A Conceptual Framework for Decentralized Energy Solutions: Exploring Pathways to Resilience and Low-Carbon Transitions

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Abstract: Decentralized energy generation solutions face persistent challenges related to the intermittency of renewable sources and the lack of adequate infrastructure in vulnerable communities. This study proposes a conceptual framework to support the development of resilient and sustainable energy solutions adapted to local vulnerabilities, considering technical, social, and environmental dimensions. The methodology adopted was Design Science Research (DSR), structured into six stages that guided the development of the artifact. The resulting framework was designed as an explanatory model, consisting of three stages and seven criteria that guide processes from data collection to energy scenario simulation and decision support. The artifact was theoretically validated using authoritative sources such as the IEA, IRENA, IPCC, and key DSR authors, ensuring alignment with the literature and the Sustainable Development Goals, particularly SDG 7, which promotes access to affordable, reliable, sustainable, and modern energy for all. The results suggest that the model contributes to enhancing local energy resilience and has strong potential for replication in low-infrastructure contexts. The proposal aligns with the global agendas for decarbonization, energy inclusion, and environmental sustainability.

Keywords: Design Science Research; Decentralized Generation; Energy Resilience; Social Technologies; Decision Support

1. Introduction

The energy transition represents a global movement aimed at increasing the share of renewable sources, such as solar and wind power, in national energy matrices [1]. To enable this shift and address the challenges posed by climate change, international agreements and specific targets have been established [2,3]. A key milestone in this context was the Paris Agreement, signed in 2015 during the 21st Conference of the Parties (COP21), which set commitments among countries to reduce greenhouse gas emissions [2].

Within this context, Sustainable Development Goal (SDG) 7 assumes a central role, aiming to ensure reliable, sustainable, modern and affordable access to energy for all [3]. One of the main challenges of the energy transition lies in expanding electricity supply infrastructure, as emphasized in target 7.b of SDG 7, which advocates the development of sustainable technologies, especially in developing countries [3]. Moreover, electricity access remains a fundamental parameter for social inclusion, particularly considering that 785 million people still lack access to electricity [4].

In this context, decentralized generation solutions, such as microgeneration and distributed generation, emerge as viable alternatives for expanding energy access in regions with limited infrastructure, as they eliminate the need to extend the conventional power grid [5,6]. This study focuses on vulnerable contexts characterized by precarious energy infrastructure, including isolated rural communities, urban peripheries, and regions exposed to extreme weather events, where the lack of reliable electricity supply undermines social and economic development. These solutions not only meet local energy demands but can also contribute significantly to improving the living conditions of affected populations [7,8]. However, to be both effective and sustainable, such solutions must be resilient [4,9].

According to the Intergovernmental Panel on Climate Change (IPCC), resilience refers to the capacity of a system to adapt to, withstand, and recover from crises, incorporating the principles of prevention, adaptation, and resistance [10,11]. Achieving this requires not only an assessment of available technologies, but also a thorough understanding of the social and environmental context, including the externalities involved, ensuring long-term, effective solutions.

Renewable energy generation presents an inherent challenge: intermittency, characterized by the natural variability of energy supply, such as fluctuations in solar radiation and wind speed [6]. A widely recommended strategy to mitigate this challenge beyond the combination of sources involves the use of energy storage systems [12]. Besides helping to ensure continuity of supply, storage enhances grid stability, especially in areas with limited infrastructure or those vulnerable to extreme weather events, thus strengthening the energy resilience of such systems [12].

