systems, ensuring long-term feasibility. By covering *O&M* costs, communities and small producers can keep their energy systems running efficiently with a limited need for constant external support. The strength of this loop depends on receiving fair compensation for surplus energy, having regulatory clarity, and having sufficient grid integration capacity.

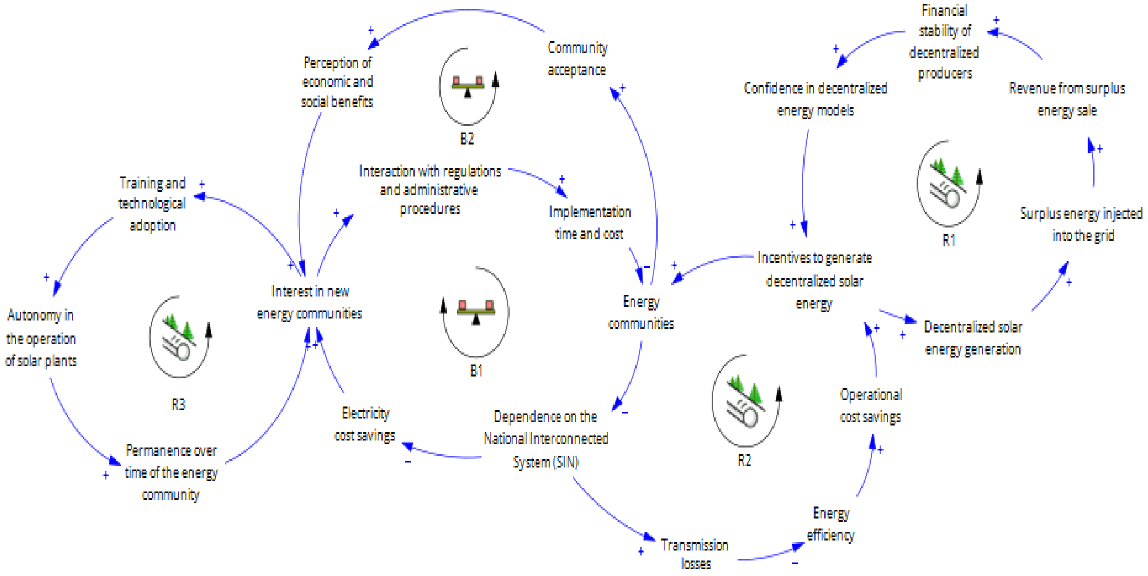


Figure 1. Causal Loop Diagram.

R2: Energy Efficiency and Reduction of Transmission Losses

The closer energy generation occurs to its point of consumption, the fewer transmission losses happen in the electrical grid. As decentralized solar generation expands, it reduces the energy that must travel long distances through transmission lines. This enhances the overall efficiency of the energy system, reducing operational costs and making decentralized generation even more financially viable.

This loop highlights a key advantage of decentralized energy production: improved system efficiency. By reducing transmission losses, more of the generated electricity is effectively used, decreasing the burden on the power grid. Lower transmission losses mean grid operators can allocate fewer resources to infrastructure maintenance and expansion. As energy efficiency improves, the economic attractiveness of decentralized *PV* projects increases, leading to broader adoption.

R3: Training and Technological Appropriation

Training in the operation and maintenance of solar plants enables *ECs* to manage their generation system. This strengthens their autonomy and supports their long-term continuity, encouraging the creation of similar initiatives in the future.

Technological appropriation is key to ensuring the long-term success of *ECs*. If members know how to operate and maintain the infrastructure, dependence on third parties is reduced, and local capacities are strengthened. This contributes to system stability and fosters the replicability of the model in other communities.

B1: Installed Capacity and Dependence on the SIN

The growth of *ECs'* installed capacity reduces their dependence on the *SIN*, generating savings in electricity costs for their members. This fosters interest in developing more *ECs*. However, interaction with regulations and maintenance costs may slow down this process.

Energy self-sufficiency is a determining factor in the expansion of *ECs*. Reducing dependence on external sources decreases long-term costs and improves the stability of the electricity supply. However, ensuring efficient operation involves facing regulatory and economic challenges. Simplifying regulations and providing access to financing mechanisms can accelerate the growth of this model, enabling broader and more effective adoption.

B2: Community Acceptance and Development of New Energy Communities

The expansion of *ECs* largely depends on the acceptance of residents. People's interest in developing new *ECs* increases as they perceive economic and social benefits. However, interaction with regulations and *O&M* costs can influence the speed at which these initiatives are consolidated.

This loop emphasizes the fundamental role of social perception in adopting community generation models. Suppose the population recognizes savings in energy costs, improvements in supply quality, and other collective benefits, such as job creation within the community. In that case, they will be more willing to promote similar new initiatives.

Dominance

Once the system's behavior is understood, a dominance analysis becomes necessary. The goal is to determine which loops substantially affect the system across different time periods. For example, the influence of variables such as social acceptance is crucial at the beginning of the project and may lose relevance during execution. This stage is also essential for understanding how the system evolves and how to prevent an undesired outcome.

The project comprised four phases: implementation, growth, maturity, and consolidation. Table 1 presents the findings.

System Phase	Dominance	Explanation	Secondary loops
Implementation	B2: Community acceptance and development of new *ECs*.	The perception of economic and social benefits determines the adoption of the model and further replication.	R3
Growth	B1: Expansion of *ECs*.	Key factors for new community creation include interest, regulation, and cost.	R2
Maturity	R1: Surplus sales and financial stability of decentralized generation	Financial stability and O*&M* cost coverage mechanisms ensure system continuity.	R3

Consolidation	R2: energy efficiency and reduction of transmission losses	Investing in new communities is justified by SIN's energy efficiency and potential for reduced losses.	R3

Table 1. System Dominance.

Leverage Points

It is now possible to identify each phase's key loops and leverage points (critical influence factors) for initial, success-assuring guidance.

- Perception of Benefits in the Community

The social acceptance of *ECs* is key to fostering these initiatives. If the residents perceive benefits (economic, social, environmental, or related to the energy supply itself), they will be more willing to participate in a related project. However, a lack of information and unfamiliarity with new technologies can limit model adoption.

Effective communication with the community is vital to overcoming these obstacles. Awareness campaigns highlighting the benefits of the decentralized generation can be beneficial; sharing the stories of individuals who have successfully participated in similar initiatives is also a good idea.

Explaining the precise set of benefits, such as reduced costs, the creation of local jobs, or the democratization of electricity, is crucial for the community's understanding and acceptance. Also, the residents' participation in the project is essential, as they need to feel a sense of ownership.

- Regulatory Framework and Surplus Energy Sales Tariffs

Energy policies and economic incentives are vital for the development and viability of *ECs*. A favorable framework can accelerate the growth rate of this model, whereas inadequate regulation can slow or even stop development completely. Proper regulation of surplus energy tariffs is vital as it directly affects the community's financial incentive. If the price is fair, more individuals are likely to be interested. Policies should reduce bureaucratic barriers to grid connections, facilitate the integration of new systems, and prevent unnecessary delays in infrastructure implementation.

- Energy Efficiency and Loss Reduction

Transitioning from centralized generation to decentralized technologies like PV installations reduces transmission and distribution losses and operational costs. System efficiency plays a crucial role and ensures more effective resource utilization. Investing in storage technologies, such as batteries, enhances energy supply management and supports the integration of *NC-SREs* generation.

Developing interconnected microgrids within the *ECs* contributes to achieving higher efficiency, and policy should acknowledge the benefits with proper incentives. Therefore, it is possible to show that this initiative benefits the residents' well-being and the grid.

- Access to Financing for Initial Infrastructure

The initial investment for *NC-SREs* projects is typically high and can be a barrier to implementing these solutions, especially when the initiative follows a top-down approach. Limited financial resources are common, especially in underserved regions, where *PV* generation can significantly improve the lives of the community and drive social growth. To address this challenge, it is crucial to develop financial mechanisms, either with funds from governments (public) or private initiatives. Favorable economic conditions include low-interest loans, subsidies, and co-ownership schemes, where members share the benefits and costs. These methods effectively support the development of new *ECs*.

- Technical Training and Operational Autonomy

ECs are not just about generating electricity through *PV* systems or other sources; another important characteristic is social impact and community participation. Therefore, to last through time, some residents must have the knowledge to operate and maintain the system. At the very least, they must understand the basic concepts to avoid dependence on third parties.

It is crucial to design a training program for residents to educate them about the functionality and maintenance of *PV* systems. Integrating energy education into community programs can help foster local ownership and strengthen community skills.

FLOWS AND LEVELS DIAGRAM

The final part of the *SD* analysis involves the System Dynamics model (refer to Annex 2 for more information), also known as the stock-and-flow diagram. The goal here is to transform the previous *CLD* scheme into a model that can simulate different behaviors and help identify the most likely outcomes under various scenarios.

After a review of the 23 slider-controlled parameters integrated into the model, four variables were identified as having a disproportionately high influence on system behavior. Table 2 lists the variables that most significantly altered the dominance of feedback loops, leading to fundamentally different system trajectories across the three scenarios. Their critical role lies in their capacity to activate or suppress reinforcing dynamics related to economic incentives, community adoption, and financial resilience. As such, they represent key structural levers within the model and serve as the foundation for scenario design. It is worth mentioning that these variables do not have specific units (except for electricity price, which represents a monetary unit). The rest of the variables are dimensionless and are used only to indicate whether the parameter is completely absent (0) from the model or has a high level of saturation (1).

Scenarios	Electricity Price (colombian pesos)	Confidence Level	Rate of Energy Communities Creation	Sensitivity To Variations in Income
BAU	100	0,3	0,01	0,5
PTSG	150	0,8	0,6	0,03
BC	400	0,9	0,7	0,01

Table 2. System Variables.

- Electricity Price: Used as a scalar to estimate annual revenues from surplus energy sales. The values (100, 150, 400) represent different market or policy contexts, not real-world tariffs, and are used to explore incentive intensity. An Initial Electricity Price of 100 defines the Business As Usual (*BAU*) baseline.
- Confidence Level: Ranges from 0.3 to 0.9 across scenarios and reflects perceived trust in decentralized energy systems. It modulates the strength of incentives and the effectiveness of community creation. Higher values promote reinforcing feedback like R1 and R3.
- Rate of Energy Communities Creation: Set between 0.01 and 0.7, this parameter defines how quickly new communities are formed.

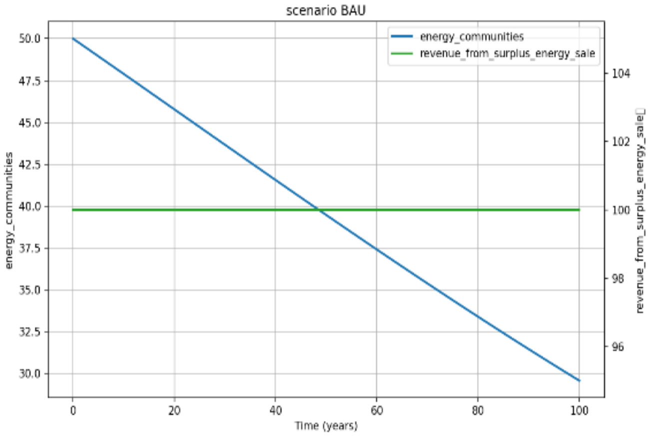
- Sensitivity to Variations in Income: This represents the financial fragility of producers, ranging from 0.5 (high sensitivity) to 0.01 (low sensitivity). Lower values buffer the impact of revenue fluctuations and allow for long-term stability and loop activation.

Business As Usual

The Business As Usual (*BAU*) scenario simulates a future in which *ECs* operate under limited support, with low electricity prices, weak confidence in decentralized models, and high financial vulnerability. This scenario explores the consequences of maintaining current conditions without significant policy or market interventions, revealing a gradual decline in *ECs* over time despite growing social interest.

The BAU scenario is defined by a low electricity price (100), low confidence in decentralized energy (0.3), minimal community creation (0.01), and high sensitivity to income variation (0.5). Under these conditions, the system shows a steady decline in the number of *ECs*, despite a gradual increase in interest.

The limited economic returns and high vulnerability prevent reinforcing feedback loops—such as financial stability and replication—from activating. As shown in Figure 2, surplus energy sales remain constant, and existing communities gradually dissolve, dominated by balancing loops that suppress expansion. This scenario illustrates how, even with social interest, insufficient market signals and institutional support lead to systemic decline.



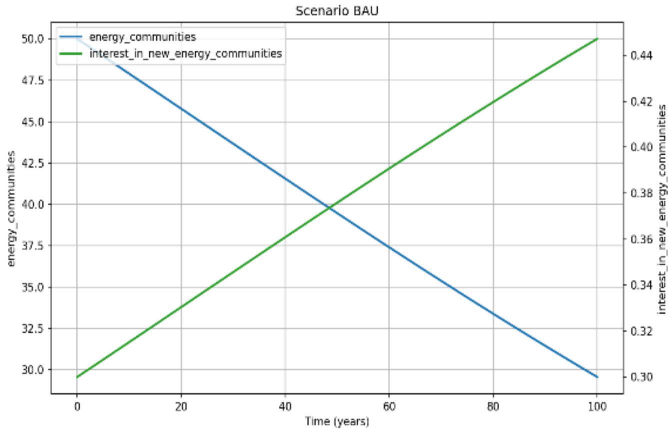


Figure 2. BAU Scenario.