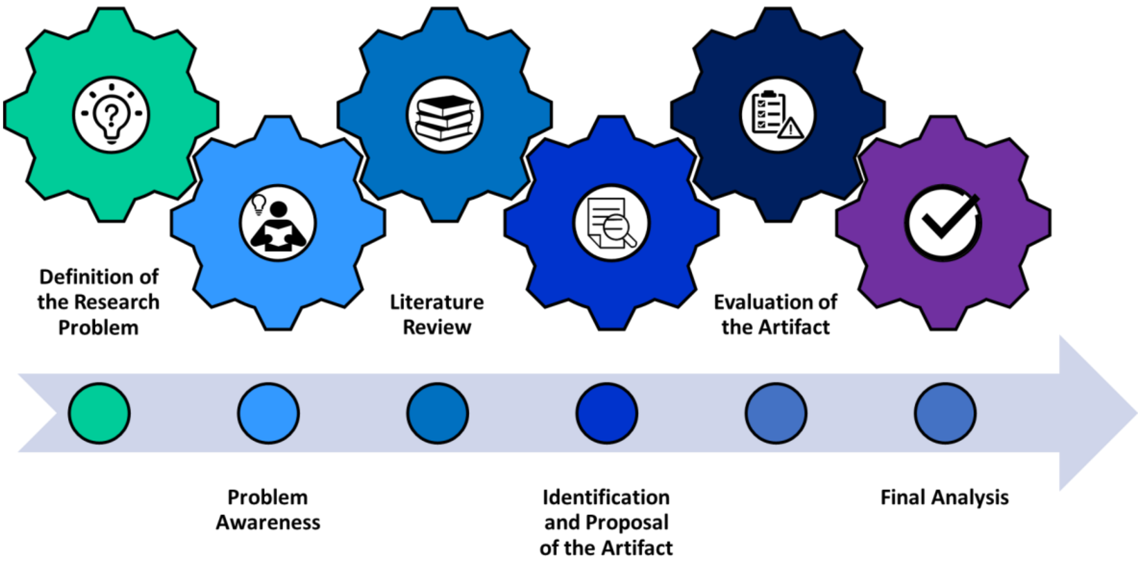
The objective of this study was to develop a framework to support the design of decentralized energy generation solutions that are resilient, sustainable, and adapted to local vulnerabilities. To guide the development of this artifact, the Design Science Research (DSR) methodology was adopted, which shows particular suitability to complex contexts in which technical, social and economic factors interact [13]. The resulting framework integrates technical, social, and environmental dimensions, supporting decision-making and the implementation of low-carbon initiatives based on social technologies. Social technology refers to any set of techniques, methods, processes, or practices developed and applied to solve social problems in a participatory, sustainable, and accessible way, fostering inclusion, improving quality of life, and strengthening communities [14].

2. Methodology

For this study, the DSR approach was adopted to guide the development of a framework aimed at creating decentralized energy generation solutions that are resilient, sustainable, and adapted to local vulnerabilities. DSR proves particularly well-suited to complex contexts involving technical, social, and environmental dimensions, following an iterative cycle of artifact construction and evaluation. [13].

Accordingly, the method was applied in six stages: (i) definition of the research problem; (ii) problem awareness; (iii) literature review; (iv) identification and proposal of the artifact; (v) artifact evaluation; and (vi) final analysis. The adopted process was illustrated in Figure 1, which outlines the activities carried out at each stage.

Figure 1. Methodologic Process. Adapted from [13,15].



2.1. Definition of the Research Problem

In this stage, the central problem was identified as the intermittency of renewable energy sources and the lack of adequate energy infrastructure in vulnerable communities. The difficulty in ensuring a continuous and sustainable energy supply led to the formulation of the following research question:

How can the development of decentralized energy generation solutions that are resilient and suited to local vulnerabilities be supported through the use of social technologies?

2.2. Problem Awareness

This stage involved analyzing institutional documents (from the IEA, IRENA, BNDES, and OECD) and academic studies addressing the energy transition, resilience, and distributed generation. This mapping enabled the identification of gaps in the practical application of low-carbon solutions in socially vulnerable contexts, with a focus on the challenges of adapting technologies to local conditions.

2.3. Literature Review

The purpose of the literature review was to identify strategies, criteria, and guidelines that underpin energy resilience in decentralized solutions. A systematic review was conducted to map key concepts related to reliability, intermittency, social technologies, energy storage, and sustainability. This theoretical foundation supported the definition of the technical and conceptual requirements for the framework.

2.4. Identification and Proposal of the Artifact

Based on the evidence gathered in the previous stages, the most appropriate solution type was identified to support the design, evaluation, and implementation of decentralized energy generation systems. The proposed artifact was a framework that integrates technical, social, and environmental aspects to support decision-making in vulnerable settings.

2.5. Evaluation of the Artifact

The artifact was evaluated to assess its applicability in addressing the identified problem. This was done through a conceptual analysis based on criteria such as practical applicability, alignment with the Sustainable Development Goals (particularly SDG 7, but also SDGs 1, 3, 9, 11, and 13), scalability, and adherence to the principles of energy resilience.

2.6. Final Analysis

The final stage consisted of consolidating the results obtained throughout the research and developing recommendations for the future application of the framework. Suggestions were also made for its validation in real-world case studies and for possible adaptations to different contexts, indicating opportunities for future research.

3. Results and Discussion

Based on the application of the DSR approach, this section presents the main results obtained from the development of the proposed framework. The artifact was designed to support the construction of decentralized energy generation solutions that are resilient, sustainable, and tailored to local vulnerabilities. The results discussed here reflect decisions made at each methodological stage, demonstrating how technical, social, and environmental elements were integrated into the final structure of the framework.

3.1. Results Achieved

The outcomes of the artifact development process were organized according to the six methodological stages: definition of the research problem, problem awareness, literature review, artifact identification and proposal, artifact evaluation, and final analysis.