Path Toward Sustainable Growth

The Path Toward Sustainable Growth (*PTSG*) scenario simulates a future where *ECs* receive moderate but strategic support through improved economic conditions, targeted policy interventions, and reduced regulatory barriers. This scenario explores the possibility of achieving a steady, self-sustaining growth of *ECs* over time, avoiding both stagnation and collapse.

With an electricity price of 150, a high confidence level (0.8), and a relatively fast rate of community creation (0.6), the system enters a growth trajectory. The reduced sensitivity to income variations (0.03) further stabilizes decentralized producers, protecting them from revenue shocks.

Simulation results show a steady and nonlinear increase in *EC* surplus revenue and social interest. Reinforcing loops, like R1 (financial incentive–generation–confidence) and R3 (autonomy–replication), are dominant. Economic returns and community replication demonstrate increasing synergy, driving expansion while remaining susceptible to systemic constraints.

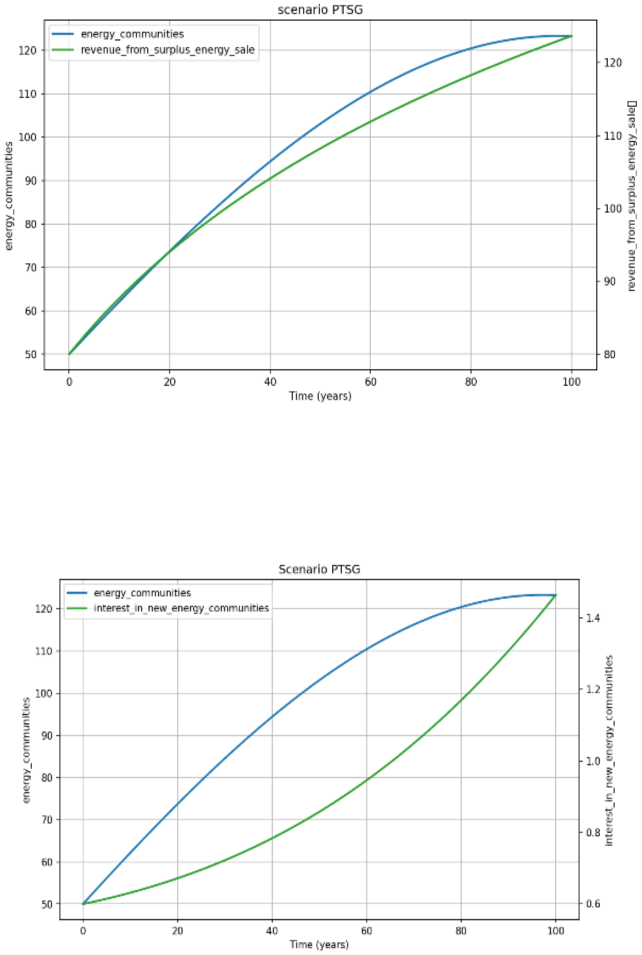


Figure 3. PTSG Scenario.

Boom and Collapse

The Boom and Collapse (*BC*) scenario is a stage where the initial trajectory is an explosive growth of *ECs* triggered by powerful incentives and favorable conditions but without sufficient structural support to ensure long-term stability. The scenario simulates the risks associated with overexpansion, resource saturation, and system fragility that can emerge when growth exceeds the system's capacity.

In this scenario, extremely favorable initial conditions—high electricity price (400), high confidence (0.9), fast community creation (0.7), and very low-income sensitivity (0.01)—generate a rapid, self-reinforcing expansion of *ECs*. Initially, the system benefits from fully activating reinforcing loops R1 and R3, resulting in exponential growth of community numbers and surplus energy revenue.

However, around year 75, the system reaches a saturation threshold. Despite growth in interest and revenue, *ECs* ultimately collapsed, most likely due to a build-up of structural issues, including operational strain, poor adaptability, and capacity overruns. This leads to a reversal of growth, with communities sharply declining toward the end of the simulation.

This scenario shows that, even under ideal conditions, exponential growth can destabilize the system, highlighting the need for regulatory, infrastructural, or adaptive mechanisms to sustain expansion.

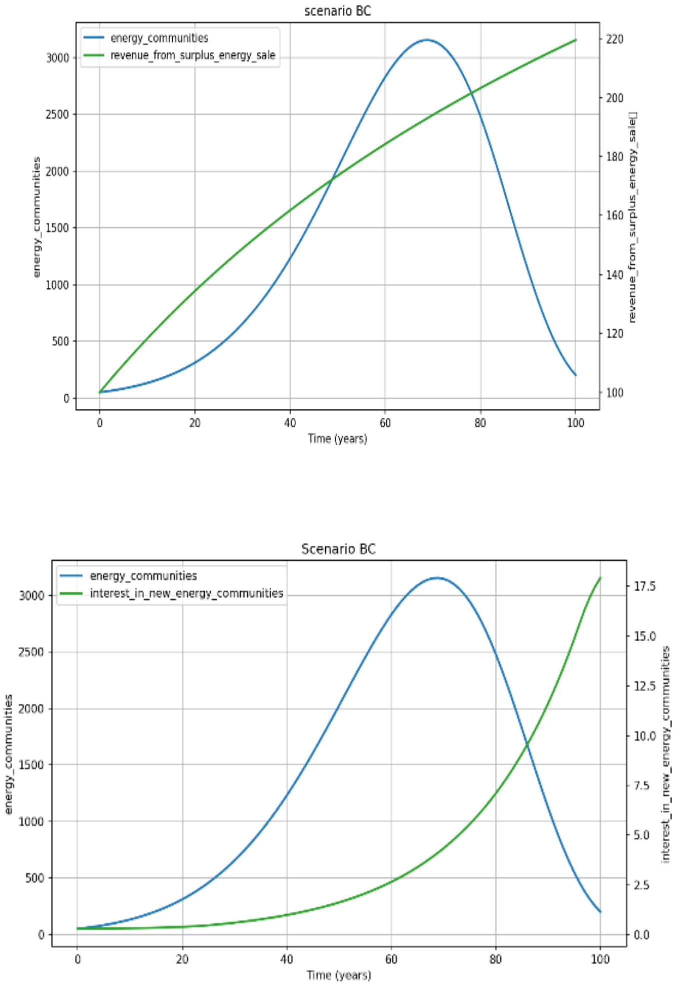


Figure 4. BC Scenario.

FINANCIAL FEASIBILITY OF IMPLEMENTING SOLAR ENERGY COMMUNITIES

A specialized web-based tool was designed to understand the financial landscape around solar *ECs*. Users receive estimated financial projections displayed in a structured and visually intuitive format by inputting relevant project parameters. The tool integrates real-time calculations and clear explanations, making it suitable for technical and decision-making stakeholders. This solution facilitates informed investment decisions in *PV ECs* by providing a preliminary, data-driven financial assessment, helping to identify the initial feasibility of a project.

Step 1: Select a Scenario

The first decision that each user needs to make is whether their project uses private funds, meaning it is a self-funding effort (bottom-up approach), or if government funding supports the initiative (top-down approach). This will determine which indicators are calculated.

Economic viability is essential when an *EC* is funded by private investment (bottom-up). Indicators, such as the payback period, *ROI*, or the project cash flow, contribute to the initiative's feasibility.

When the initiative comes from outside the community (top-down), the economic perspective is essential but not vital. In these cases, the project's goal is more closely related to social development and enhancing the well-being of residents. Here, SROI is calculated, and public spending is used as a substitute for cash flow.

Step 2: Select Input Variables

After selecting the type of financial resource, the user must provide other details about the project. First, the location is a key factor in calculating energy production and panel requirements. Inserting the location or placing it directly on a map is possible here. Currently, this study focuses on Colombia; therefore, the data available regarding solar irradiation (extracted from the NASA weather database) is limited to this territory. Then, the user must estimate the number of households in the community; this allows for an estimation of energy consumption. Here, the calculations are based on the basic consumption (defined as the minimum amount of electricity used by a typical household in a month to meet essential needs that can only be satisfied with this form of energy), as established in Resolution 355 of 2004, issued by the Mining and Energy Planning Unit [39]. The essential consumption is set at:

- **173 kWh/month** for areas below **1,000 meters above sea level**.
- **130 kWh/month** for areas at or above **1,000 meters above sea level**.

To simplify the calculations and consider the study's longevity, an essential consumption of 173 kWh per month is assumed for all cases.

Then, the user can choose between two panels: one with higher efficiency and a higher price, or another with lower efficiency and a more affordable price.

Reference	Efficiency	Cost	Area	Power
550W 24V Monocrystalline Solar Panel JA SOLAR	21.3%	168 USD	2,58 m2	550W
340W 24V Monocrystalline PERC Solar Panel JA Solar	20.2%	143 USD	1,68m2	340W

Table 3. Panel options [40].

Lastly, the user must choose whether the community will be connected to the grid. If not, the project can be considerably more costly, as batteries need to be purchased. Also, the possibility of selling the surplus generation to the grid depends on the connection.

Step 3: Run Analysis to Calculate the Indicators

After the user selects the scenario (private or public funding) and enters the input variables, the next step is to calculate the corresponding indicators. The method behind each calculation will be explained briefly in the following section.

- Required panels

This indicator determines the solar panel quantity required to fulfill the community's electricity needs. This is calculated by dividing the total annual energy use (kWh) by the yearly output of one panel. The result estimates the minimum number of panels required to cover the demand.

- Total area in square meters

This metric determines the physical space required to install all the solar panels. It is calculated by multiplying the number of required panels by the surface area of one panel (in m²). This value is essential to verify whether enough space is available on rooftops or land for the installation.

- Annual energy generated

This refers to the total electricity the solar energy system will produce in one year. It is calculated by multiplying the number of panels by the annual energy output of each panel. This helps assess whether the generation will meet, exceed, or fall short of the community's energy needs.

- Total CAPEX

The following costs are added together to determine *CAPEX*:

i. Panel Cost: Cost of purchasing the solar panels (number of panels multiplied by the price of each panel)
ii. Inverter Cost: 30% of the panel cost (approximate cost).
iii. Battery Cost: If not connected to the grid, the cost is three times the panel cost (approximate cost).
iv. Connection Cost: Fixed cost for connecting to the grid.
v. Mechanical Installation Cost: USD 15 per panel for mounting and installing the panels.
vi. Electrical Installation Cost: USD 15 per panel for electrical connections.
vii. Safety Cost: A fixed cost of $1,000 is required to ensure the safety of the installation.
viii. Soft Costs: A fixed cost of $3,000 for non-hardware-related expenses.

- Annual OPEX

Starting from a base value (3% of the *CAPEX*), this cost is adjusted annually to the expected inflation rate (fixed value of 7% per year). It includes maintenance, insurance, and administrative expenses. It also includes the average yearly cost, which is calculated by summing all yearly OPEX values and dividing by 25.

Indicators for private funding

- Annual cash flow

The annual cash flow represents the net income from the *PV* system. It is calculated by multiplying the total annual energy output by the electricity price per kWh (depending on whether the community is connected to the grid) and subtracting the operating costs. This value reflects either the savings from self-consumption or the revenues from selling surplus electricity to the grid (the kWh price differs for both cases). A discount rate applies to future cash flows to account for the expected decline in system efficiency over time (Approximately 1% per year). The electricity tariff projection is also an important factor influencing this cash flow, which estimates how electricity prices will evolve in the coming years based on an assumed annual percentage increase.

- Payback Period

It is calculated by summing the discounted cash flows yearly until the total amount equals or surpasses the *CAPEX*. If the accumulated discounted cash flows never reach *CAPEX* within a 25-year project horizon, the model will show that the investment will not be recovered. This metric is essential to understanding the project's risk and liquidity.

- *ROI*

It is determined by dividing the sum of all discounted cash flows throughout the system's lifetime by the initial *CAPEX*. The result is expressed as a percentage, showing how much return is generated relative to the investment made. A project's *ROI* reflects its profitability and efficiency: high *ROI* is positive, and negative *ROI* signals losses and infeasibility.

Indicators for government funding

- Public Expenditure

To estimate the public expenditure associated with the project, a dedicated function calculates the total outflows over a 25-year period. Initial *CAPEX* and projected annual *OPEX* (with a 7% yearly inflation adjustment) are included. The sum of all these values represents the total amount of public spending required to sustain the project.