3.1.1. Definition of the Research Problem

This stage identified the need to develop decentralized energy generation solutions that are resilient, sustainable, and adapted to vulnerable contexts. This demand arises from the intermittency of renewable sources and the lack of adequate energy infrastructure, which hinders the continuous and reliable supply of electricity. Accordingly, an opportunity was identified to create an artifact capable of supporting decision-making processes focused on formulating low-carbon energy initiatives.

3.1.2. Problem Awareness

Through an analysis of institutional documents (IEA, IRENA, BNDES, OECD) and scientific literature, gaps were mapped in the practical implementation of sustainable solutions in socially vulnerable regions. A key issue identified was the challenge of adapting technologies to local conditions, which undermines the resilience, effectiveness, and scalability of decentralized initiatives.

3.1.3. Literature Review

To establish a solid theoretical foundation for the artifact, a systematic literature review was conducted. The results of this stage were presented by Brito et al. [16]. To ensure methodological rigor, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol was followed. This systematic approach ensures transparency and consistency in the selection of sources and allows for a comprehensive mapping of strategies related to energy resilience and decentralized solutions.

3.1.4. Identification and Proposal of the Artifact

Based on the data gathered in the earlier stages, the artifact was classified as an explanatory model, according to Hevner et al. [13] and Vom Brocke et al. [15], as it seeks to describe the dynamics and causal relationships among the elements involved in the decentralized energy generation process.

As a result, the Dynamic Assistant for the Resilience of Decentralized Solutions framework was developed, as shown in Figure 2. The model comprises seven criteria, distributed across three main stages:

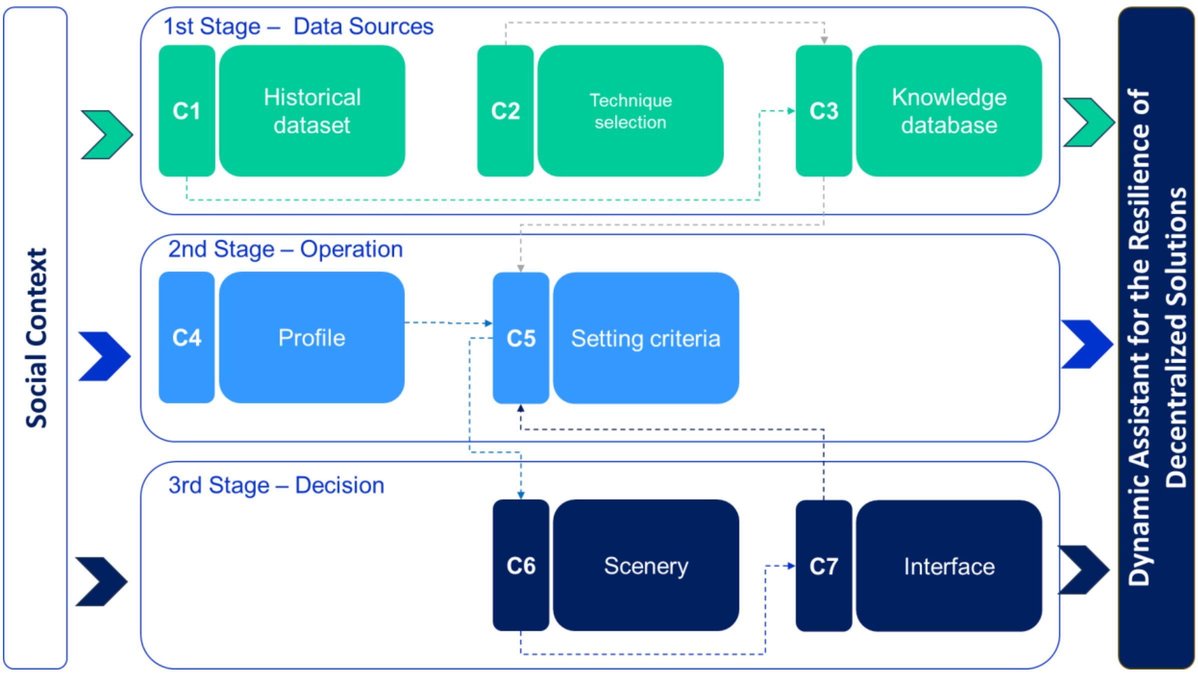
- Criterion 1 (C1) – Historical dataset: Collection of historical data on energy sources and consumption patterns;
- Criterion 2 (C2) – Technique selection: Selection of techniques compatible with the local context;
- Criterion 3 (C3) – Knowledge database: Organization of the internal database;

- Criterion 4 (C4) – Profile: Engagement of local managers in defining demand profiles;
- Criterion 5 (C5) – Setting criteria: Establishment of technical, social, and economic requirements for scenario building;
- Criterion 6 (C6) – Scenery: Generation of operational scenarios based on the previous data;
- Criterion 7 (C7) – Interface: Decision-support interface, generating parameters to inform managers and allow for dynamic adjustments, enhancing system resilience.