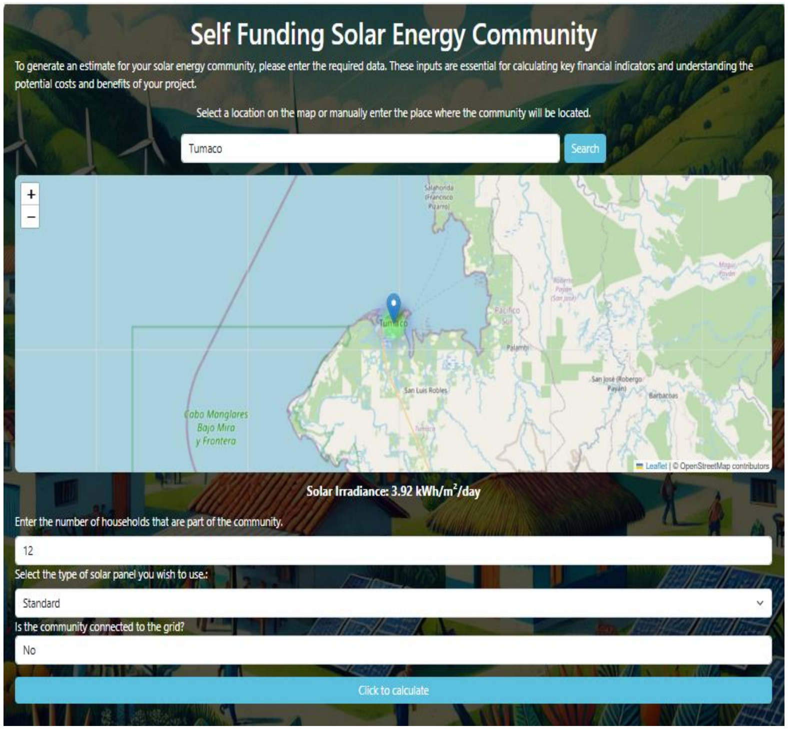
- Social Return on Investment (SROI)

Is computed by comparing the total investment (*CAPEX* + *OPEX*) with the cumulative social benefits generated throughout the project's life cycle. These benefits include monetary savings from reduced electricity bills due to local generation, avoided CO_2 emissions (valued at USD 30 per ton), income from job creation (based on average annual salaries), and health-related cost reductions. The SROI is expressed as a ratio, representing how much social value is created for every dollar invested in the project.

Example of use

With the tool now properly introduced, the following section presents examples of its use and explains how to interpret the results.

As a first example, the tool allows the user to identify places where installing solar panels without a grid connection is not profitable. For instance, a simulation was made for the Tumaco district with the details shown in Figure 5. It is possible to observe here that the solar radiation is 3.92 kWh/m2/day.



Self Funding Solar Energy Community

To generate an estimate for your solar energy community, please enter the required data. These inputs are essential for calculating key financial indicators and understanding the potential costs and benefits of your project.

Select a location on the map or manually enter the place where the community will be located.

Tumaco

Solar Irradiance: 3.92 kWh/m²/day

Enter the number of households that are part of the community.

12

Select the type of solar panel you wish to use.:

Standard

Is the community connected to the grid?

No

📈 Payback Period

You will not recover your investment in 25 years.

💰 Return On Investment

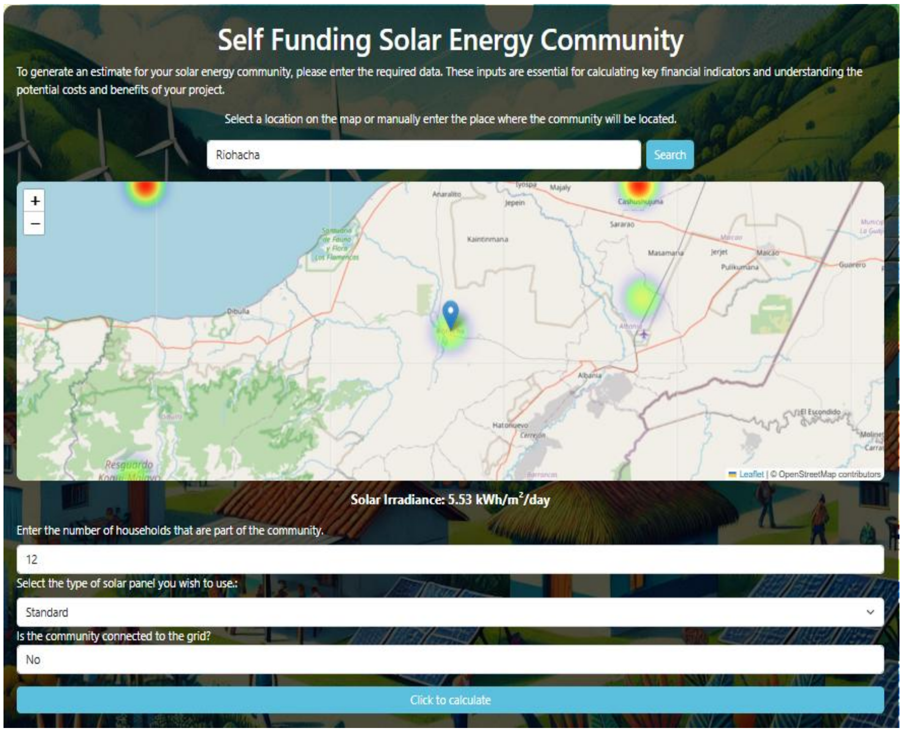
ROI: -31.63%

Levelized Cost of Energy

$0.0488 USD/kWh

Figure 5.Tumaco Simulation.

Figure 5 shows the infeasible project results from the initial Tumaco scenario. The payback period, for example, is more than the lifetime of the project (25 years) and the *ROI* is negative. Therefore, from an economic perspective, inversion is unattractive. This is interesting, as it demonstrates the cost problem associated with projects that are not connected to the grid, as batteries and other storage technologies are too expensive.



Self Funding Solar Energy Community

To generate an estimate for your solar energy community, please enter the required data. These inputs are essential for calculating key financial indicators and understanding the potential costs and benefits of your project.

Select a location on the map or manually enter the place where the community will be located.

Riohacha

Solar Irradiance: 5.53 kWh/m²/day

Enter the number of households that are part of the community.

12

Select the type of solar panel you wish to use.:

Standard

Is the community connected to the grid?

No

Payback Period

You will recover your investment in 13 years.

Return On Investment

ROI: 18.95%

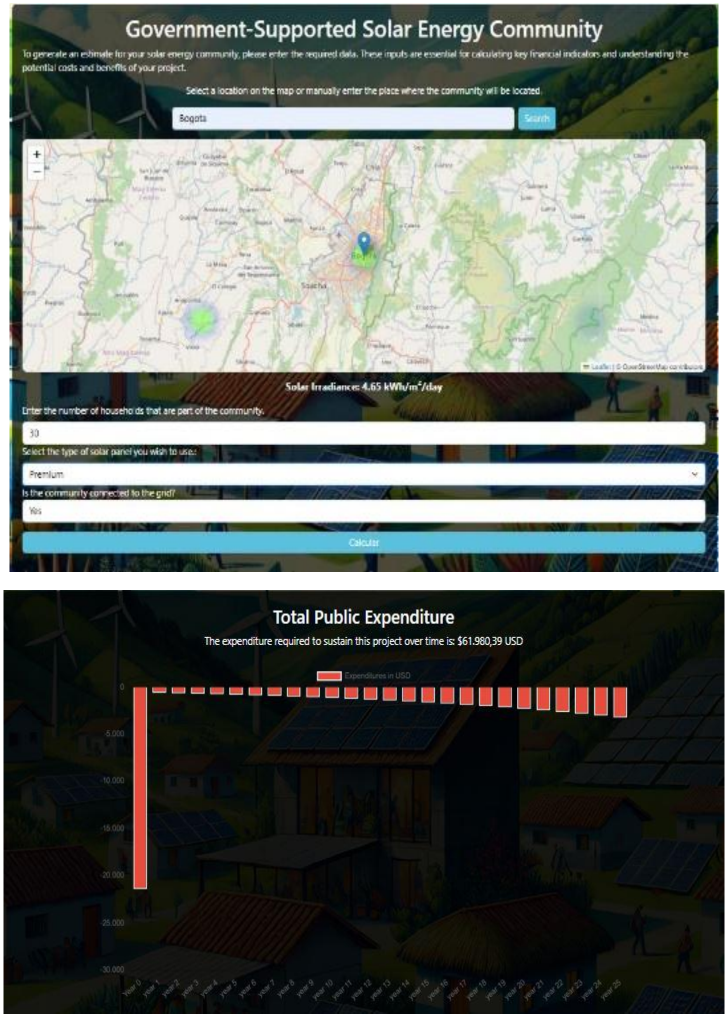
Levelized Cost of Energy

$0.0564 USD/kWh

Figure 6.Riohacha Simulation.

The second scenario is a replication of the first one (same demand and is not connected to the grid either), however, in this case, the simulation was made for Riohacha, another geographical location in Colombia, with greater radiation 5.53 kWh/m2/day. As is shown in Figure 6, in this case, the payback period is 13 years and the *ROI* is positive. Despite the extended payback period, the project's economic viability remains, especially considering its community focus, which prioritizes wellbeing and opportunities over profit.

Another interesting example of use is the difference between the indicator for self and public financing. Figure 7 shows the public expenditure necessary to maintain the project over the lifetime period. This is crucial because *CAPEX* is usually the only cost considered, and as previously noted, government support in top-down approaches must be consistent throughout the project, not just initially.



Government-Supported Solar Energy Community

To generate an estimate for your solar energy community, please enter the required data. These inputs are essential for calculating key financial indicators and understanding the potential costs and benefits of your project.

Select a location on the map or manually enter the place where the community will be located.

Bogota

Solar Irradiance: 4.65 kWh/m²/day

Enter the number of households that are part of the community.
30

Select the type of solar panel you wish to use.:
Premium

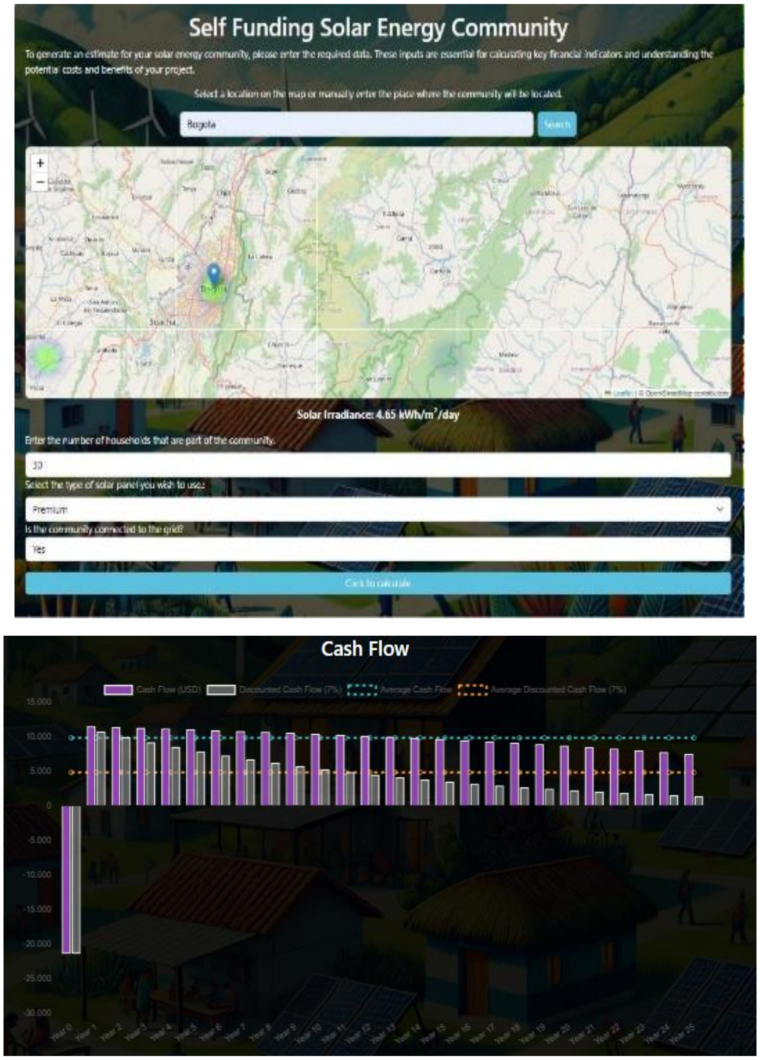
Is the community connected to the grid?
Yes

Total Public Expenditure

The expenditure required to sustain this project over time is: $61.980,39 USD

Figure 7.Public Simulation.

Regarding self-funded projects, Figure 8 presents the projected cash flow, first-year *CAPEX,* and annual savings from reduced community electricity bills or potential surplus energy sales to the grid.



Self Funding Solar Energy Community

To generate an estimate for your solar energy community, please enter the required data. These inputs are essential for calculating key financial indicators and understanding the potential costs and benefits of your project.

Select a location on the map or manually enter the place where the community will be located.

Bogota

Solar Irradiance: 4.65 kWh/m²/day

Enter the number of households that are part of the community.

30

Select the type of solar panel you wish to use:

Premium

Is the community connected to the grid?

Yes

Figure 8.Private Simulation.

The tool enables analysis of various implementation scenarios and their associated cost impacts, providing valuable support for decision-making.

DISCUSSION

Alignment Between Leverage Points and Scenario Parameters

A key finding of this research is the strong relation between leverage points derived from *CLD* analysis and the four variables that influence the dynamics of the simulated levels and flows model. This cross-validation between conceptual structure and model behavior strengthens the system's internal consistency and reveals critical pathways for intervention. In addition to this key finding, five key observations were made.