The model's structure was organized into the following stages:

- Stage 1 – Data Sources: comprises C1, C2, and C3, focused on building a structured knowledge base;
- Stage 2 – Operation: includes C4 and C5, where analytical models and requirements are defined;
- Stage 3 – Decision: includes C6 and C7, where generated parameters are assessed, and define the feasibility of the proposed scenarios in terms of energy resilience.

Figure 2. Dynamic Assistant Framework for the Resilience of Decentralized Solutions. Provided by authors.



3.1.5. Evaluation of the Artifact

Given that the artifact was conceptual and has not yet been applied in a real-world case study, a structured theoretical validation was carried out. Table 1 presents a mapping of the framework's seven criteria to their respective theoretical references.

Table 1. Theoretical foundation associated with each technical criterion used in the development of the framework, providing the methodological basis for validation in the DSR process. Provided by authors.

Criteria	Explanation	Source
C1	Historical analysis of energy data enables the identification of usage and generation patterns, essential for planning context-appropriate solutions.	[17]
C2	Selecting technologies based on geographical, social, and environmental contexts ensures the efficiency and acceptance of energy solutions	[6,9]
C3	The systematic organization of primary and secondary data can be crucial for effective use of analytical models and simulations.	[15]
C4	Including local managers in decision-making increases flexibility and enhances governance and social participation.	[18]
C5	Developing prospective scenarios helps address technical and climatic uncertainties in energy systems.	[19]
C6	Scenario modeling allows simulation of future conditions, serving as a strategic tool in sustainable energy planning.	[20]
C7	Decision support systems facilitate the use of data and models by non-experts, improving accessibility and agility in energy management.	[13,15]

Logical or conceptual validation has gained broad acceptance in DSR-based projects, particularly during early stages focused on proposing robust theoretical structures for future real-world testing. This step helps ensure the model's technical soundness and potential for generalization prior to empirical validation.

Furthermore, the evaluation criteria were derived from both the literature and methodological guidelines for explanatory artifacts in complex environments [13,15].

3.1.6. Final Analysis

The final analysis demonstrates that the artifact integrates the core dimensions involved in building resilient energy solutions. From a technical perspective, the framework includes historical data gathering, operational scenario modeling, and dynamic decision support, enabling adaptive responses to the intermittency of renewable sources. In the social dimension, the model emphasizes the active participation of local managers, the contextual selection of technologies, and the promotion of governance and social inclusion, key aspects for ensuring solution appropriateness and community acceptance. Finally, on the environmental front, the artifact incorporates criteria that ensure sustainable use of natural resources, mitigation of environmental impacts, and adaptation to climate vulnerabilities, aligning with sustainability principles and global energy transition goals.

3.2. Discussion

This study presents an innovative framework that integrates technical, social, and environmental dimensions to support the development of resilient and sustainable decentralized energy generation solutions in vulnerable contexts. The explanatory model clarifies the dynamics among involved elements, supporting informed decision-making by managers and policymakers.

As a conceptual model validated primarily through theoretical foundations, its practical applicability still needs to be tested in real-world scenarios. The absence of empirical validation limits understanding of the framework's performance in the face of local variability and complexity. Moreover, external factors such as public policy and economic conditions were not directly incorporated into the model.

The proposed model represents a promising starting point; however, practical validation must be conducted to assess ts effectiveness and its potential impact on enhancing energy resilience in vulnerable communities.

4. Conclusion

This study proposed a conceptual framework, grounded in the DSR approach, to support the development of decentralized energy generation solutions that are resilient, sustainable, and sensitive to local vulnerabilities. Structured into three stages and seven criteria, the artifact integrates historical, contextual, and operational data to guide the design of energy scenarios aligned with specific socio-environmental conditions.

Drawing on authoritative sources such as the IEA, IRENA, and IPCC, the framework provides a theoretical structure for supporting decision-making in contexts characterized by limited energy infrastructure. While the framework aligns conceptually with global agendas on decarbonization, energy access, and social inclusion—particularly SDG 7—it has not yet been applied to a specific low-carbon transition context. Its current contribution lies in providing a theoretical basis for future research that seeks to integrate technical, social, and environmental dimensions in decentralized energy planning.

While the framework conceptually aligns with international sustainability agendas addressing energy and social inclusion, it has not yet been applied to a specific low-carbon transition context. Instead, it offers a theoretical foundation that may inform future research aiming to integrate technical, social, and environmental dimensions in decentralized energy planning.

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