First, the electricity price, a highly influential variable within the simulations, is directly linked to the regulatory framework and the leverage point presented by surplus energy tariffs. The simulation results confirm that fair and sufficiently high energy tariffs can trigger a virtuous cycle by increasing surplus revenues, boosting confidence, and accelerating the replication of *ECs*. However, the *BC* scenario highlights that without regulation and adaptive limits, excessively favorable conditions lead to unsustainable exponential growth ending in collapse. This reinforces the notion that regulatory pricing mechanisms are not merely enablers—they are structural levers whose design must balance incentives with system resilience, preventing feedback saturation and long-term instability.

Second, the confidence level in decentralized energy systems aligns closely with the leverage point concerning the perception of community benefits. The model reveals that higher confidence amplifies incentives, accelerates community creation, and helps stabilize the system against external shocks. This shows that community engagement, transparent communication, and trust-building are not secondary strategies but core system drivers.

Third, the rate of *EC* creation reflects the combined effects of various qualitative factors, such as access to funding, technical training, and regulatory support. The ability to convert interest into operational communities depends on removing financial and procedural bottlenecks, which influence whether reinforcing loops are activated or remain inactive.

Fourth, the variable sensitivity to variations in income reflects the economic vulnerability of decentralized producers. This vulnerability can be mitigated through adequate financing schemes and stable regulatory frameworks. A low sensitivity value in the model correlates with long-term system stability, while high sensitivity leads to collapse, as seen in the *BAU* scenario.

Finally, it is important to note that energy efficiency and loss reduction were the only marginal leverage points in the simulated scenarios. Despite being important *CLD* features, they appear to have little influence on *ECs'* creation or loss rates.

Implication for Strategic Design

The convergence between simulated drivers and conceptual leverage points suggests that intervening in a few high-leverage areas—specifically pricing policy, community engagement, and financial stability—can lead to large-scale systemic change. These findings reinforce the importance of designing coherent strategies that integrate technical, social, and regulatory dimensions, rather than focusing on isolated components.

The identification of these key parameters is important, as it can support the development of new public policies or the evaluation of existing regulations. Moreover, this work demonstrates that, with proper effort, *ECs* are viable initiatives, while also highlighting their sensitivity to favorable environments and external factors.

Economic Viability Analysis

The results obtained from the simulation tool provide key insights into the economic behavior of *PV-based EC* projects under different configurations. One of the most relevant findings is the significant increase in total project costs when the system is not connected to the grid. This scenario requires the addition of energy storage systems—primarily batteries—which represent a high capital cost and considerable ongoing maintenance expenses. Numerous times, these off-grid systems fail to achieve payback within the 25-year evaluation period,

The geographic location of the community plays a critical role as well. Reduced solar irradiance in a given area results in lower annual energy generation, demanding a greater number of solar panels, increasing both surface area coverage and financial investment, to satisfy community energy needs. This variation emphasizes the importance of site-specific assessments for planning and resource allocation.

Two financing scenarios were explored: one based on private funding and the other on public/state funding. While public support often focuses on covering the *CAPEX*, the results suggest that this approach alone is insufficient. To ensure long-term sustainability, strategies must also cover *OPEX* costs throughout the project's lifespan. This could include mechanisms such as subsidized maintenance programs, community-managed operation models, or integration with national rural electrification funds.

These findings highlight the need for a holistic financing model that considers both upfront costs and ongoing operational requirements, especially in vulnerable or remote regions where grid connection is not feasible.

CONCLUSIONS

This research has shown that identifying feedback loop dominance and systemic leverage points is not only a conceptual exercise but also a validation mechanism when aligned with key parameters from the stock-and-flow diagram. This alignment enabled a realistic assessment of leverage points within the operational dynamics of *ECs*, generating actionable knowledge to support their long-term viability. Crucially, the study revealed that even well-intentioned incentives can lead to unintended consequences if they oversaturate the system, underscoring the need for carefully calibrated policy interventions.

The web tool developed offers significant value, particularly in assessing the financial viability of solar *EC* projects. It goes beyond traditional CAPEX evaluation by incorporating OPEX dynamics, providing a more comprehensive view of long-term sustainability over a 25-year operational horizon. This is especially relevant for public sector actors and funding bodies, as it allows them to make informed decisions not only about project initiation but also about ongoing financial resilience.

From a theoretical standpoint, this work contributes to the growing literature on socio-technical transitions by integrating system dynamics with the practical realities of community-based energy initiatives. It highlights the importance of systemic coherence and dynamic validation in the governance of decentralized energy systems.

Practically, this research suggests that policymakers and municipal planners should consider leverage point sensitivity before designing subsidy schemes or regulatory frameworks. Likewise, community leaders and project developers should adopt dynamic modeling tools to assess the long-term impact of their strategic decisions.

Future research should focus on expanding the model to include social acceptance dynamics, inter-community cooperation, and institutional path dependencies. Additionally, comparative studies across different national contexts could further validate the robustness and transferability of the framework presented here.

Overall, this work provides both theoretical depth and practical insight, advancing the understanding of how to design, support, and sustain *ECs* in complex and changing environments.

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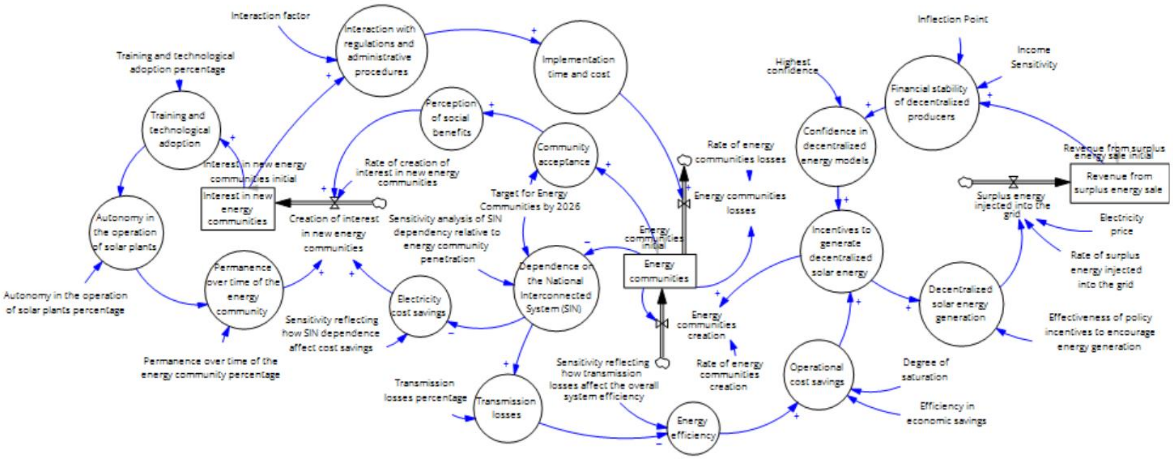
Annex 1 Feedback Loop Literature References

Feedback Loop	Bibliography reference
R1: Surplus Sales and Financial Stability of Decentralized Generation	1. Monsberger, C., Fina, B., & Auer, H. (2021). *Profitability of energy supply contracting and energy sharing concepts in a neighborhood energy community*. Energies, 14(4), 921. [DOI: 10.3390/en14040921] 2. Dino, G. E., et al. (2023). *Modeling of a bidirectional substation in a district heating network: Validation, dynamic analysis, and application to a solar prosumer*. Energy, 284, 128621. [DOI: 10.1016/j.energy.2023.128621]
R2: Energy Efficiency and Reduction of Transmission Losses	1. Fleischhacker, A., et al. (2019). *Portfolio optimization of energy communities to meet reductions in costs and emissions*. Energy, 173, 1092–1105. [DOI: 10.1016/j.energy.2019.02.104] 2. Almeida, L., Soares, A., & Moura, P. (2023). *A Systematic Review of Optimization Approaches for the Integration of Electric Vehicles in Public Buildings*. Energies, 16(13), 5030. [DOI: 10.3390/en16135030]
R3: Training and Technological Appropriation	1. Buonomano, A., Barone, G., & Forzano, C. (2023). *Latest advancements and challenges of technologies and methods for accelerating the sustainable energy transition*. Energy Reports, 9, 3343–3355. [DOI: 10.1016/j.egyr.2023.02.015] 2. Pelka, S., et al. (2022). *Participation of active consumers in the electricity system: Design choices for consumer governance*. Energy Strategy Reviews, 44, 100992. [DOI: 10.1016/j.esr.2022.100992]
B1: Installed Capacity and Dependence on the SIN	1. López, I., et al. (2024). *European energy communities: Characteristics, trends, business models and legal framework*. Renewable and Sustainable Energy Reviews, 197, 114403. [DOI: 10.1016/j.rser.2024.114403] 2. Haji Bashi, M., et al. (2023). *A review and mapping exercise of energy community regulatory challenges in European member states*. Renewable and Sustainable Energy Reviews, 172, 113055. [DOI: 10.1016/j.rser.2022.113055]
B2: Community Acceptance and Development of New Energy Communities	1. Costa, V., & Campanini, F. (2024). *Community-Centred Energy Planning: Within and beyond Administrative Borders*. Sustainability, 16(5), 2049. [DOI: 10.3390/su16052049] 2. Bauwens, T., et al. (2022). *Conceptualizing community in energy systems: A systematic review of 183 definitions*. Renewable and Sustainable Energy Reviews, 156, 111999. [DOI: 10.1016/j.rser.2021.111999]

Annex 2 Level and Flows Diagram

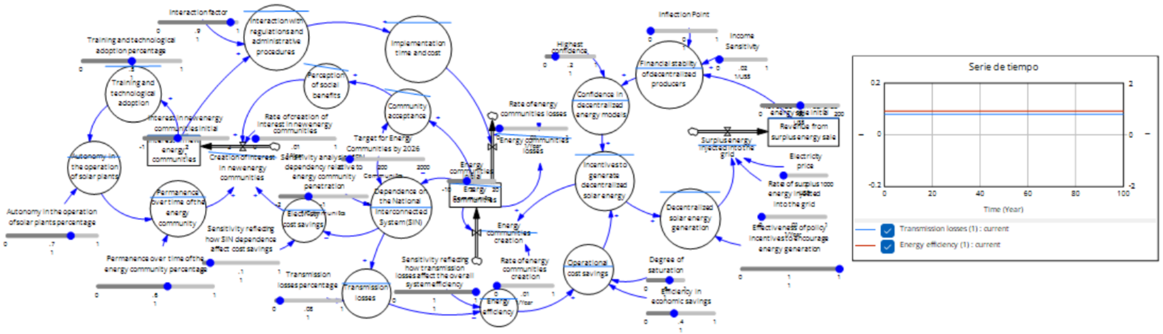


Levels and Flows Diagram.

Parameters and Numeric Value for Simulated Scenarios

[Escenarios.xlsx - Hojas de cálculo de Google]

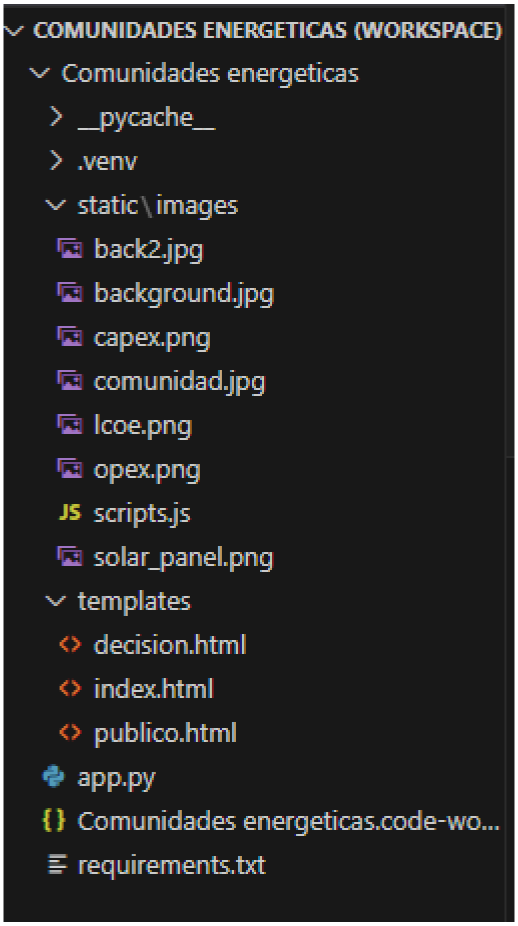
Annex 3 Sensibility Test



- This test was conducted using the stock and flow diagram. Essentially, it involved setting all 23 slides to their maximum value (1) to observe the system’s response. The test revealed that the system is particularly sensitive to variables related to electricity price. The test showed that the system is particularly sensitive to variables related to electricity price and that it cannot tolerate certain sensitivity levels approaching 1. The test is carried out directly in the model using Vensim, and the behavior is observed in real time.

Annex 4. Code

Code Structure:



```
COMUNIDADES ENERGETICAS (WORKSPACE)
  Comunidades energeticas
    __pycache__
    .venv
    static\images
      back2.jpg
      background.jpg
      capex.png
      comunidad.jpg
      lcoe.png
      opex.png
      scripts.js
      solar_panel.png
    templates
      decision.html
      index.html
      publico.html
    app.py
    Comunidades energeticas.code-wo...
    requirements.txt
```

Complete code:

https://drive.google.com/file/d/1c0TbAemAuBk_zs09sM2mAKSziC88tjo0/view?usp=sharing